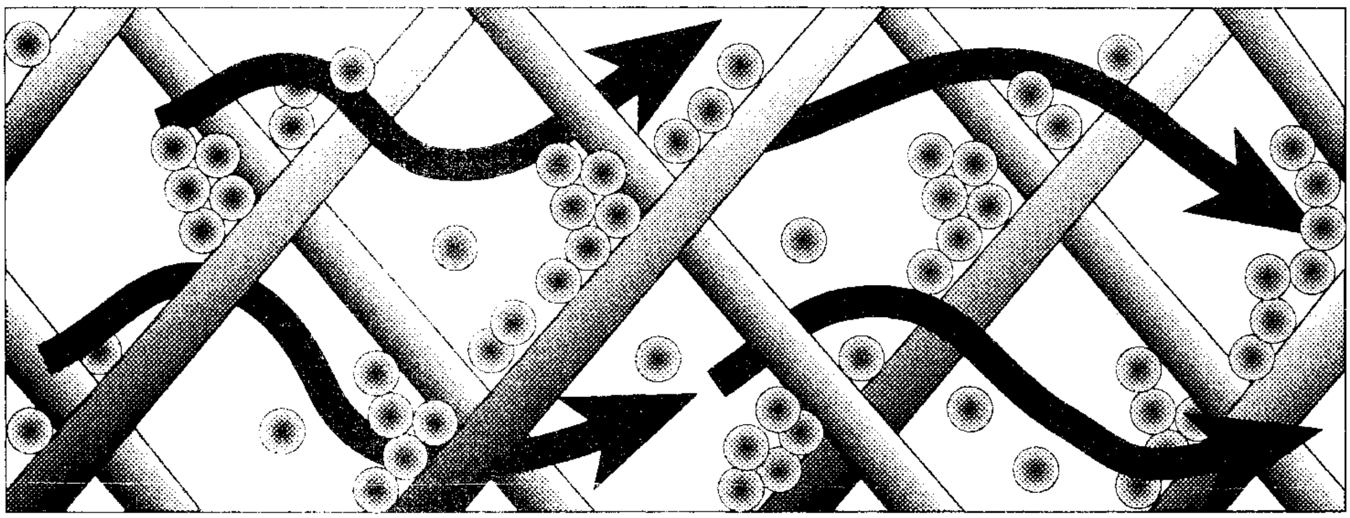
FOULING AND MODULE DESIGN WORKSHOP



University of Delaware
Lewes, Delaware
October 30 - November 1, 1993

NWRI
National Water Research Institute

NATIONAL SCIENCE FOUNDATION

Fouling and Module Design Workshop

Sponsored by

National Water Research Institute

with the cooperation of

The Office of Chemical and Transport Systems
National Science Foundation

Virden Conference Center
University of Delaware
Lewes, Delaware
October 30 - November 1, 1993

Published November 4, 1993
by

NATIONAL WATER RESEARCH INSTITUTE
10500 Ellis Avenue
P.O. Box 20865
Fountain Valley, California 92728-0865

National Water Research Institute Occasional Paper Number NWRI-93-3

FOREWORD

This report describes the objective, organization, and results of a workshop which addressed the issues associated with membrane module design and fouling. The workshop was organized by the National Water Research Institute (NWRI) of Fountain Valley, California, with the cooperation of the National Science Foundation.

Twenty-two participants from the United States Government, water utilities, the university community, and industry attended the workshop at the University of Delaware's Virden Conference Center at the Marine Studies Complex in Lewes, Delaware, arriving in the late afternoon of October 30, 1993. The contents of this report were generated by the participants on Monday, November 1st. The question placed before the participants was: ***What research is needed to understand the underlying phenomena of fouling and their relative importance in membrane module design for aqueous separations?***

The workshop results are presented in the order of importance attached to them by the participants. The top ten problem rankings in the three subgroups (i.e., research, design and operation) are presented in the Preliminary Analysis Section and are fully described in Appendix A with added information on the Strength of Feeling of the participants for each priority problem. Graphical data analysis are also presented for other categories of participant affiliation.

We want to acknowledge the important contributions made to the success of this workshop by the participants themselves; the staff of the Virden Center; Patricia Linsky, workshop coordinator/report editor; Joseph Pezely, workshop graphics expert; Tammi Wrice and Belinda Patrick, word processors; and Robert Bowden, photographer.

Ronald B. Linsky
Executive Director
National Water Research Institute

William S. Gaither
Gaither & Associates
Workshop Chair

CONTENTS

Contents (Continued)

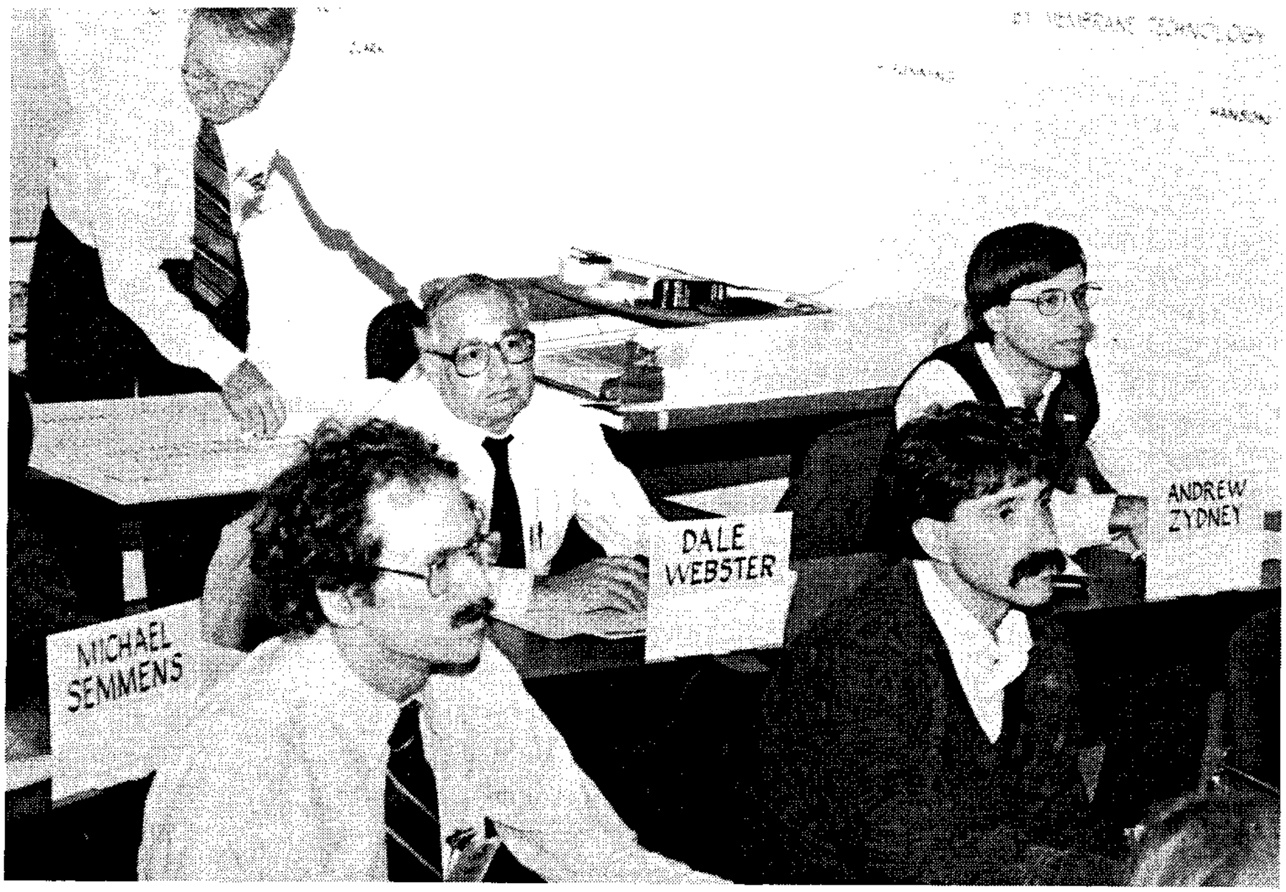
PARTICIPANTS

Top Row: (Left to Right) Mike Pirbazari, Mike Semmens, Bob Riley, Steve Hanson, Rob Davis, Amulya Atayde

Standing: John Pellegrino, Clint Kopp, Harry Ridgway, Dale Webster, Joe Pezely (Graphics), Mark Clark, Bill Eykamp, Andrew Zydney, Dave Forgach, Hubert Fleming

Seated: Joe Henry, Belinda Patrick (Word Processor), Patricia Linsky (Coordinator/Editor), Tammi Wrice (Word Processor), Clark Colton, Leo Gaddis

Floor: Ron Linsky (Secretary), Hans Flemming, Tony DiLeo, D.B. Bhattacharyya, Bill Gaither (Chair), Ed O'Rear


MICHAEL SEMMENS
DALE WEBSTER
ANDREW ZYDNEY

WORKSHOP ORGANIZATION

Preparations

In early 1993 the National Water Research Institute (NWRI) began discussions with the Office of Thermal and Separations Systems of the National Science Foundation (NSF) concerning the prospect of holding a jointly-sponsored workshop on the subject of membrane design and fouling. On September 16, 1993, nationally-recognized experts were invited to attend the workshop and were briefed on the workshop objective and the question to be addressed. Upon receipt of acceptances, materials were sent that described the process to be followed as well as problem identification forms and other working papers. A copy of the confirming workshop letter is included Appendix L. Each participant was asked to arrive at the workshop with several problems identified and written on the forms provided.

Following dinner on Sunday evening October 31st, the participants took their assigned seats in the workshop room where the procedures and homework expected were discussed. Questions and answers followed. The group adjourned at 9:00 p.m. urged by the workshop chair to return to their rooms to complete any write-ups not yet ready for presentation.

Agenda

Breakfast was served at 7:00 a.m. on November 1st, and the workshop convened in the Virden Center at 8:00 a.m., sharp. The process followed was a modified form of the Nominal Group Technique (NGT) originated in the late 1960's by Professor Andre Delbecq of the University of Wisconsin in collaboration with Professor Van de Ven (Ref. 1). Five steps were completed during the ensuing nine hour period. These steps were:

- 8:00-12:00 noon — Identification and posting of problems proposed by the participants
- 12:00-12:45 p.m. — Group Photograph and Lunch
- 12:45-4:15 p.m. — Problem consolidation
- 4:15-4:30 p.m. — Problem Ranking by Individual Participants
- 8:45 a.m.-4:40 p.m. — Problem text editing and preparation of figures

Problem Identification and Posting

Participants were seated in alphabetical order at work tables facing a lectern. Name signs, reading front and back, were provided at each participant's place. Each was invited, in turn, to present his highest priority response to the workshop question posted at the front of the room. Several graphs, tables, and figures were used in the presentation and are included in this report as part of the problem description. A maximum of three minutes was allowed for each presentation. An electronic timer with audible alarm was used to remind the presenter when time was up. At the conclusion of each presentation, the title proposed was reviewed for clarity and accuracy by the workshop secretary. If the title was deemed to not be adequately descriptive of the verbal presentation, the proposer was asked by the secretary to consider a revised and improved title. Suggestions for improvement of the title were also made by the participants. The chair ensured that only question of clarification were allowed. No presenter was challenged on the veracity of his proposed problem during the problem identification phase.

Seventy-seven problems were identified by the participants during the period between 8:00 a.m. to 12:00 noon. Some individuals identified only two problems; others identified six or more. The average for this group of 22 was 3.5 problems identified per participant. Typically, approximately half of the problems proposed by an NGT group are stimulated by interaction with other group members during the workshop.

As each problem was presented, and the title agreed to by the originator and the secretary, the title was quickly lettered in large and highly visible printing, numbered sequentially, and posted neatly on the walls of the workroom for continuous reference by all participants. A sample problem identification form is included in Appendix M. Simultaneously, the text was taken by the workshop coordinator to word processors in a nearby room and entered electronically into the format of this report. Copies of the problem text were then printed as drafts and returned to the originators for further editing and improvement. Re-edited drafts of problem write-ups were returned, corrected, to the author as many times as necessary to obtain his concurrence.

Consolidation

When all 77 problem titles had been introduced and posted, each was re-examined in sequential order to determine which, if any, could logically be consolidated into a larger overarching idea. The goal was to group individual problem proposals together so that meaningful descriptions of the larger ideas proposed by the participants could be ranked in priority order at the end of the workshop.

Without the consolidation process, the votes of the participants might be scattered among several ideas of agreed importance but which were described in several different problem titles.

To assist the workshop chair in expediting the process of consolidation, each problem originator was asked to start a consolidation worksheet, as shown in Appendix O of this report, whenever he offered a problem. The chair then called on each problem originator, in order, to lead the discussion of consolidation. Typically, he cited several other problem descriptions. The originators were then asked by the chair for their reactions to the proposal to consolidate their problem description with an earlier number. This resulted in extensive discussion in the early part of the consolidation period which began at 12:45 p.m. As the consolidation process went forward, decisions were reached at a more rapid pace. Each proposer of a problem was given the absolute right to determine the disposition of their problem. Options included: (1) be subsumed under another title, (2) become the lead title for several projects, (3) wait until later in the consolidation process to decide, or, (4) let the problem title stand alone.

During the consolidation process, the 77 problem titles proposed in the identification and posting phase were reduced to 24. It should be noted that even though a proposed project was subsumed under another project, the full text is printed as a discrete part of the final project description.

Ranking

The final step in the formal NGT process is the ranking by each participant of the project titles remaining following the consolidation step. Each participant was asked to rank the top ten highest priority problems from the 24 remaining on the workroom wall at the end of the consolidation step. These results were tallied using a software program developed for this purpose. A copy of the ranking sheet used is shown in Appendix P of this report.

Text Approval

At approximately 8:45 a.m. typed texts of each participant's written presentation began to be returned to the authors. This process continued throughout the day as project identification sheets were presented and turned in. The text of each problem presented was edited and approved by the originator before they left the workshop. With these participant approvals in hand, it was possible to move ahead rapidly and to produce this report.

PRELIMINARY ANALYSIS OF RESULTS

The results of the workshop were analyzed in two ways. The first source of data was the Problem Ranking Sheets (see Appendix P) completed by each of the 22 participants. The second source of data were the Participant Categorization Sheets as shown in Appendix N of this report. Each participant selected the categories which best described their position and work in the field.

The following four sets of results show the top ten priority problems selected by (1) all 22 participants, as well as the subsets of, (2) the 14 research participants, (3) the five design participants, and (4) the three operations participants. In Appendices B, C, D, and E, the "Strength of Feeling" of the individuals in each category are computed for each of the final 24 problems which they ranked. A description of the ranking systems is given in Appendix A.

In Appendices E, F, G, H, I, J, and K, the prioritizations by participants categorized in several ways are presented graphically. These presentations of data provide the reader with a sense of unanimity or dis-unanimity among the various individual participants, depending which sub-categories they indicated that they see themselves belonging to.

The following four sets of data represent the priority preferences by all workshop participants and also by the participants when self-identified as part of the three sub-categories of research, design, and operation. Abbreviated titles are used in the data analysis, both in the lists below and in the appendices. Full titles are given in (1) the Table of Contents, and (2) the Priority Ranking section of this report.

<u>Top Ten Problems Ranked by All Participants (22)</u>

1. Taxonomy of Fouling: etc.
2. Membrane Biofouling: Mechanisms, etc.
3. Understanding & Reducing Biofouling thru Fluid Mech. & Mass Transfer
4. Chemical Modification of Membrane Surfaces, etc.
5. Effective Pretreatment Strategies, etc.
6. Development & Characterization of Well-Defined Membranes, etc.
7. Development of Cost-Effective, High Performance Membrane Modules
8. Development of Standard Tests for Characterization of Surfaces, etc.
9. Role of Organic-Membrane Interactions & the Impact of Surface Chemistry, etc.
10. Protein Adsorption: A Dynamic Process

Top Ten Problems Ranked by Research Participants (14)

1. Taxonomy of Fouling: etc.
2. Membrane Biofouling: Mechanisms, etc.
3. Understanding & Reducing Biofouling thru Fluid Mech. & Mass Transfer
4. Chemical Modification of Membrane Surfaces, etc.
5. Effective Pretreatment Strategies, etc.
6. Development & Characterization of Well-Defined Membranes, etc.
7. Development of Standard Tests for Characterization of Surfaces, etc.
8. Development of Cost-Effective, High Performance Membrane Modules
9. Protein Adsorption: A Dynamic Process
10. Role of Organic-Membrane Interactions & the Impact of Surface Chemistry, etc.

Top Ten Problems Ranked by Design Participants (5)

1. Taxonomy of Fouling: etc.
2. Understanding & Reducing Biofouling thru Fluid Mech. & Mass Transfer
3. Membrane Biofouling: Mechanisms, etc.
4. Protein Adsorption: A Dynamic Process
5. Chemical Modification of Membrane Surfaces, etc.
6. Effective Pretreatment Strategies, etc.
7. Development of Cost-Effective, High Performance Membrane Modules
8. Role of Organic-Membrane Interactions & the Impact of Surface Chemistry, etc.
9. Development & Characterization of Well-Defined Membranes, etc.
10. Cleaning Techniques for Fouled Membranes

Top Ten Problems Ranked by Operations Participants (3)

1. Understanding Silica Crystalline Structures and Their Attachment
2. Development of Cost-Effective, High Performance Membrane Modules
3. Development of a Flux-Loss Predictable Model, etc.
4. Taxonomy of Fouling: etc.
5. Membrane Biofouling: Mechanisms, etc.
6. Understanding & Reducing Biofouling thru Fluid Mech. & Mass Transfer
7. Development & Characterization of Well-Defined Membranes, etc.
8. Chemical Modification of Membrane Surfaces, etc.
9. Development & Characterization of Well-Defined Membranes, etc.
10. Cleaning Techniques for Fouled Membranes

PRIORITY RANKING OF PROBLEMS

Notes:

1. The following 24 problems are presented in descending order of importance as ranked by all (22) workshop participants.

2. In some cases, a priority problem will consist of a number of problems proposed by several participants. One lead participant was designated by the chair as the person responsible for composing a new title, the wording of which was acceptable to all originators of problems subsumed under the new title. In the case where the lead participant composed only a new and overarching title, the individual problems subsumed under that title are presented alphabetically by author name. If more than one problem title is included by one originator, the numerical order in which the originator presented his problems at the workshop determined the order in which the problems are listed.

3. In the case where the designated lead person composed not only a new title, but also a new statement of importance, objectives, and/or approach, this full text is presented immediately beneath the new title, followed by all of the problems, listed in alphabetical order as described in Note 2 above.


MASSOUD
PIRBAZARI

Priority Rank 1: **Taxonomy of Fouling: Systematic Identification of Fouling Mechanisms**

Originators: Colton on behalf of himself, Eykamp, Henry, O'Rear, Pirbazari, and Zydney

The following research problems were subsumed under the above priority problem title:

Problem: **Identification of Fouling Mechanisms**

Originator: Colton

Importance:

Fouling mechanisms depend on the nature of the application. Important variables include the nature of the stream (composition, concentration-dilute vs concentrated), time scale, and where fouling occurs (inside the membrane, on the surface, or in the adjacent boundary layer). When the mechanism (s) is/are known, one can look to modification of surface properties, changes in module design and/or operating conditions, and pretreatment of the stream.

Objective:

To identify specific mechanisms by which fouling occurs in selected applications

Suggested Approach:

This is a "global" or generic macroscopic approach. One must pick an application where fouling (reduced flux , charged rejection) has been observed and develop a fundamental approach to identify the mechanisms involved.

Problem: **The Role of Denatured Proteins in Fouling**

Originator: Colton

Importance:

There is evidence that trace concentrations of denatured proteins in the feed stream adsorb to membrane surfaces tenaciously and cause fouling. Elimination of denatured proteins in the feed may markedly reduce fouling. Existing evidence is largely anecdotal.

Objective:

Develop methods and use them to study the importance of denatured proteins in adsorption to and fouling of membranes (UF and MF).

Suggested Approach:

Develop methods to analyze for the concentration of trace denatured proteins in solution and on surfaces. Use these to study adsorption isotherms of denatured proteins and compare with that of native protein.

Problem: **The Role of Conditioning Films in Membrane Fouling**

Originator: Eykamp

Importance:

The mechanism for the initial substance adsorbed on a membrane seems to involve some intermediary to which subsequent foulants adhere. In practice, it is known that fouling begets fouling. By preempting the formation of a first adhering layer, we should be able to prevent subsequent fouling layers.

Objective:

Find surfaces which, because of their energy or their adsorbed or bonded coatings, do not attract the first substrate layer.

Suggested Approach:

Search literature and nature for leads. The kidney, for instance, is not fouled by blood constituents. Look especially to fundamental surface chemistry for surface materials which might conceivably be incorporated onto a functioning membrane.

Problem: **Development of a Framework for Classifying the Interactions of Liquid Phase Components with the Membrane Surface and/or Pores**

Originator: Henry

Importance:

Process development work on membrane processes often involves much more effort in understanding the relevant solution and interfacial chemistry than typical flow, pressure and module design parameters. Cross flow filtration vendors often do not wish to get involved in applications that involve complex solution and interfacial chemistry complications. While it is unlikely that models will evolve soon to permit a predictive design environment in such chemically complex applications, it is certainly true that a more systematic approach to classifying such complications would drastically reduce the experimental complexity and risk with such applications.

Oil field produced waters from both water and steam floods, extracts from lysed cell cultures and particle removal from highly multi-component phases are just a few examples where chemical and interfacial complexities dominate the applications membrane processes.

Objective:

Develop a framework for classifying the interactions of both high and trace concentration solutes that can interact with membrane surfaces or pores. The primary objective would be to develop parameter selection and experimental strategies that would assure discriminating experiments and reduce the number of experiments involved.

Suggested Approach:

- Systematize the solute functionalities and membrane interactions that can produce dynamic membranes whose origin is natural components in the feed.
- Identify families of important solute-solute interactions that will lead to stronger or weaker membrane interactions.
- Focus on trace as well as moderate to high concentration solutes.
- Develop strategies for selecting feed stream additives that will minimize solute fouling interactions.

Problem: **Reduction of Fouling of Product Site Membrane Support (Substrate)**

Originator: Henry

Importance:

Both solutions which permeate membranes and cleaning solutions in reverse flow can severely foul the membrane support and lower permeate flux.

Objective:

Identify feed stream and/or cleaning agent constituents that plug porous support and significantly lower flux.

Suggested Approach:

- Reduce path length on down stream side of membranes.
- Avoid bacterial cell contaminants in cleaning solutions.
- Identify regimes of pore blockage in porous supports.

Problem: **Taxonomy of Fouling - Where are Answers Known and Where is Research Needed?**

Originator: O'Rear

Importance:

Fouling is a very generic term and carries a very different connotation to various groups. Taxonomy can be important to determine those cases where a solution(s) to fouling already exists and those where fundamental research on underlying mechanisms is critical.

Objective:

Identify the critical factors and range of values that influence the performance of membrane modules. Define principal classifications with known approaches (where they exist) to address fouling. Search for unifying features.

Suggested Approach:

I would consult with representatives from the many different communities using membrane methods, as well as an analysis of the literature.

Problem: **Diagnosis of Fouling by Membrane Autopsy**

Originator: Pirbazari

Importance:

Membrane fouling can be caused by a variety of factors including colloidal fouling, organic fouling, inorganic scaling, and biofouling. Although potential fouling mechanisms can be guessed based on the nature of the feed, and the properties of the membrane (such as hydrophobicity or hydrophilicity, pore size, and internal morphology), the exact cause of permeate flux deterioration remains unknown. If this information were known, definitive theoretical and practical approaches may be developed to solve the problem. Superior cleaning agents may be employed, and appropriate cleaning protocols may be observed to restore the permeate flux.

Objective:

This study will include the autopsy of fouled membranes by combinations of different instrumentation techniques. The same techniques will be used to analyze cleaned membranes as well, so that the quality of the cleaning operation may be evaluated.

Suggested Approach:

This research will involve a combination of techniques for delineating the causes of fouling. These techniques will include scanning electron microscopy (SEM), secondary or back-scattered electron imaging, energy dispersive X-ray (EDX) analysis, EDX mapping, infrared spectroscopy (attenuation transmitted reflectance, or transmission methods), and combinations thereof such as SEM-EDX methods. These techniques will be used to analyze the "fouled membrane" as well as the "cleaned membrane." These analyses will provide a good understanding of potential fouling mechanisms in various applications, and will be helpful in reducing membrane fouling and developing effective cleaning methods.

Problem: **Identification and Characterization of Critical Fouling Components**

Originator: Zydney

Importance:

Without a basic understanding of the physical and chemical characteristics of those species involved in membrane fouling, it is essentially impossible to develop appropriate design strategies to minimize fouling during actual process operations. In many process streams, the fouling is actually governed by the presence of trace components, e.g., denatured as aggregated protein.

Objective:

The overall objective of this study would be to identify those species (dissolved and colloidal) involved in membrane fouling and to evaluate the physical and chemical characteristic of these components.

Suggested Approach:

Several coordinated approaches would be attractive including: use of surface characterization techniques to perform elemental and species analysis of the surface of fouled membranes, analysis of membrane fouling using very well-defined "models" for aqueous process streams (e.g., humic acids, inorganic salts, proteins, etc.) both alone and in combinations.

Priority Rank 2: **Membrane Biofouling: Mechanisms, Effects, and Countermeasure**

Originators: Ridgway on behalf of himself, H.C. Flemming, Pirbazari, and Semmens

The following problems were subsumed under the above proposed priority problem title:

Problem: **Detection and Monitoring of Fouling**

Originator: H.C. Flemming

Importance:

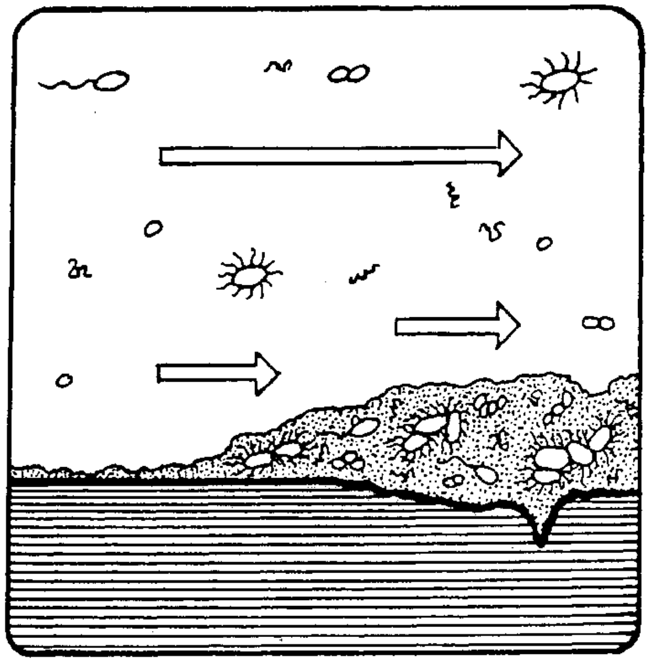
Anti-fouling measures must be based on identification of foulants and on the extent of fouling layers.

Objective:

- Develop non-destructive, on-line, real time and time-dependent observation of fouling layer formation.
- Detect biofouling in an early stage and monitor cleaning efficiency.

Suggested Approach:

- Measure on surfaces, not only in the water phase.
- Use light reflectance as a tool to assess fouling layer formation and to identify the foulant (integrated in module).
- FTIR-ATR-Spectroscopy: formation of fouling layer on crystal (ATR) in a bypass.
- Microscopical image analysis.
- Sacrificial modules, destructive analysis.



Problem: **Towards a Biocide-Free, Anti-Fouling Strategy**

Originator: H.C. Flemming

Importance:

Biocides are toxic, can harm the system, require special precautions in handling, are frequently ineffective, and represent a potential environmental hazard.

Objective:

Keep biofilms below the level of interference and live with "domesticated biofilm" (i.e., live with biofilms and keep them below the level of interference).

Suggested Approach:

Limit the extent of biofilm growth by:

- Limiting the nutrients.
- Increasing the shear forces.
- Learning how much biofilm (what extent of growth) a system may tolerate.

Problem: **Improving the Permeability of Existing Fouling Layers**

Originator: H. C. Flemming

Importance:

In many cases, fouling layers cannot be removed. It may be helpful to make them more permeable.

Objective:

Find and test additives which improve the permeability of fouling layers.

Suggested Approach:

- Further investigate substances which improve permeability.
- Avoid substances which decrease permeability (e.g., formaldehyde).
- Investigate the underlying mechanisms and design new formulations.

Problem: **Measurement of Adhesion and Cohesion Forces in a Biofilm**

Originator: H.C. Flemming

Importance:

Removal of biofouling layers has to overcome physical stability of biofilms. What forces have to be applied in order to clean biofouled surfaces sufficiently?

Objective:

Quantify the efficiency of cleaners and design of cleaning strategies.

"WHAT CLEANERS REALLY DO"

* Influence on permeability (J/J_0)
* Filtercake of P. diminuta
* Thickness 1 mm, pressure 1 bar
* Concentration of the agent: 1 % if not otherwise indicated
* Value of J/J_0 as measured 2 h after replacement of the agent by water

Agent	J/J_0
Ultrasil 10	5,3
Ultrasil 53	5,1
Ultrasil 92	3,6
Ultrasil 62	1,7
Ultrasil 56	1,6
SDS	1,5
Pluronic 64	1,5
pH 11	1,3
Triton X 100	1,3
Urea (6 M)	1,0
Ultrasil 60 A	0,9
pH 2	0,6
Formaldehyde	0,6
Ultrasil 70	0,4
Tannin	0,36

Suggested Approach:

- Develop a standard method for measuring adhesion and cohesion of biofilm (viscosity, lifting power).

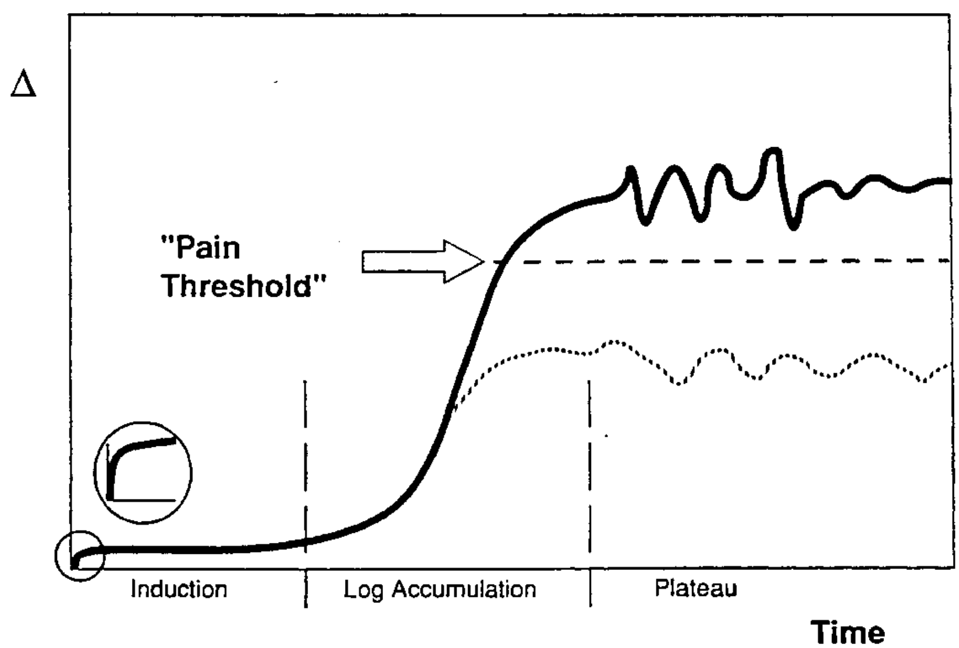
- Measure biofilms before and after application of cleaners.
- Utilize drag resistance devices, “deviation of a needle”, shear force gradient (“Fowler Cell”).

Problem: **What is the Tolerable Level of (Bio)Fouling Layers?**

Originator: H.C. Flemming

<u>Importance</u>:

Only if the extent of fouling layers exceeds the level of interference, do countermeasures have to be taken.



<u>Objective</u>:

Identify the level of interference and answer the question,“To what extent of fouling layer accumulation can the system live?”

Suggested Approach:

- Autopsy of well-working modules.
- Measure fouling layer thickness, viscosity, permeability, and drag resistance.

Problem: **Mechanism of Primary Adhesion of Microorganisms on a Molecular Basis**

Originator: H.C. Flemming

Importance:

If we want to prevent fouling, we have to block initial adhesion. Thus, we have to know the mechanisms of attachment.

Objective:

- Find the basic mechanisms of how bacteria adhere.
- Describe what happens between the cell and the surface of membrane.

Suggested Approach:

- Select suitable test systems (not all organisms use the same mechanism).
- Interfere with defined inhibitors.
- Use FTIR, microscope, etc.

Problem: **Modifying The Adhesive Properties of Membranes, Microorganisms and Enzymes to Discourage Biofouling**

Originator: Pirbazari

Importance:

Biofouling greatly undermines the applicability and economic viability of membranes in water and waste water treatment processes.

Objective:

This study will investigate the mechanisms of interaction between bacteria and their enzymes with the membrane surface to discourage bacteria attachment.

Suggested Approach:

Treat the water with appropriate chemicals that will either discourage bacteria attachment and/or alter their polymer-producing characteristics.

Problem: **Multidisciplinary Approach to Membrane Bio-Fouling**

Originator: Ridgway

Importance:

Biofouling:

- Is a widespread problem in membrane applications.
- Degrades membrane performance and/or shortens life resulting in higher costs of operation and maintenance.
- May preclude membrane application in some instances.

Objective:

- Define the mechanism of bacterial attachment and factors influencing biofilm growth (e.g., nutrients, hydrodynamics, etc.).
- Delineate specific microbial properties or processes resulting in performance decline of membranes (e.g., role EPS).
- Identify the effects of biofilms on membrane performance.

- Identify strategies to prevent or avoid effects of befouling, including identification of novel cleaning agents and methods.

Suggested Approach:

A multi-disciplinary approach is required, including:

- Microbiology (microbial ecology) of biofilm.
- Feedwater Physics - chemical and biological factors.
- Membrane (substratum) physico-chemical properties.
- Process engineering (e.g., use of new spacers, altering shear forces).

Problem: **Identification and Analysis of Biodeterioration in Membrane Systems**

Originator: Ridgway

Importance:

Significance underestimated. Extremely important as a principal determinant of membrane life and system performance.

Objective:

Explore interaction of bacteria and their metabolic products (EPS, enzymes) with membrane polymers and other module materials, such as glues, spacer materials, and o-rings.

Suggested Approach:

Some methods to apply to determine whether biofilm cells degrade membrane materials are FTIR, TEM, AFM, and radiotracer.

Problem: **Development of Rapid Feedwater Bio-Assay to Predict Membrane Biofouling Potential**

Originator: Ridgway

Importance:

- SDI is inadequate to predict biofouling potential.
- Feedwater nutrients represent the potential biofilm.

Objective:

Create/develop an on-line device to monitor response of biofilm cells to feed water nutrients.

Suggested Approach:

- Use of starved recombinant bacteria containing a cloned lux operon under control of a growth-related promoting sequence. Bacteria are placed in a gel to create an "artificial" biofilm. Optical fiber is used to transmit light emission to photomultiplier. Light emission would presumably be proportional to carbon (i.e., nutrient) processing by biofilm cells.
- Use of fluorescent redox dye CTC to quantify carbon processing.

Problem: **Synergistic Interactions Between Bacterial Fouling and Scaling**

Originator: Ridgway

Importance:

Bacteria are known to promote biogeochemical reactions, especially at surfaces. It is very probable that biofilm cells may promote mineral scaling at membrane surfaces (i.e., within the biofilm matrix).

Objective:

Determine the role of biogeochemical reactions in membrane biofilms.

Suggested Approach:

- Test supersaturated solutions with different bacterial strains (as selective nucleation sites).
- Form biofilms with "nucleation bacteria" and explore extent of precipitation/scaling.

Problem : **The Use of Gas Permeable Membrane as a Tool in Controlled Biofilm Experiments**

Originator: Semmens

Importance:

Characterizing and controlling the experimental conditions at the membrane surface are fundamental to understanding the processes that occur in biofilms.

Objective:

Control the water chemistry and the redox/pH conditions at the membrane surface for model studies on biofilm behavior.

Suggested Approach:

Cultivate the test biofilm on a gas permeable membrane. Control the conditions at the membrane interface by passing air, oxygen, $C0_2$, CH_4, H_2 and other gases over one side of a membrane. In this way the behavior of the biofilm can be characterized under well-defined chemical conditions.

Priority Rank 3: Understanding and Reducing Membrane Fouling through Study and Application of Fluid Mechanics and Mass Transfer

Originators: Davis on behalf of himself, Athayde, DiLeo, Gaddis, Fleming, and Semmens

The following research problems were subsumed under the above priority problem title:

Problem: **Develop a Rational Basis for Spiral-Wound Module Spacer Selection and Design**

Originator: Athayde

Importance:

The most important component in determining the fluid dynamics in a module is the spacer. But the selection of this spacer is very often a trial-and-error process restricted to available materials. Computer simulation is a cheaper and faster route to spacer selection and could also be used to design spacers.

Objective:

Numerical simulation of fluid flow in membrane modules.

Suggested Approach:

- Develop numerical models of fluid flow in spiral-wound modules. The models will be based on actual spacers and will describe flow, pressure and concentration profiles, as well as fouling.

- Correlate actual module performance with model predictions.

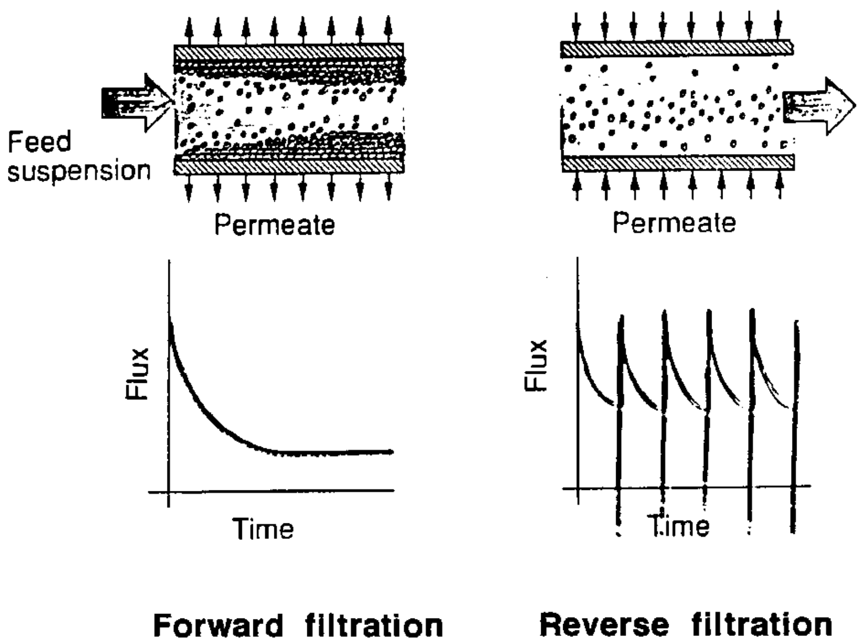
- Identify the critical spacer parameters that will minimize fouling and maximize membrane performance.

Problem: **Fouling Prevention and Reversal by Transmembrane Pressure Pulsing**

Originator: Davis

Importance:

Fouling reduces flux and selectivity. Some fouling mechanisms, such as cake formation and pore plugging, may be reversible. By identifying reversible fouling phenomena and in situ methods for preventing or reversing these phenomena, high levels of flux and selectivity may be maintained.



Objective:

Identify reversible fouling mechanisms and develop a module design and in situ process for preventing or reversing these fouling mechanisms.

Suggested Approach:

Reversible fouling mechanisms will be defined as those which may be reversed by a chemical or hydrodynamic technique which can be applied periodically without stopping the filtration process or taking the membrane module apart. Example techniques include backflushing, high shear, periodic axial pressure pulsing or reversal, and periodic pH or ionic strength pulses. A suggested approach is rapid transmembrane pressure pulsing, which has been shown to reduce concentration polarization and cake formation and which may also prevent pore plugging and adsorption.

Problem: **Artificial or Natural Turbulence Promotion. How does it Effect Fouling Rates?**

Originator: DiLeo

Importance:

Turbulence promotion is known to effect boundary layer phenomena, but little data exists comparing screens (artificial promoters) and natural hydrodynamic turbulence promoters (such as vortices, Taylor and Dean) to fouling phenomena. Turbulence promotion, especially that resulting in air interfaces and cavitation, could promote fouling due to denaturation. Hydrodynamic turbulence would eliminate these events.

Objective:

Determine the effect of turbulence promoters on fouling phenomena, especially the occurrence of vapor interfaces. Also, does screen/membrane contact influence results?

Suggested Approach:

Investigate the hydrodynamics of a turbulence promoter screen within the weave and at the membrane surface. Combine this with protein denaturation and adsorption studies, each as a function of operating conditions and start up. MRI studies would be helpful.

Problem: **Mathematical Models Predictive of Scale-Up; Incorporating Hydrodynamic, Geometric and Fouling Mechanisms**

Originator: DiLeo

Importance:

- The ability to predict scale-up performance based on data using lab scale devices is important.
- Critical design variables need to be controlled for efficient scale-up, both on the retentative and permeate fluid sides.

Objective:

Develop scale-up and design models based upon hydrodynamic, geometric factors, and generic fouling mechanisms.

Suggested Approach:

Detailed fouling data can be obtained using small devices and scaled via model.

Problem: **Development of Surface Contours For Lateral Flow of Concentrated Solute**

Originator: Gaddis

Importance:

Eventual accumulation of concentrated solute will reduce flux.

Objective:

Provide transverse pressure gradients at the surface by action of over-running shear flow.

Suggested Approach:

- Computer design.
- Experimental verification.

Problem: **Development of Techniques for Real Time Characterizing Hydrodynamic Effects in Membrane Module Operation**

Originator: H.L. Fleming

Importance:

The bottom line in membrane operation is maximizing mass transfer.

Objective:

Develop techniques for characterization of hydrodynamic effects in membrane module operation.

Suggested Approach:

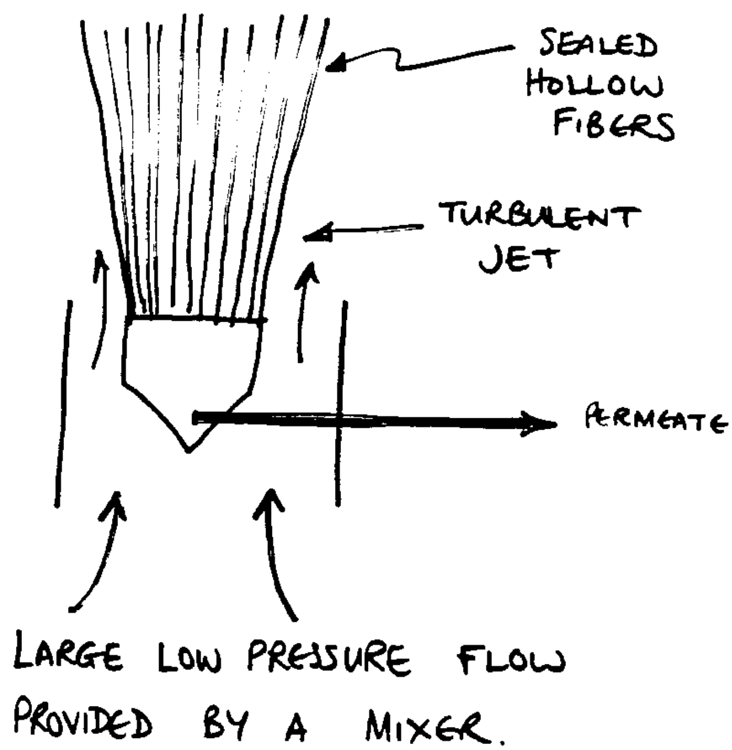
- Magnetic Resonance Imaging.
- Tracer studies (diffusive).

Problem: **Characterize the Mass Transfer Behavior of Unconfined Hollow Fibers in Turbulent Flow and Develop Module Design Correlations**

Originator: Semmens

Importance:

When hollow fibers are used in an unconfined mode, large numbers of fibers can be used, and the energy requirements are reduced. Construction costs and operating costs should be much less expensive. The fouling should be less because of lower fluxes and the self-cleaning action of the fibers.



Objective:

- Define mass transfer correlations for unconfined fibers.
- Define flux/power relationships.
- Define long-term behavior compared to a conventional UF.
- Compare with conventional systems.

Suggested Approach:

- Characterize mass transfer behavior of free fibers as a function of jet Reynolds number, power input/volume, and fiber diameter and length.
- Evaluate best module configuration using mass transfer experiments and video analysis.
- Conduct flux/performance studies on best design.

Priority Rank 4: Chemical Modification of Membrane Surfaces to Prevent Fouling and Facilitate Cleaning

Originators: Athayde on behalf of himself, Colton, Forgach, Kopp and Riley

The following research problems were subsumed under the above priority problem title:

Problem: **Fouling-Resistant, Chemically-Modified Membranes**

Originators: Athayde

Importance:

Membranes will foul during use. The rate of fouling can be slowed by suitable fluid dynamics in the module. However, eventually the membrane will foul and the performance will drop below acceptable levels. If the membrane surface could be chemically treated to minimize the adhesion of foulants, fouling could be delayed or eliminated altogether.

Objective:

Chemical modification of the membrane to produce a fouling-resistant surface without affecting the membrane flux or selectivity.

Suggested Approach:

- Determine surface interaction between membrane polymer and foulants.
- Identify surface-modification techniques that would result in lower interaction, i.e., decrease sorption/adhesion.
- Screen out techniques that diminish flux/selectivity.

Problem: **Development of Membranes with Low Macromolecule Adsorption: Hydrophilic and Polyethylene Glycol - Functionalized Surfaces**

Originator: Colton

Importance:

Fouling is often associated with macromolecule adsorption onto the membrane surface, especially adsorption of proteins.

Objective:

Functionalize membrane surface with characteristics thought to minimize adsorption: hydrophilic groups, and especially polyethylene glycol.

Suggested Approach:

A key problem is to functionalize the surface of the hydrophobic polymers used for membranes (e.g., polysulfone). Heavy duty polymer chemistry is required here.

Problem: **Surface Treatments for the Prevention of Bio-fouling and for Enhancing the Cleanability of Reverse Osmosis Membranes**

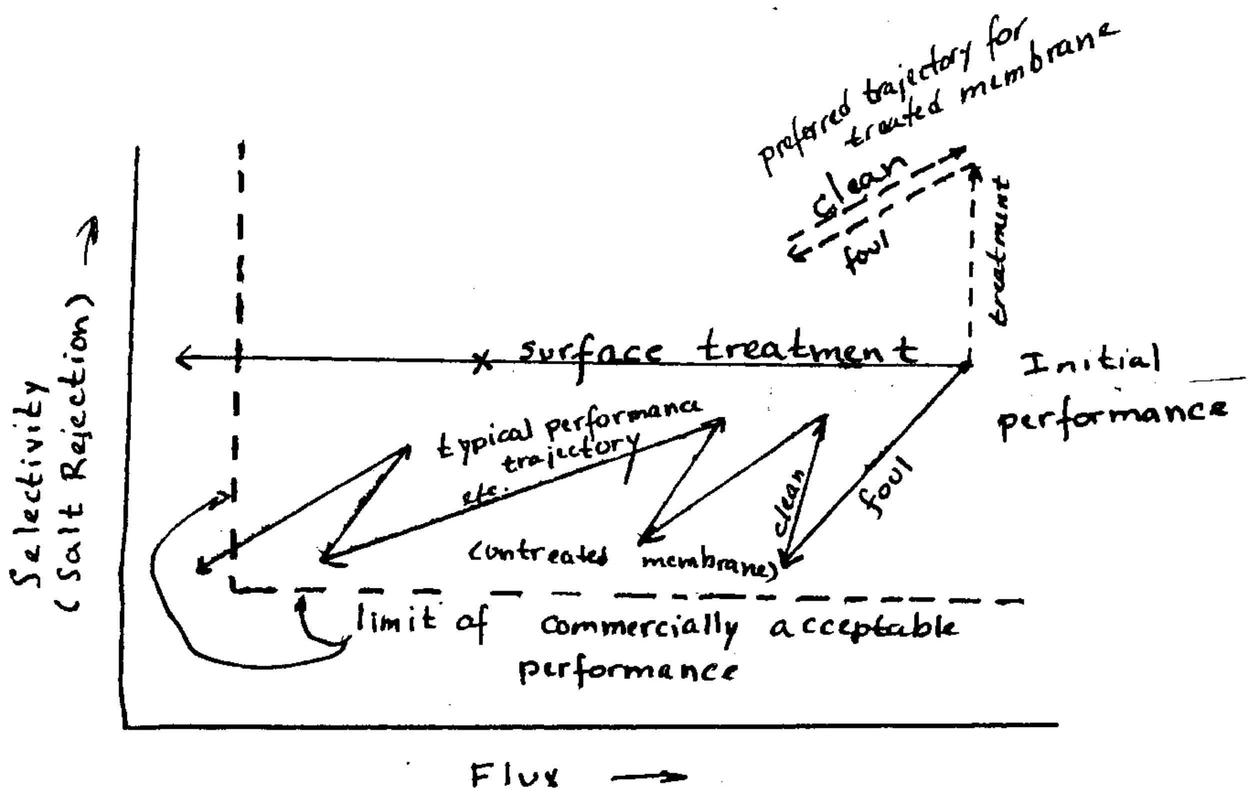
Originator: Forgach

Importance:

- Prevention of fouling - increases service intervals between system shut down for membrane cleaning.
- Enhanced cleanability - increases membrane service life; simplifies cleaning regimen.

Objective:

- Surface treatment must be simple to apply so that it can be easily and economically adapted to existing manufacturing techniques.



- Treatment must survive for service life of membrane or must be easily re-applied in situ.

- Preferably generic - works for a family of foulants.

Suggested Approach:

- Coatings.

- Membrane covalent modifications.

Problem: **Development of Chemistries and Methods for Surface Modifications that do not Significantly Decrease the Performance of the Membrane**

Originator: Kopp

Importance:

Surface treatments will only work if membrane performance is not significantly decreased.

Objective:

Develop chemistries and methods for surface modifications that do not significantly decrease the performance of the membrane.

Suggested Approach:

Obtain membranes and develop chemistries and methods.

Problem Title: **Elimination of Charge from the Transport Surface of Reverse Osmosis Membranes to Reduce Fouling**

Originator: Riley

Importance:

Carboxylic acid groups are present on the surface of most thin-film composite membranes thereby creating a negative surface charge. Cationic polymers are frequently used in the pretreatment ahead of reverse osmosis to coagulate colloidal material. Carryover of these materials into the feed stream can result in severe fouling. The presence of charge on the surface of these membranes may also enhance biofilm formation. The presence of charge also dictates the selection of cleaning agents and biocides.

Objective:

Ideally, the transport surface of reverse osmosis membranes should be neutral. The objective, therefore, is to reduce and/or eliminate charge from the surface of reverse osmosis membranes.

Suggested Approach:

A multi-facet approach is proposed:

- Modify the chemistry and process variables of the interfacial reaction to eliminate surface charge.
- Post treat to chemically modify the surface of charged membranes to eliminate charge.

Priority Rank 5: Development of Effective Pretreatment Strategies for Reducing Membrane Fouling

Originators: Zydney on behalf of himself, Bhattacharyya, Clark, Eykamp, and Pirbazari

The following research problems were subsumed under the above priority problem title:

Problem: **Optimization of Hybrid Membrane Processes to Minimize Fouling**

Originator: Bhattacharyya

Importance:

Membrane processes for pollution control or waste minimization often require integrated steps. There is also a need to develop solvent resistant supports for membranes.

Objective:

- Develop selective separation and material recovery.
- Determine thermal solvent effects on membrane-solute interactions.

Suggested Approach:

- Establish criteria for input stream specifications.
- Develop computer simulation models.
- Develop criteria to be used for membrane material selection and membrane processes.

Problem: **Modeling of Foulant Pre-Adsorption in Hybrid Adsorption/Membrane Systems**

Originator: Clark

Importance:

Modeling of adsorption of foulants in pretreatment systems is underdeveloped.

Objective:

Develop models of pretreatment adsorption for complicated adsorbent and adsorbate residence times and multiple mass transfer limitations.

Suggested Approach:

Compare model simulations with experimental results.

Problem: **Adsorb Foulants Prior to Membrane Processing**

Originator: Eykamp

Importance:

By preventing foulants and foulant precursors from reaching the membrane, fouling would be minimized. This would occur only where potential foulants are minor constituents.

Objective:

Since membranes are attractive to foulants, there needs to be developed materials similar to the membrane to adsorb the foulants as a preemptive measure. (Regeneration of the sacrificial materials might be simpler.)

Suggested Approach:

Begin with membrane materials and try to make them like adsorption resins to see if they prevent migration of fouling materials. This only applies to streams where the permeate is the only useful product.

Problem: **Ultrafiltration Pretreatment for Reverse Osmosis**

Originator: Pirbazari

Importance:

Integrated ultrafiltration and activated carbon adsorption has the potential to provide effective pretreatment for reverse osmosis. This integrated approach can efficiently remove foulants such as dissolved organic matter, microorganisms and colloids, and simultaneously maintain high permeate flux. The removal of microorganisms and microbial byproducts will eliminate the use of oxidants that potentially cause membrane damage.

Objective:

The purpose of this investigation is to evaluate the effect of this pretreatment technique in protecting the reverse osmosis membrane.

Suggested Approach:

The integrated pretreatment will be carried out using ultrafiltration membranes of different materials including polymerics and ceramics. Ceramic membranes have recently been used in several industrial applications because of their superior resistance to oxidants, microbial attack, and pH. The commercial use of ceramic membranes will open new areas in membrane research and development. The research will also compare the performances of hollow-fiber and tubular ultrafiltration membranes and evaluate their effectiveness in preventing reverse osmosis membrane fouling.

Problem: **Development of Effective Pretreatment Strategies for Reducing Membrane Fouling**

Originator: Zydney

Importance:

In many processes, the observed fouling is due to trace components or contaminants that the membrane was not designed to remove. In these cases it may be possible to dramatically reduce fouling by appropriate modifications of the process stream (as opposed to the membrane).

Objective:

The overall objective would be to develop effective strategies to reduce fouling through the pretreatment or modification of the process stream.

Suggested Approach:

- Examine strategies to remove colloids/aggregates.
- Determine effects of different pretreatment strategies on the actual composition of the process stream and in turn the performance of the membrane device.

Priority Rank 6: **Development and Characterization of Well-Defined Membranes through the Systematic Modification of Surface Chemistry and Morphology for Fouling Studies**

Originators: Semmens on behalf of himself, Colton and Pellegrino

The following research problems were subsumed under the above priority problem title:

Problem: **Standardized, Well-Characterized Membranes for Research on Fouling**

Originator: Colton

Importance:

Commercial membranes are poorly characterized.

Objective:

Develop an inventory of membranes whose physical and chemical properties are well determined for use in research on fouling.

Suggested Approach:

Someone, or a group, needs to set up an inventory.

Problem: **Systematic Modification and Characterization of Membrane Surfaces**

Originator: Pellegrino

Importance:

There are many surface modification techniques. How to choose between them is uncertain. It would be valuable to have a group contribution-type technique to predict surface activities so that surfaces could be tailored for specific streams.

Objective:

Differentiate and quantify the elementary steps when classes of foulants interact with membrane and modified-membrane surfaces which have been well characterized in terms of physico-chemical properties.

Suggested Approach:

Modify membrane surfaces with chemistry which is highly reproducible and facilitates incremental changes, such as sequential addition of monomers to oligomeric surface species. Then use techniques like SANS, laser Raman, IR (ATR and ellipsometry), and NMR to characterize interactions with various classes of foulants.

Problem : **Systematic Evaluation of Surface Chemistry and Surface Morphology on the Fouling Behavior of UF Membranes**

Originator: Semmens

Importance:

Well-defined membranes are not generally available for fouling research studies. Commercial membrane suppliers provide limited information, and well-controlled studies with these membranes are impossible. Characterization of the membrane surface is key to controlled scientific studies.

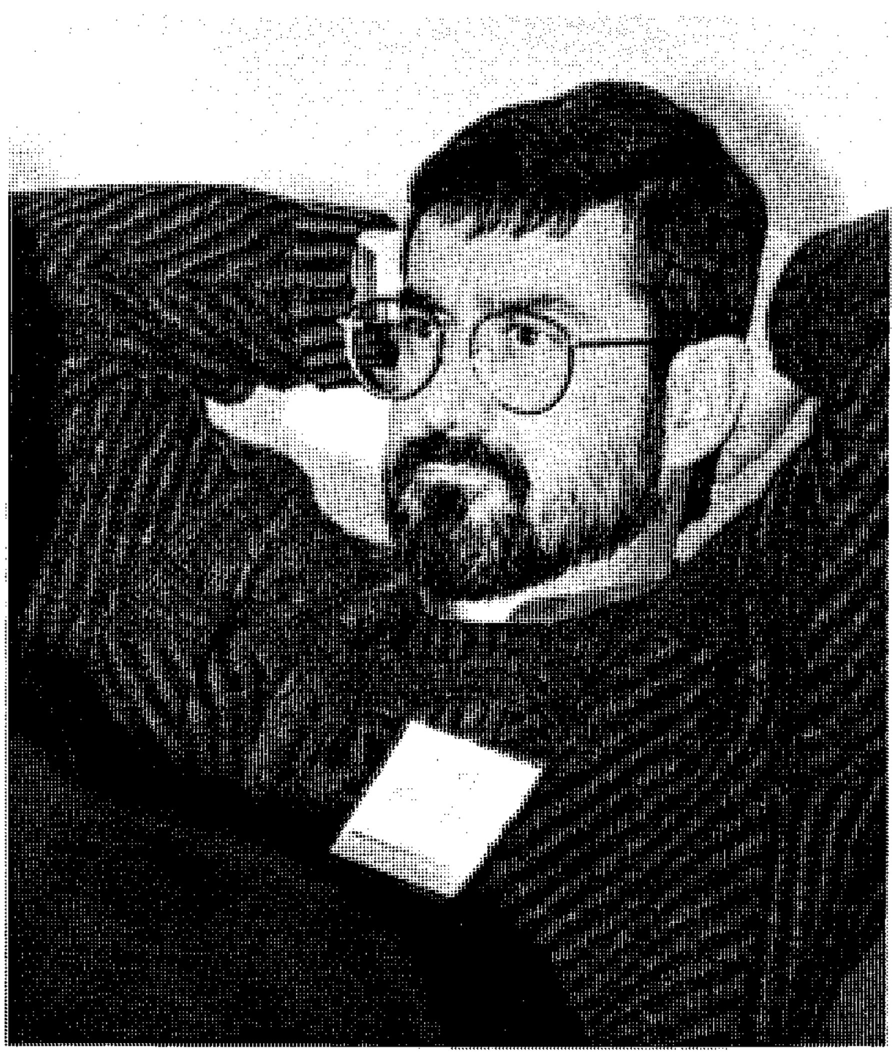
Objective:

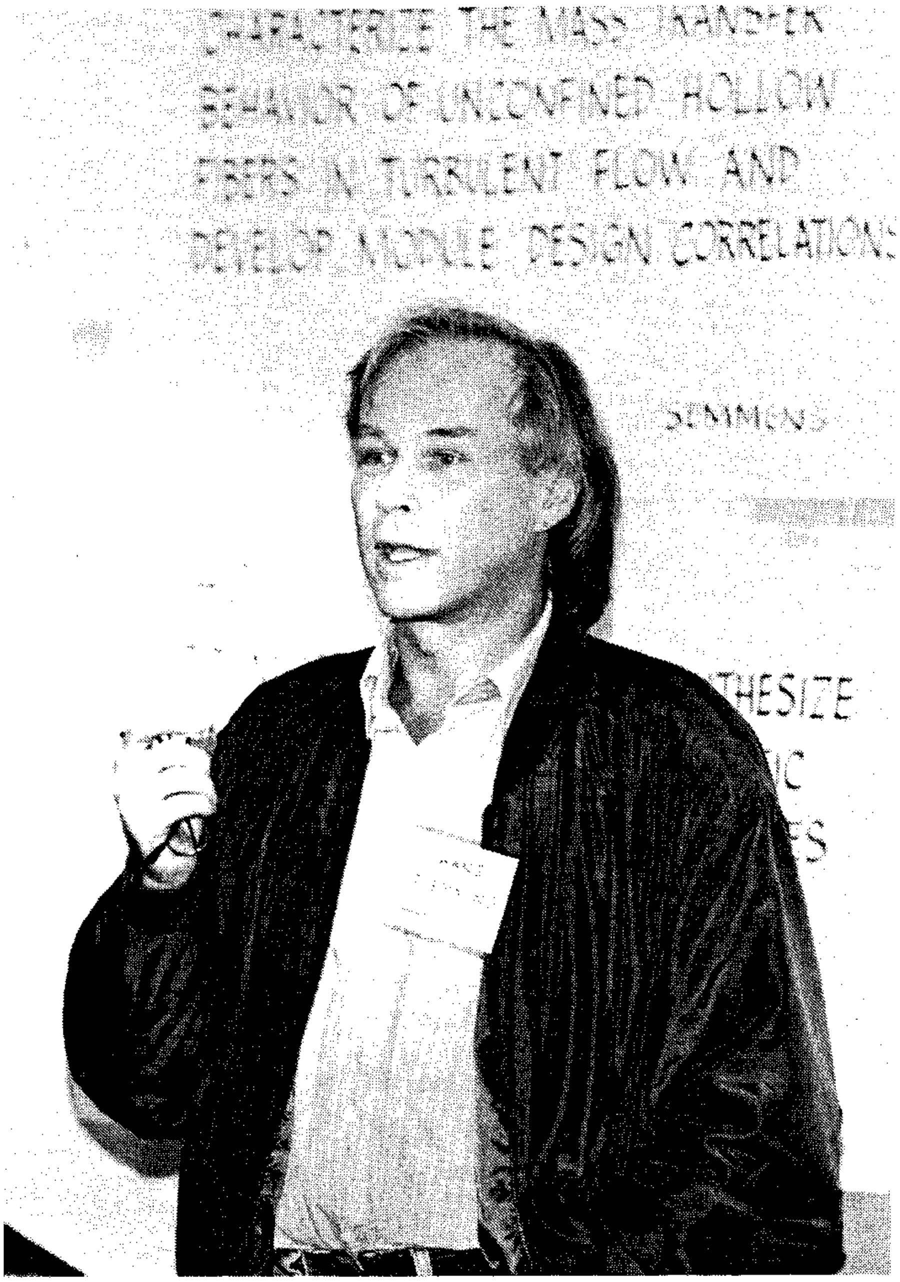
- Generate a series of membranes having different morphology surface roughness - (same surface chemistry).
- Modify surface chemistry of membranes having the same morphology.

- Characterize the influence of morphology and surface chemistry on performance.

Suggested Approach:

- Select a microporous membrane that is available commercially in a reproducible form.
- Use plasma polymerization techniques to coat the surface and confer different chemical characters.
  - Varying coating thickness will affect surface roughness and the precursors which affect chemistry.
- Measure membrane performance.




CHARACTERIZE THE MASS TRANSFER
BEHAVIOR OF UNCONFINED HOLLOW
FIBERS IN TURBULENT FLOW AND
DEVELOP MODULE DESIGN CORRELATIONS

Priority Rank 7: Development of Cost Effective, High Performance Membrane Modules

Originators: H.L. Fleming, on behalf of Athayde, Davis, EyKamp, Forgach, Henry, Riley, and Semmens

The following research problems were subsumed under the above problem priority title:

Problem: **Develop a Rational Basis for Spiral-Wound Module Spacer Selection and Design**

Originator: Athayde

Importance:

The most important component in determining the fluid dynamics in a module is the spacer. But the selection of this spacer is very often a trial-and-error process restricted to available materials. Computer simulation is a cheaper and faster route to spacer selection and could also be used to design spacers.

Objective:

Numerical simulation of fluid flow in membrane modules.

Suggested Approach:

- Develop numerical models of fluid flow in spiral-wound modules. The models will be based on actual spacers and will describe flow, pressure and concentration profiles, as well as fouling.

- Correlate actual module performance with model predictions.

- Identify the critical spacer parameters that will minimize fouling and maximize membrane performance.

Problem: **Membrane Module Design for Oily Aqueous Streams**

Originator: Davis

Importance:

Aqueous streams which are contaminated with oil as well as particulates include product water from oil wells, wash and cooling streams from industrial operations, and ground water from spill sites. Hydrocyclones are not always successful in removing contaminating droplets and particulates, especially when these contaminants are small or neutrally buoyant.

Objective:

Identify and design membrane materials and modules which are capable of producing purified water from oily aqueous streams, so that the effluents may be recycled or discharged.

Suggested Approach:

It is recommended that ceramic membranes be used because of their ability to withstand elevated temperatures, backflushing, and chemical and steam cleaning. They are also often hydrophilic, or can be coated with hydrophilic materials, so that they preferentially transmit water while rejecting oil. The oil droplets and particulates may foul the membranes, and so fouling reduction techniques such as the use of surfactants, low transmembrane pressures, and backflushing should be explored.

Problem: **Low Cost, Low Driving Force Module Development**

Originator: Eykamp

Importance:

High transmembrane pressure alters retention for macrosolutes and encourages fouling.

Objective:

Decouple the depolarizing force from the driving force module and system development in order to design economical equipment. The equipment must have low costs per unit of permeate produced and must have low capital costs.

Suggested Approach:

Nature uses massively parallel systems, but these are hard to engineer at reasonable costs. Controlled back-pressure to regulate transmembrane pressure is another approach.

Problem: **Evaluation of Modules of Novel Geometric Design for Flux Optimization**

Originator: H.L. Fleming

Importance:

The ultimate importance of membrane technology is its commercial application in an economical way. Maximum flux is one key parameter.

Objective:

To demonstrate a phenomenological understanding of process by developing membrane modules which minimize the controlling flux-loss mechanism in defined applications.

Suggested Approach:

One approach is to focus on hydrodynamics and maximize turbulence Surface Reynolds Number through hydrodynamic mechanical means. Encourage the movement away from conventional geometries (spiral, tubular, etc.).

Problem: **Hollow Fiber Module Construction that Alleviates Channelling and Dead Space in Shell Side Hollow Fiber Modules**

Originator: Forgach

Importance:

Elimination of channelling and dead space in shell side hollow fiber modules would eliminate a major source of fouling in this type of module.

Objective:

Design optimized hollow fiber wrapping geometries and a mechanical means for achieving them.

Suggested Approach:

- Hydrodynamic modeling to guide design strategies.
- Construction of prototype.
- Testing under exaggerated fouling conditions.
- "Post - mortem" analysis of membrane performance.

Problem: **Development of Module Configurations for High Flux Applications**

Originator: Henry

Importance:

Current flux rates in cross flow and ultrafiltration applications are often an order of magnitude higher that the 10 to 30 GFD flux rates that were common when most of the present module configuration were developed in the early 1970's. The much higher fluxes that are common now result in increased fouling tendencies either due to concentration polarization or other transport mechanisms. A fresh look at module configuration and the related fouling agent transport mechanisms should improve the productivity and range of application of both cross follow and ultrafiltration systems.

Objective:

- Systematically assess flow channel geometry and flow turbulence enhancement devices.
- Develop a cohesive transport mechanism framework to permit design of various module geometry options.
- Identify application regimes where the flow resistance in the membrane support can adversely impact module performance.

Suggested Approach:

- Assess the practicality of a longitudinally varying cross-section area for flow and examine alternative spacer designs.
- Assess boundary layer disruption and turbulence inducing inserts.
- Consider cases where axial velocity decrease in a single pass limit due to high flux rates limiting transport of fouling components away from membrane or filter surface.
- Explore alternatives to drastically reduce the length of the flow path in the membrane support and/or the module flow channel on the permeate side of the module. This is especially important in applications that involve viscous liquids.

Problem: **Develop New Feed Spacer Materials for Spiral-Wound Elements**

Originator: Riley

Importance:

Feed spacers used in spiral wound membrane elements are inadequate and poorly designed, contribute to fouling, and trap suspended solids. Other deficiencies include:

- Inadequate and non-uniform mixing.
- Low shear at the membrane surface.

- Create areas of stagnation.
- Create low cleaning efficiencies.

The feed spacer is the weakest component of current spiral design. A new spacer design is required to extend the use of spiral elements into new and more demanding applications.

Objective:

Design, develop and produce a new feed spacer material that:

- Exhibits low pressure drop.
- Is thin and flexible.
- Has minimal contact with the membrane surface.
- Allows suspended solids to pass through the element.
- Promotes uniform and required mixing.
- Is capable of being manufactured at a competitive cost.

Suggested Approach:

Develop new spacer designs, reduce design to CAD drawings, conduct computer modeling, optimize for mixing efficiencies, select design, produce prototype sheets of spacer material, evaluate flow patterns and mixing efficiencies in transparent test cells, and determine method of manufacturing and associated costs.

Problem: **Characterize the Mass Transfer Behavior of Unconfined Hollow Fibers in Turbulent Flow and Develop Module Design Correlations**

Originator: Semmens

Importance:

When hollow fibers are used in an unconfined mode, large numbers of fibers can be used, and the energy requirements are reduced. Construction costs and

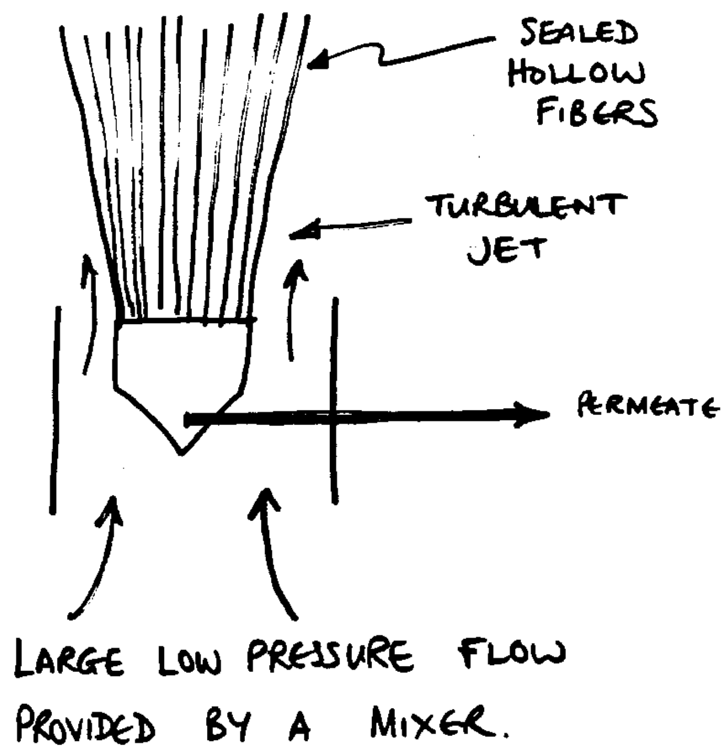
operating costs should be much less expensive. The fouling should be less because of lower fluxes and the self-cleaning action of the fibers.

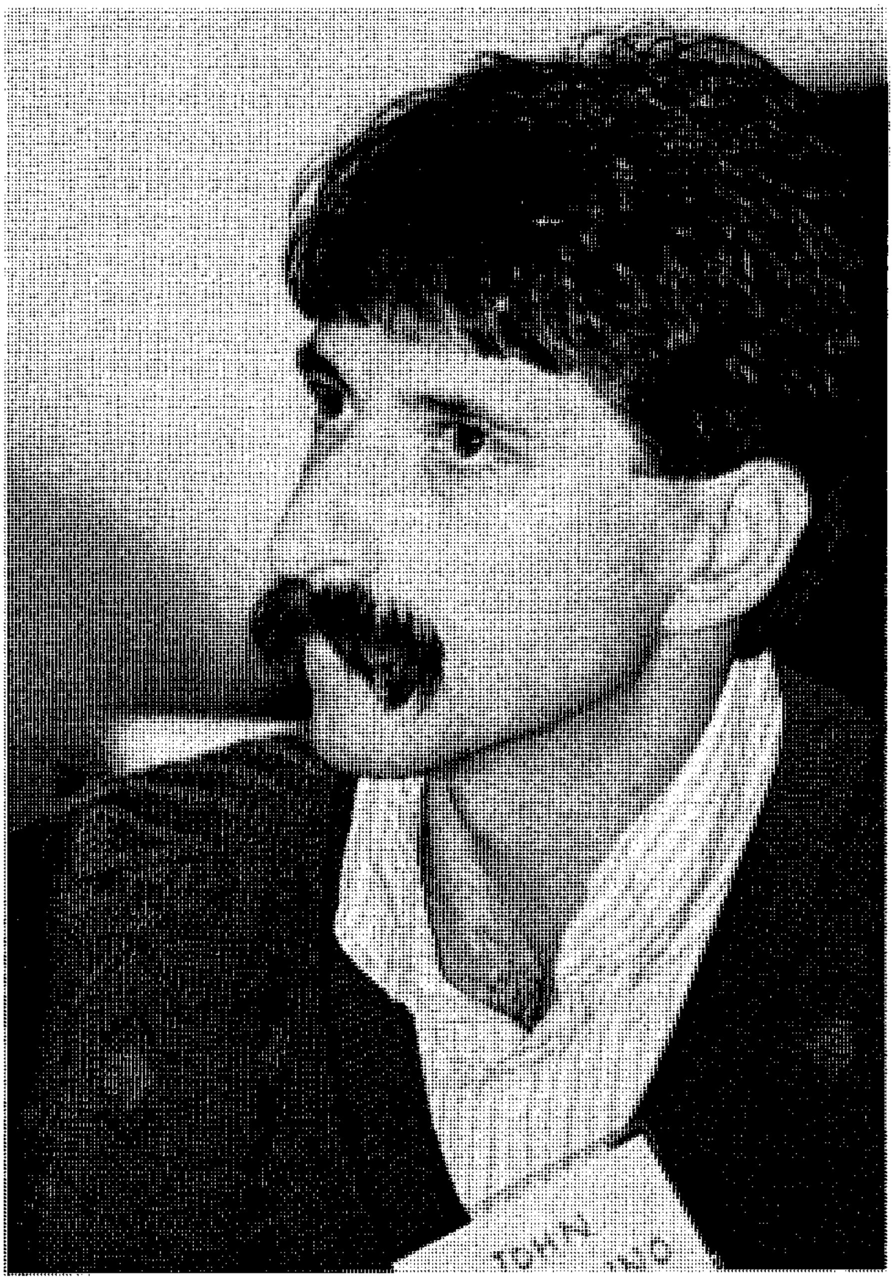
Objective:

- Define mass transfer correlations for unconfined fibers.
- Define flux/power relationships.
- Define long-term behavior compared to a conventional UF.
- Compare with conventional systems.

Suggested Approach:

- Characterize mass transfer behavior of free fibers as a function of jet Reynolds number, power input/volume, and fiber diameter and length.
- Evaluate best module configuration using mass transfer experiments and video analysis.
- Conduct flux/performance studies on best design.





Priority Rank 8: **Development of Standards Tests for Characterizations of Membrane Surfaces and Compatibility of Different Membranes with Natural Water**

Originators: Clark, on behalf of himself, Forgach and Pellegrino

The following research problems were subsumed under the above priority problem title:

Problem: **Development of Standard Tests for Characterizations of Membrane Surfaces and Compatibility of Different Membranes with Natural Waters**

Orignator: Clark

Importance:

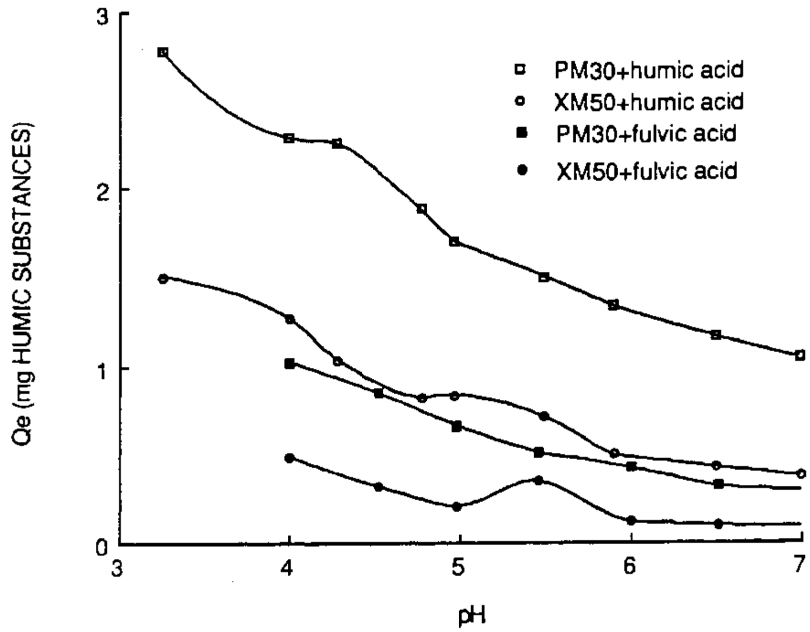
Can we better predict long term fouling of membranes?

Objective:

Optimize and speed up screening of membranes for treatment of natural waters.

Suggested Approach:

Survey of different techniques (e.g., porosity, hydrophobicity, charge, roughness) for characterizing surface and application to a wide range of membranes. Comparison of short-term screening tests with experiments on longer-term fouling.



Mass of Humic Substances Adsorbed (Q_e) on Amicon XM and PM Membranes as a Function of Solution pH (Ref. 2)

Problem: **Physical Chemical Characterization of a Generic Macromolecular Biofoulant of Reverse Osmosis Membranes**

Originator: Forgach

Importance:

This characterization would provide a road map for the design of physical-chemical based strategies to remediate fouling.

Objective:

- Identification of mechanisms or classes or mechanisms typically responsible for fouling of RO or other membranes.
- Design of rapid and facile screening methods to evaluate fouling remediation measures.

Suggested Approach:

Empirical and computationally-based structure/function activity relationships.

Problem: **Can Lumped Parameters be Useful for Predicting Fouling Effects in Complex Mixtures?**

Originator: Pellegrino

Importance:

Real aqueous solutions are complex mixtures that get more complex at the membrane interface. Mixture correlating parameters could help facilitate choosing the correct membrane and/or operating conditions.

Objective:

Develop correlating parameters for complex aqueous mixtures such that different mixtures with equal values of the correlating parameters would cause similar fouling effects on membranes of a specific type.

Suggested Approach:

- Define standard "fouling effects," test mixtures and membranes.
- Define potentially significant physico-chemical properties.
- Create non-dimensional groups (correlating parameters).
- Make many measurements.
- Attempt correlation....try again!


ROBERT
RILEY
MICHAEL
SEMMENS

Priority Rank 9: **Role of Organic-Membrane Interactions and Impact of Surface Chemistry and Morphology on Adsorptive Fouling of RO/UF/NF Membranes**

Originators: Bhattacharyya on behalf of himself, Clark, and Kopp

The following research problems were subsumed under the above priority problem title:

Problem: **RO Membrane Fouling: Effects of Low Molecular Weight Organics Adsorption and Interactions**

Originators: Bhattacharyya

Importance:

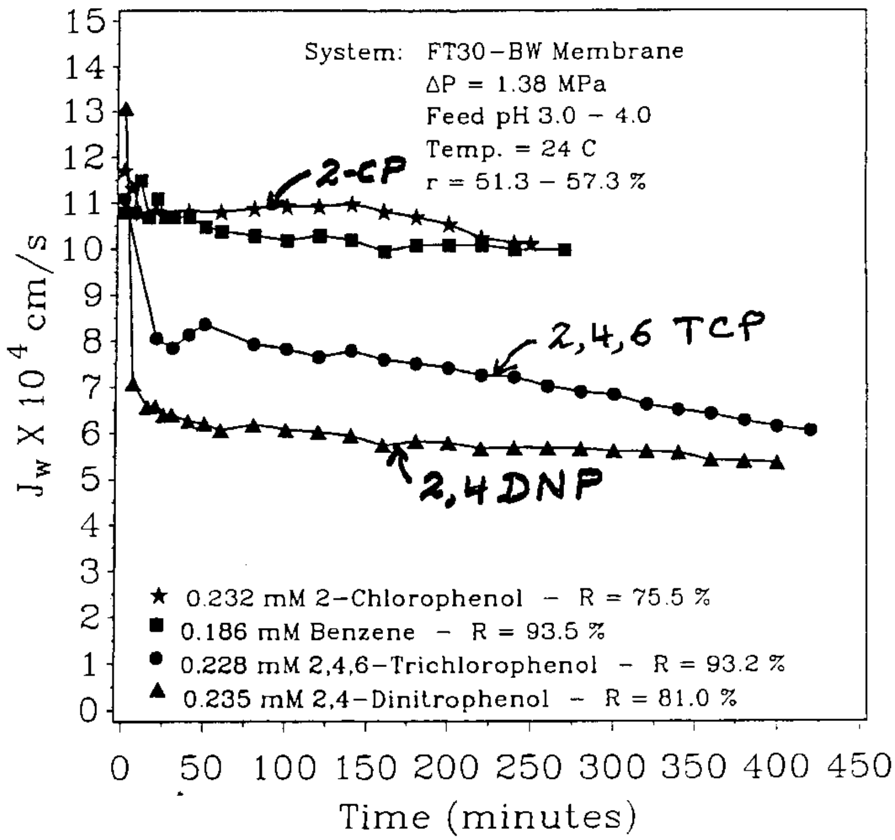
Many RO applications involve the simultaneous separation of salts and hazardous organics from water/waste water. Process optimization will require polymer modification and/or pretreatment for the reduction of organic-polymer interactions.

Objective:

- Obtain useful and simple transport models to include the effects of specific interactions between organics and polymers.
- Develop methods to minimize organics adsorption.

Suggested Approach:

- Experimentally, obtain correlation between flux drop and organic-polymer interaction parameters for various types of commercial RO membranes.



Flux vs. time for selected hazardous organics

(Batch System)

- Determine extent of solute loss (due to both specific and non-specific adsorption) on both membranes and supports.
- Develop new generation polymers to minimize organics adsorption/sorption.

Problem : **How are Physico-Chemical Properties of Natural Organic Matter (NOM) and Membrane Related to Adsorptive Fouling of Membranes by NOM?**

Originator: Clark

Importance:

Adsorptive fouling of membranes by NOM during drinking water treatment causes severe flux losses. Solution of this problem will make membrane processes more attractive.

Objective:

- Characterize interaction of NOM with membranes.
- Correlate physico-chemical properties of NOM & membrane to adsorption of NOM.
- Examine changes in membrane surface due to NOM adsorption.

Suggested Approach:

- Develop methods for measuring adsorption isotherms and kinetics.
- Measure solubility, partition coefficients, size-MW, and calcium binding of NOM as a function of solution chemistry (pH, ionic strength, calcium concentration).
- Characterize clean and fouled membrane surfaces using contact angle, charge, roughness and elemental analysis measurements.

Problem: **What is the Relationship of RO Membrane Chemistry to Organic Fouling in the Treatment of Secondary Effluent?**

Originator: Kopp

Importance:

Recovery of sewage effluent for water reuse is becoming a critical issue around the world.

Objective:

Determine the best membrane chemistries or fouling controlling methods for cost effective treatment.

Suggested Approach:

Evaluate all commercially available RO membranes.

Priority Rank 10: Protein Adsorption: A Dynamic Process

Originator: DiLeo on behalf of himself and Bhattacharyya

The following research problems were subsumed under the above priority problem title:

Problem: **Quantification of Protein Adsorption and Protein/Surface Interactions**

Originator: Bhattacharyya

Importance:

It is quite well known that adsorption of proteins on membrane surfaces causes substantial flux drop. A direct method (on solid phase) of protein analysis will establish the time dependent adsorption and desorption phenomena.

Objective:

Use of Scintillation Proximity Assay (SPA) technique to quantitatively establish the extent of protein adsorption.

Suggested Approach:

- SPA is a powerful technique to establish nanogram quantities of radiolabled (C^{14} or I^{125}) proteins.
- Ultra violet light emission (scintillations) from B-particles (proteins) interaction with fluor molecules can be quantified to establish protein concentrations.
- EPR spectroscopy for protein/protein and protein/surface interactions.

Problem: **Protein Adsorption: A Dynamic Equilibrium Process**

Originator: DiLeo

Importance:

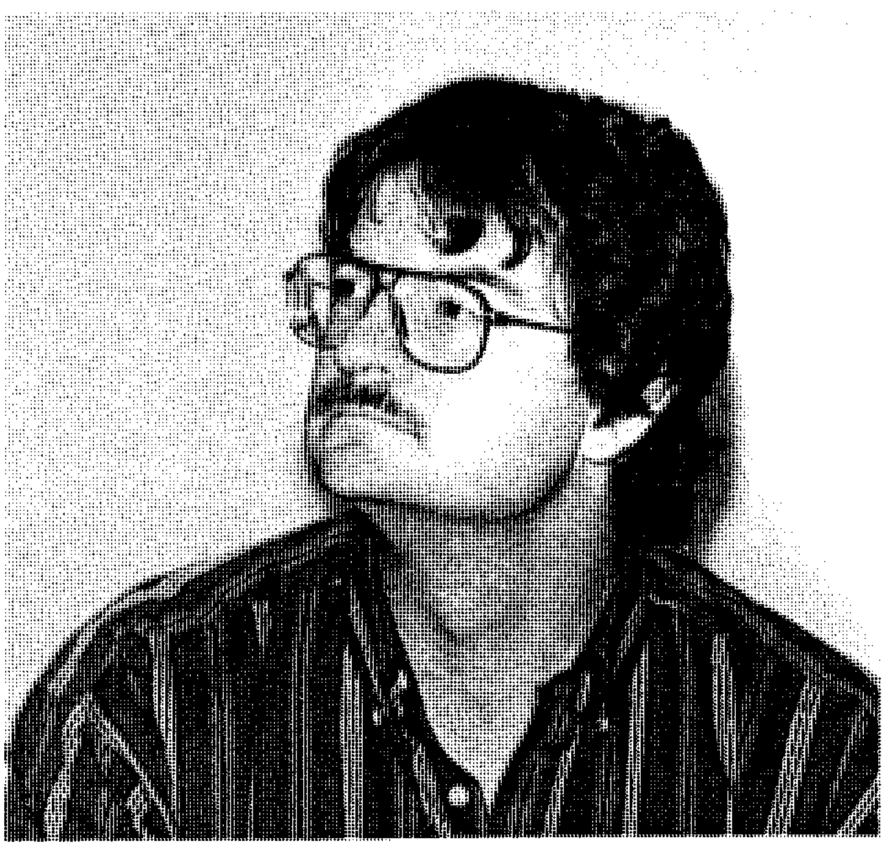
We have observed that proteins adsorb to membrane surfaces to different extents. Depending upon solution conditions, operating pressure and membrane materials, we have observed denatured protein dissolving from the membrane surface, particularly at early times. Selective spaces adsorption may effect membrane selection, device start-up, and operating conditions.

Objective:

Define the principles upon which to determine protein (fouling) adsorption, i.e., membrane selection criteria and the factors effecting adsorption dynamics with highly adsorptive surfaces.

Suggested Approach:

Using labeling proteins, optical rotational measurements study the amount and speciation of adsorbed proteins as a function of membrane type and operating conditions. Focus on effect of start-up dynamics on ultimate pseudo steady-state conditions.



Priority Rank 11: Cleaning Techniques for Fouled Membranes

Originators: Pirbazari on behalf of himself, Athayde, Kopp, and Webster

The following research problems were subsumed under the above priority problem title:

Problem: **Application of Nano-Technology/Microbes to Membrane Cleaning**

Originator: Athayde

Importance:

It may be impossible to prevent membrane fouling. Cleaning methods in use today and under development require interruption of operation. Nano-machines on the membrane surface would operate continuously. Microbes could be selected to feed on the foulant and contain or reduce the extent of fouling.

Objective:

To develop nano-machinery and identify microbes suitable for cleaning fouled membrane surfaces.

Suggested Approach:

These are both high-risk, long-term efforts. Exploratory research in these areas is best handled by an interdisciplinary effort.

Problem: **Development of Cost-Effective Chemical Cleaning Methods for Membrane Systems**

Originator: Kopp

Importance:

Improvement of cost effectiveness of membrane processes.

Objective:

Optimization of chemical cleaning methods for membrane systems.

Suggested Approach:

Problem: **Membrane Rejuvenation for Reverse Osmosis and Nanofiltration Membranes**

Originator: Pirbazari

Importance:

Deterioration in membrane rejection characteristics often occurs due to surface damage caused by the action of strong chemical cleaning agents. A rejuvenating agent is employed to provide "surface treatment" (surface coating on the membrane), and "hole plugging," to restore the rejection characteristics. The choice of rejuvenation agent essentially depends on the membrane material because there must be compatibility between them. However, after rejuvenation, although rejection recovery is achieved, it is at the expense of permeate flux, a factor that has a direct bearing on the process economics. The development of better rejuvenation chemicals and appropriate methodologies is therefore important.

Objective:

This study will involve the use of rejuvenating agents for different types of membranes and feeds in typical applications. The permeate flux recovery and species rejection must be simultaneously studied for each type of rejuvenation process.

Suggested Approach:

The suggested approach is to investigate compatible rejuvenating agents for a certain membrane material and feed combination, and to evaluate the membrane rejection and permeate flux. The membrane rejuvenation effectiveness can be studied from a more fundamental viewpoint by scanning electron microscopic

analyses of the membrane after cleaning, prior to and subsequent to rejuvenation. This approach would provide good information on the changes in the membrane morphology during rejuvenation.

Problem: **Cleaning Techniques for Fouled Membranes**

Originator: Pirbazari

Importance:

The use of strong chemicals potentially lead to gradual material deterioration in different types of membranes. In this regard, it is necessary to use appropriate cleaning solutions to restore membrane flux without adversely affecting the membrane selectivity and rejection characteristics. The choice of appropriate cleaning agents is necessary not only to treat membranes affected by organic and inorganic fouling, colloidal fouling, or scaling, but also those affected by biofouling. Development of effective membrane cleaning methods to restore the membrane capabilities is an important research area, for the above factors often dictate the applicability and economic viability of membrane processes for water and waste water treatment or water reclamation.

Objective:

The investigation will involve the appropriate combination of cleaning agents that may include weak but effective oxidants or reductant (that may not damage the membrane), and a surfactant for complete removal of the foulants. On the other hand, the cleaning agent may be a properly chosen enzyme that will be capable of removing biofoulants and organic foulants, in combination with a surfactant.

Suggested Approach:

The suggested approach is to investigate combinations of different types of cleaning solutions, based on sound theoretical principles, to remove foulants and restore membrane flux and rejection characteristics. This study will involve membranes cast from different materials with variable pore sizes, and different types of feeds for which these membranes are commonly used. The fouled membranes must be cleaned by combinations of cleaning agents to mitigate fouling and restore the permeate flux. This investigation will involve the measurements of flux of the fouled membranes, as well as the cleaned membranes to evaluate the effectiveness of cleaning. Analysis of fouled membranes in comparison with cleaned membranes using techniques such as scanning electron

microscopy, infrared spectroscopy, and energy dispersive X-ray spectroscopy can provide valuable information.

Problem: **To Model, Design, and Synthesize Small Particles with Proteolytic Activity for Cleaning Membranes Fouled with Protein**

Originator: Webster

Importance:

Membranes fouled with proteins that can be successfully cleaned will save the cost of membrane replacement.

Objective:

To produce small peptide proteases capable of cleaning proteins from membranes, both surface and non-surface.

Suggested Approach:

Use the known x-ray crystallographic structures of proteases, in which the geometry of the catalytic site is known in atomic detail, to model and design, using appropriate computer software, small synthetic peptides with protease activity. These peptides will be tested for their ability to clean membranes fouled with proteins. The peptides can be designed with surface chemistry (e.g., hydrophobicity, hydrophilicity) suitable for cleaning different membranes.

Priority Rank 12: Development of a Flux-Loss Predictable Model for Specification of System Operation

Originator: H.L. Fleming on behalf of himself, Hanson and Pellegrino

The following research problems were subsumed under the above priority problem title:

Problem: **Development of a Flux-Loss Predictable Model for Specification of System Operation**

Originator: H.L. Fleming

Importance:

The bottom line in the design and operation of a commercial system is prediction of throughput vs. time/pressure, etc. Current programs are grossly conservative, resulting in large cost over-runs.

Objective:

By incorporating key flux-loss terms (adsorption, physical, degra-reversible/irreversible) and good empirical input, the developed model yields a real-time flux output as a functioning system parameters, useful for system design and operation.

Suggested Approach:

- Identify key flux-loss mechanisms.
- Develop correlations for each phenomena related to flux/operating parameters.
- Integrate into a user-friendly model requiring inputs by anyone basically knowledgeable with the system.

Problem: **Mathematical Modeling and Computational Design, or "National Labs: Sources or Sinks?"**

Originator: Hanson

Importance:

Computational capabilities and modeling techniques abound at the national labs. Development of communication processes could lend resources to researchers, designers and manufacturers.

Objective:

Promote effective and efficient use of computer modeling capabilities at national labs to enhance understanding of fouling mechanisms and flow dynamics.

Suggested Approach:

- Identify personnel at labs currently working in the membrane area.
- Place lab personnel on variety of boards/committees related to membrane use.
- Collaborate (working groups) with universities and industry on modeling of biological, chemical, physical properties, and design.

Problem: **The Underlying Phenomena of Fouling are Understood - What Next? Coupling Models.**

Originator: Pellegrino

Importance:

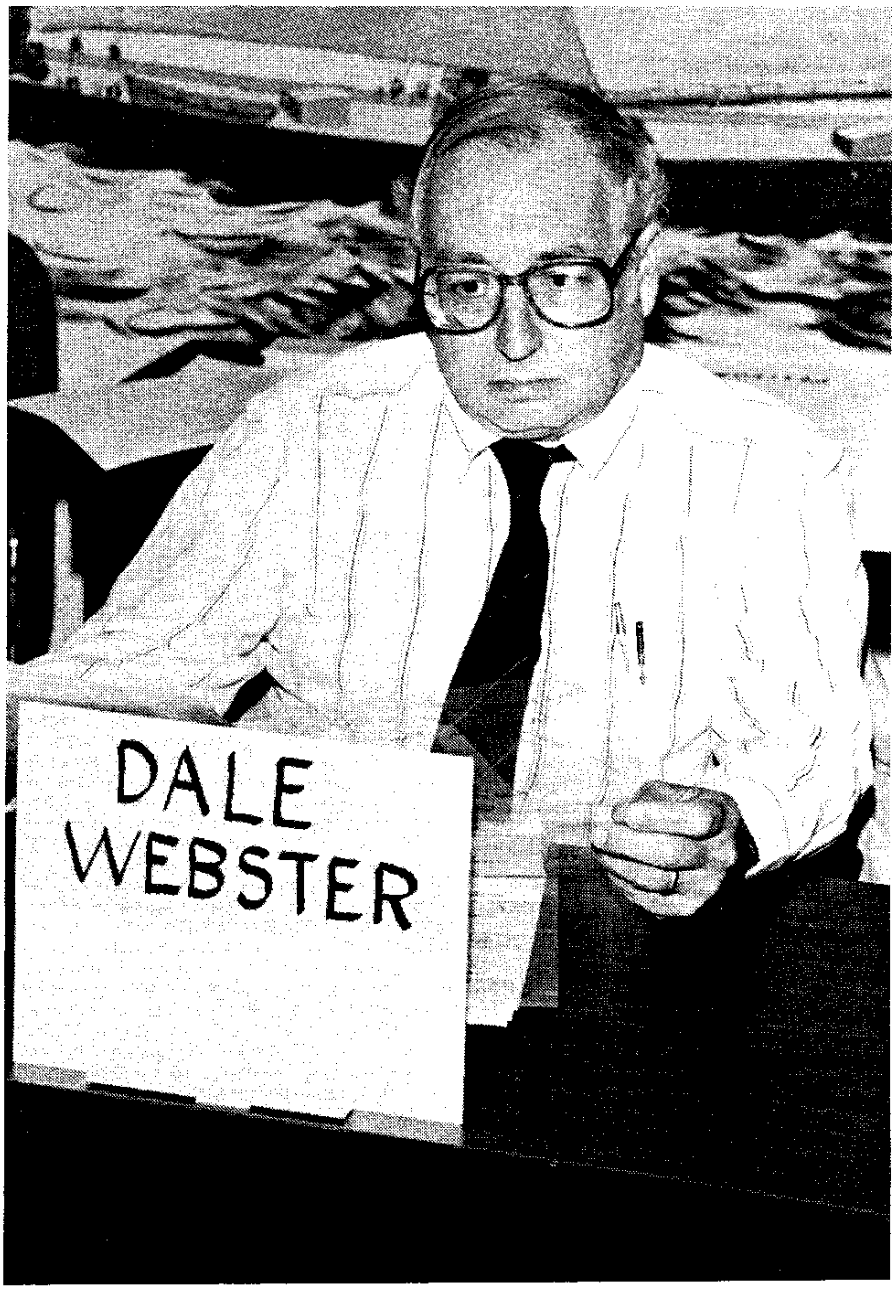
The relative importance of various fouling mechanisms in simple systems can be very different from that in real, multi-component aqueous solutions.

Objective:

Develop accurate, numerically-efficient models for multi-component, time-dependent coupled phenomena that occur at the membrane interface.

Suggested Approach:

Use a focus group to develop a consensus of key phenomena that occur in a real system. Consider whether adaption of atmospheric modeling techniques may be appropriate.




HARRY

Priority Rank 13: Understanding Silica Crystalline Structures and Their Attachment Mechanisms Associated with Other Foulants and Specific Ionic Species

Originator: Hanson on behalf of himself and subsuming one of his other problems.

Importance:

Silica naturally occurs in very high concentrations in the raw waters in the southwest. The ability to successfully bind the silica with a chemical additive, thereby enhancing removal efficiencies of the membrane by effectively negating the fouling tendencies naturally inherent in silica structures, would be beneficial in a wide variety of applications.

Objective:

Develop a working model of various silica crystalline structures under normal operating pressures and temperatures of membrane systems. This work would lead to the development and implementation of a variety of materials effective in binding the silica matrix and preventing its polymerization tendencies.

Suggested Approach:

Utilize natural resources containing 80 ppm of naturally occurring silica in specifically designed unit operations. Development of chemicals will be conducted in laboratory facilities co-located with the unit operations, relying primarily on work previously performed which identifies approximately 200 potential silica inhibitors.

The following research problem was subsumed under the above priority:

Problem: **Determination of Fouling Potential of Radionuclides on Membrane Systems**

Originator: Hanson

Importance:

Lower discharge limits, along with proposed EPA/NMED authority, makes membrane treatment an attractive alternative. Little is known, however, concerning membrane degradation due to radiation. Degradation potential is assumed to be increased with residence time due to fouling of membrane surfaces.

Objective:

Determine if colloidal/adsorbed particles containing radionuclides are readily removed by membrane filtration (MF, UF), or if radionuclides are best removed in ionic form.

Suggested Approach:

Utilize pilot testing to determine:

- Fouling potential.
- Nature of particle.
- Removal capabilities in ionic form.

Priority Rank 14: Reduction of Roughness on the Transport Surface of Composite Membranes to Reduce Fouling

Originator: Riley

Importance:

Roughness on the surface of polyamide composite membranes is a major cause of fouling by particulate matter. Surface roughness contributes to:

- Increased boundary layer.
- Reduced membrane performance.
- Entrapment of suspended solids and colloidal matter.
- Enhanced biofilm formation.
- Reduced cleaning efficiencies.

Objective:

Reduce fouling exhibited by polyamide thin-film composite membranes by modifying the surface morphology on the transport surface. The latter must be accomplished without reducing the transport properties of the membrane.

Suggested Approach:

Evaluate and determine the process variables responsible for determining surface morphology during the interfacial formation of polyamide composite membranes. Characterize the surface morphology of the resulting membranes by standard methods for correlating cause and effect. Conduct fouling studies on the modified membranes using waste water feeds.


LEO
GADDIS
LEO

Priority Rank 15: Fouling by Viscous Particulate Layers Including Effects of Compression and "Sticky" Inclusions

Originators: Gaddis on behalf of himself and Bhattacharyya

Importance:

Many micro- and ultra-filtration applications have fluxes limited by layer of viscous material. Improved comprehension will lead to reduced cost and increase the generally beneficial application of expanded utilization.

Objective:

- Determine the viscosity and resistivity of the layer under the compression of filter action.
- Identify the forces tending to suspend the particles.
- Perform tests to evaluate the hypotheses.

Suggested Approach:

The viscous cake may be more fluid under shear and less fluid with the addition of some "sticky" organic substances. Tests are expected to demonstrate whether shear and pressure have effects on the already deposited layer. Other tests for pH and electrolyte concentration are appropriate. Also deposit/removal hysteresis should be evaluated.

The following problems were subsumed under the above priority problem title:

Problem: **Effects of Organics on Particulate Fouling in Membranes**

Originator: Bhattacharyya

Importance:

Many organics adsorb on particles, and thus the "stickiness" property of the particles is often enhanced.

Objective:

To isolate the individual fouling effects of particles and particles with adsorbed organics.

Suggested Approach:

- Need effect of hydrodynamic flows on deposition of particles (with adsorbed organic).
- Determine effects of particulate surface charge on adsorption and fouling.

Problem: **Compressible Viscous Fouling Layers**

Originator: Gaddis

Importance:

Many micro- and ultra-filtration applications have fluxes limited by a layer of viscous material. Improved comprehension will lead to reduced cost and increase the generally beneficial application of expanded utilization.

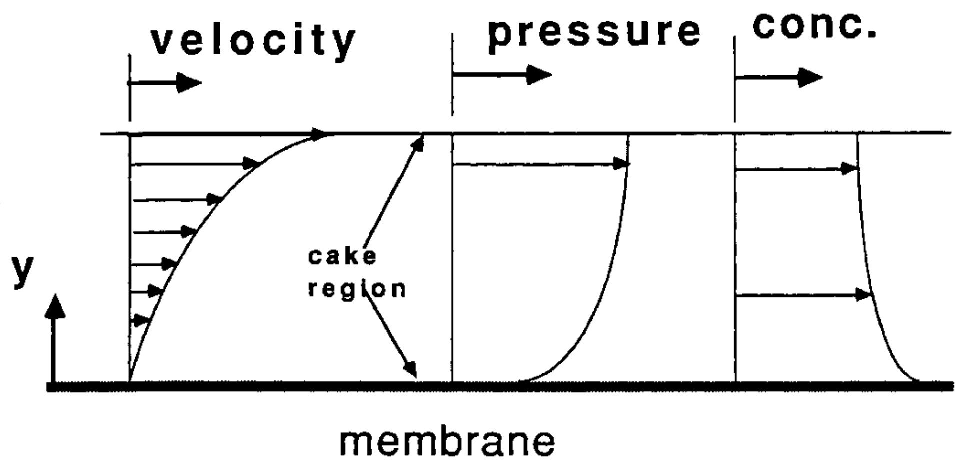
Objective:

- Examine existing data to determine the parameters (viscosity and resistivity) of the average layer.
- Estimate the forces needed to suspend the particles in the flow to the level indicated by data.

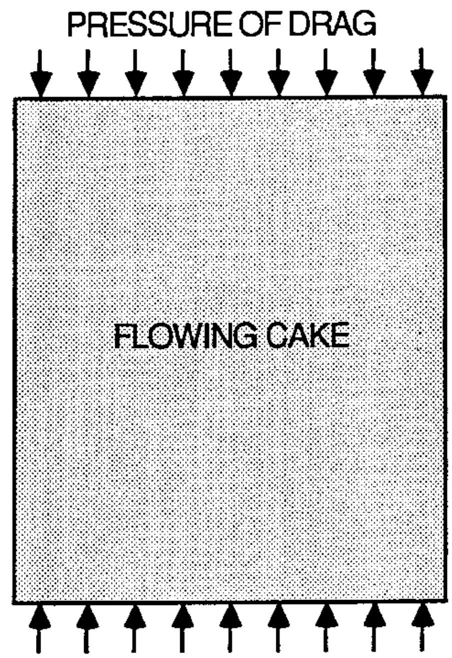
- Propose an hypothesis and test a set of force models in actual filtration of suspended particles.

Suggested Approach:

The data from published experiments indicates the mean volume concentration of flowing slurries is very close to 0.59 and is dependent on the compression applied by the operating flux. It is desired to detect whether the resistance of a frozen-in-place layer remains constant or increases; whether there are modifications by pH or electrolyte concentrate; and, whether there is deposit/erosion hysteresis. Results should promote remediation measures.



ELEMENTARY CAKE CONCEPTS



SUSPENDING FORCES:

A) dispersion forces
B) coulombic forces
C) mechanical linkage
D) fluid dynamic
    1) extensions of dilute inertial forces
    2) extensions of rheology-based concepts

Priority Rank 16: **Solute Fractionation with Ultrafiltration Membranes: Extending the Range of Applicability**

Originator: Henry

Importance:

Ultrafiltration membranes can in principle be used to fractionate solutes in the same molecular weight and conformation range. In practice, this is only possible in near infinite dilution in the absence other dynamic membrane forming solutes. If the understanding of physico-chemical interactions of solutes with membranes could progress to the point where either additives or membrane phase treatments could prevent the formation of dynamic membrane layers that obscure the solute fractionation properties of the original membrane, it would be possible to generate greatly expanded range of application.

Objective:

Investigate the limits of membrane fractionation of solutes of close molecular weight or functionality.

Suggested Approach:

Utilize results of solute interactions and improved characterizations of solute interactions on membrane surfaces.

Priority Rank 17: Develop a Handbook that will Organize and Parameterize the Available Experimental Data

Originator: Pellegrino

Importance:

Put information in a format which makes it easier to compare between systems; avoid redundancy; focus efforts on filling in important gaps; and put information in a format which makes it easier to extract parameters useful for predictive modeling.

Objective:

Develop a database/bibliography which groups classes of foulants: (inorganic, organic, biomolecules, organisms) and contains such parameters as adsorption isotherms, equilibrium parameters, solubilities, kinetics.

Suggested Approach:

Organize a group to create a comprehensive handbook. Use focus groups to identify data categories and reporting format.

Priority Rank 18: **Removal of Cell Debris from Cell Lysates by Membrane Filtration**

Originator: Davis

Importance:

Many biotechnological protein products are intracellular, so cells must be lysed in order to release protein. The resulting cell debris must be removed from the cell lysate as an initial step in product purification. The use of centrifugation is inefficient.

Objective:

Develop membrane filtration processes which efficiently remove cell debris from cell lysates while maintaining high protein transmission.

Suggested Approach:

Use cross flow or rotary microfiltration with high shear and low transmembrane pressure. Secondary flows, prefiltration, and rapid transmembrane pressure pulsing are also suggested.

Priority Rank 19: **Develop a Biological Na+ Pump for Desalination that would Operate at Zero Pressure**

Originator: Webster

Importance:

This would be a totally different approach for desalination that would use a new technology. It has the potential to operate at lower cost and might not be susceptible to some types of fouling since only ions, not water, would flow through the membrane.

Objective:

To study further the structure and Na+-pumping characteristics of the cytochrome o Na+-pump. This information will facilitate the incorporation of the protein into a suitable conducting membrane and allow the development of a stable synthetic derivative.

Suggested Approach:

The genes for the cytochrome o terminal oxidase will be cloned in E. coli using appropriate vectors. Three techniques for selection of the genes will be tested in this order: 1) using a terminal oxidase deficient mutant of E. coli that cannot grow aerobically, 2) employing the PCR (polymerase chain reaction) technique with primers based on nucleotide sequences of homologous genes, 3) using immunological methods, i.e., antibodies to the protein products of the genes.

Priority Rank 20: Methods to Study the Structure and Energetics of H_2O at Interfaces

Originator: Pellegrino

Importance:

In aqueous separations, water is the major species. Keeping H_2O at the membrane interface precludes fouling.

Objective:

Develop instrumental techniques that can do depth profile characterization of H_2O structure and energy states at membrane interfaces.

Suggested Approach:

- Neutron scattering with D_2O.
- Neutron reflectometry.
- Combination of spectrometry techniques.

Priority Rank 21: **Development of Chlorine-Stable RO and NF Membranes**

Originator: Forgach

Importance:

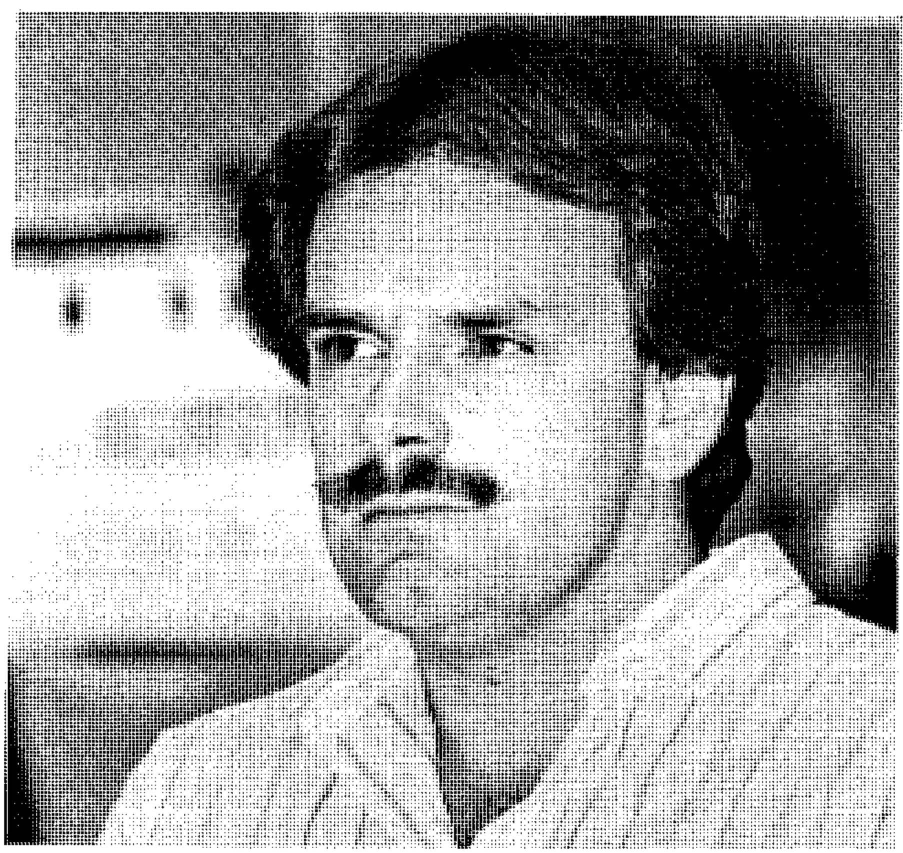
Inclusion of Cl_2 in the feedwater would greatly reduce fouling load to a membrane.

Objective:

Develop new membrane chemistries whose performance is stable to ppm levels of chlorine during service life of membrane (>50,000 ppm hrs.).

Suggested Approach:

Conduct a survey of membrane chemistries.



Priority Rank 22: **Assess Mechanical Cleaning Techniques to Maintain Acceptable Fouling Levels in Membranes**

Originator: Semmens

Importance:

Some fouling must be tolerated - it cannot be avoided. Turbulence promoters elevate the energy requirements for treatment. Mechanical cleaning techniques may be feasible at a lower energy cost.

Objective:

Reevaluate module design to consider mechanical means of cleaning. Air scouring, fiber/fiber contact, and suspended solid cleaning agents may be tested.

Suggested Approach:

Select a UF membrane having a smooth surface morphology. Develop and/or design a module for application with the cleaning agents. Include a control study (with and without cleaning agent procedures) for comparison.

Priority Rank 23: **Regenerable Surfaces via Dynamic Membranes**

Originator: Pellegrino

Importance:

If the surface can be "sloughed," cleaned and returned to service at low cost, then the impact of fouling can be minimized.

Objective:

Develop dynamic membrane materials which can be easily detached from the surface, cleaned and recycled at low cost.

Suggested Approach:

Focus on tubular membrane modules and sol gel particles with brush polymer attachments.

Priority Rank 24: Coupling of Fundamental Research in Other Areas to Help Address Fouling

Originator: O'Rear

Importance:

Basic research exists or is underway that will facilitate addressing certain mechanisms of fouling.

Objective:

Accelerate the transfer and utilization of fundamental knowledge in solving the practical problem of fouling.

Suggested Approach:

Take advantage of existing methods of technology transfer as well as develop new techniques. This could include meetings and conferences (Gordon conferences, workshops) and "people transfer."


HARRY
RIDGWAY

LIST OF WORKSHOP PARTICIPANTS

Dr. Amulya Athayde
Membrane Technology & Research
1360 Willow Road
Menlo Park, CA 94025
Tel: (415) 328-2228
Fax: (415) 328-6580

Dr. Dibakar Bhattacharyya
University of Kentucky
Department of Chemical Engineering
163 Anderson Hall
Lexington, KY 40506
Tel: (606) 257-2794
Fax: (606) 257-7251

Dr. Mark Clark
Lyonniase des Eaux-Dumez
38, rue du President Wilson
78230 Le Pecq
FRANCE
Tel: (33) 1-34802345
Fax: (33) 1-34800901

Dr. Clark Colton
Department of Chemical Engineering
Room 66-452
MIT
25 Ames Street
Cambridge, MA 02139
Tel: (617) 253-4585
Fax: (617) 253-9695
E-mail: Ckcolton@athena.mit.edu

Dr. Robert Davis
Department of Chemical Engineering
University of Colorado
Boulder, CO 80309
Tel: (303) 492-7314
Fax: (303) 492-4341

Dr. Anthony DiLeo
Millipore Corporation
80 Ashby Road
Bedford, MA 01730
Tel: (617) 275-9211, x-26611
Fax: (617) 275-9053

Dr. William Eykamp
246 Pleasant Street
Arlington, MA 02174
Tel: (617) 646-3320
Fax: (617) 646-5955

Dr. Hubert Fleming
Zenon
13 Estates Drive
Sussex, NJ 07461
Tel: (201) 702-0174
Fax: (201) 702-1374

Dr. Hans-Curt Flemming
Biofilm Control
Universitat Stuttgart
Institute fur Siedlungswasserbau
Bacdtale 1, D-7000 Stuttgart 80
GERMANY
Tel: (49)-711-6855444
Fax: (49)-711-2991201

Dr. David Forgach
Dow Chemical
Building 1702
Midland, MI 48674-1702
Tel: (517) 636-8124
Fax: (517) 638-9623

Dr. J. Leo Gaddis
Department of Mechanical Engineering
College of Engineering
318 Riggs Hall
Box 340921
Clemson University
Clemson, SC 29634-0921
Tel: (803) 656-3294
Fax: (803) 656-4435

Mr. Steve Hanson
Los Alamos National Laboratory
P.O. Box 1663
MS E518
Los Alamos, NM 87545
Tel: (505) 667-4301
Fax: (505) 665-6320

Dr. Joseph Henry
Department of Chemical, Biological
and Materials Engineering
Arizona State University
Tempe, AZ 85287
Tel: (602) 965-3316
Fax: (602) 965-0037

Dr. Clint Kopp
MEMTEC Limited
LMB 1
Windsor, New South Wales 2756
AUSTRALIA
Tel: (61) 45-770916
Fax: (61) 45-776829

Dr. Edgar O'Rear
National Science Foundation
1800 G Street, NW
Room 1110
Washington, DC 20550
Tel: (202) 357-9606
Fax: (202) 357-5184

Dr. John Pellegrino
National Institute of Standards
and Technology
Chemical Engineering Science Division
325 Broadway
Boulder, CO 80303
Tel: (303) 497-3416
Fax: (303) 497-5224

Dr. Massoud Pirbazari
Department of Engineering
University of Southern California
Los Angeles, CA 90089
Tel: (213) 740-0592
Fax: (213) 744-1426

Dr. Harry Ridgway
Orange County Water District
Biotechnology Department
P.O. Box 8300
Fountain Valley, CA 92728-8300
Tel: (714) 378-3266
Fax: (714) 378-3373

Mr. Robert Riley
Separations Systems Technology
4901 Morena Blvd.
Building 809
San Diego, CA 92117
Tel: (619) 581-3765
Fax: (619) 581-1211

Dr. Michael Semmens
Department of Civil and Mineral Engineering
University of Minnesota
Minneapolis, MN 55455
Tel: (612) 625-9857
Fax: (612) 626-7750

Dr. Dale A. Webster
Dept. of Chemical and Biological Sciences
Division of Biology
Illinois Institute of Technology
Chicago, IL 60616
Tel: (312) 567-3491
Fax: (312) 567-3491
BITNET: BIOLWEBSTER W/ IIT VAX

Dr. Andrew Zydney
Dept. of Chemical Engineering
University of Delaware
Newark, DE 19716
Tel: (302) 831-2399
Fax: (302) 831-1048
E-Mail: Zydney @ CHE.UDEL.EDU

REFERENCES

1. Delbecq, Andre L., A. H. Van deVen, and D. H. Gustafson, *Group Techniques for Program Planning - a guide to nominal group and delphi processes,* Green Briar Press, 6612 Green Briar Road, Middleton, Wisconsin 53562, 1975: 174p.

2. Clark M. and C. Jucker, *Interactions Between Hydrophobic Ultrafiltration Membranes and Humic Substances,* Proceeding of AWWA Membrane Technology Conference, Baltimore, Maryland, 1993.

APPENDICES

APPENDIX A

Explanation of Priority Ranking Systems and Data Displays

Two methods were employed to analyze the results of this workshop and to assist the reader in appreciating the level of agreement or disagreement among the participants as to the importance of each problem proposed.

Numerical Computation of Strength of Feeling

The first and most basic categorization of priorities is shown in the organization of the contents of the report. Each of the 22 participants completed a Problem Ranking Sheet at the conclusion of the workshop. On that sheet they ranked in descending order of importance, the problems which they regarded as most important to address and solve. The data from these sheets were entered in a computerized tabulation program which produced three sets of information. These sets of information included:

- The total number of points assigned to each problem by the rankers. The maximum credit which can be given to a problem by an individual is ten. Credit is assigned in descending order down to a one which is assigned to the 10th priority problem. The software assigns all unranked problems the score of zero. Thus, the maximum number of points which could be assigned to a problem in this workshop if all rankers agreed and gave a certain problem a ten is 220 (i.e., 10 points x 22 rankers = 220). The actual number of total points assigned to each problem is shown as the denominator of the fractions in the first column in Appendices B, C, D, and E.

- The number of times a problem is picked by all rankers. This number appears as the numerator of the fractions in the first column in Appendices B, C, D, and E.

- The "Strength of Feeling" is the third category of information and is presented as a percentage in the second column of Appendices A, B, C, and D. This percentage is computed by dividing the actual number of points assigned to each problem (as represented by the denominator of the column of fractions in the appendices listed above) by the total number of possible points which could be assigned if all rankers gave it a score of ten, or a total of 220 points. This fraction multiplied by 100 gives the Strength of Feeling as a percentage. If all rankers agreed on a highest priority problem, it would receive a 100%.

Similarly, if all rankers agreed on a second highest priority problem, it would receive a 90%, and so on.

Graphical Representation of Level of Agreement

The second method used to present the data from the workshop is to plot the divergence from the "average response" to each question ranked. This became the "base rank." Since there were 24 questions to be ranked, the graphs in Appendices F, G, H, I, J, and K show the base ranking as the line x=y. The problems were listed in decreasing order of importance as ranked by all participants. This ranking is shown numerically by the numbers assigned in the Table of Contents and as the problems are presented in the Priority Ranking section of the report which contains detailed descriptions of the problems.

Each participant was asked to assign himself an appropriate subcategory in each of six categories. These six categories are listed on the Participant Categorization Sheet shown in Appendix N of this report. Each category was graphically analyzed to determine if there were any segments of the group which greatly disagreed with the prioritization of the group as a whole. Individual responses (y-axis) were plotted against the ranking all the participants (x-axis). Clusters of responses of any individual subcategory which fall far from the x=y line suggest a difference of opinion from the group as a whole.

APPENDIX B

All Problems (24) Ranked by All Workshop Participants (22)

Rank	Abbreviated Title	Times Picked/Points	Strength of Feeling
1.	Taxonomy of Fouling:etc.	20/144	65.5%
2.	Membrane Biofouling: Mechanisms, etc.	17/129	58.6%
3.	Understanding & Reducing Biofouling thru Fluid Mech. & Mass Transfer	17/103	46.8%
4.	Chemical Modification of Membrane Surfaces, etc.	18/100	45.5%
5.	Effective Pretreatment Strategies, etc.	19/96	43.6%
6.	Development & Characterization of Well-Defined Membranes, etc.	17/87	39.5%
7.	Development of Cost-Effective, High Performance Membrane Modules	14/85	38.6%
8.	Development of Standard Tests for Characterization of Surfaces, etc.	14/65	29.5%
9.	Role of Organic-Membrane Interactions & the Impact of Surface Chemistry, etc.	9/59	26.8%
10.	Protein Adsorption: A Dynamic Process	9/55	25.0%
11.	Cleaning Techniques for Fouled Membranes	14/51	23.2%
12.	Development of a Flux-Loss Predictable Model for Specification of System Operation	8/39	17.7%
13.	Understanding Silica Crystalline Structures, etc.	5/28	12.7%
14.	Reduction of Roughness on the Transport Surface, etc.	6/26	11.8%
15.	Fouling by Viscous Particulate Layers, etc.	5/22	10.0%
16.	Solute Fractionation with Ultrafiltration Membranes, etc.	5/22	10.0%
17.	Develop a Handbook, etc.	4/20	9.1%
18.	Removal of Cell Debris from Cell Lysates, etc.	3/15	6.8%
19.	Develop a Biological Na+ Pump of Desalination, etc.	2/14	6.4%
20	Methods to Study the Structures and Energetics, etc.	2.13	5.9%
21.	Development of Chlorine-Stable RO and NF, etc.	4/12	5.5%
22.	Assess Mechanical Cleaning Techniques, etc.	3/11	5.0%
23.	Regenerable Surfaces via Dynamic Membranes	3/10	4.5%
24.	Coupling of Fundamental Research in Other etc.	2/4	1.8%

APPENDIX C

All Problems (24) Ranked by Research Participants (14)

Rank	Abbreviated Title	Times Picked/Points	Strength of Feeling
1.	Taxonomy of Fouling: etc.	14/98	70.0%
2.	Membrane Biofouling: Mechanisms, etc.	11/87	62.1%
3.	Understanding & Reducing Biofouling thru Fluid Mech. & Mass Transfer	11/66	47.1%
4.	Chemical Modification of Membrane Surfaces, etc.	12/64	45.7%
5.	Effective Pretreatment Strategies, etc.	12/62	44.3%
6.	Development & Characterization of Well-Defined Membranes, etc.	11/61	43.6%
7.	Development of Standard Tests for Characterization of Surfaces, etc.	9/55	39.3%
8.	Development of Cost-Effective, High Performance Membrane Modules	8/40	28.6%
9.	Protein Adsorption: A Dynamic Process	6/38	27.1%
10.	Role of Organic-Membrane Interactions & the Impact of Surface Chemistry, etc.	5/36	25.7%
11.	Cleaning Techniques for Fouled Membranes	11/33	23.6%
12.	Development of a Flux-Loss Predictable Model for Specification of System Operation	4/16	11.4%
13.	Reduction of Roughness on the Transport Surface, etc.	4/15	10.7%
14.	Solute Fractionation with Ultrafiltration Membranes, etc.	3/15	10.7%
15.	Develop a Biological Na^+ Pump of Desalination, etc.	2/14	10.0%
16.	Methods to Study the Structure and Energetics, etc.	2/13	9.3%
17.	Develop a Handbook, etc.	3/13	9.3%
18.	Removal of Cell Debris from Cell Lysates, etc.	2/12	8.6%
19.	Fouling by Viscous Particulate Layers, etc.	2/9	6.4%
20.	Assess Mechanical Cleaning Techniques, etc.	2/8	5.7%
21	Regenerable Surfaces via Dynamic Membranes	2/6	4.3%
22.	Development of Chlorine-Stable RO and NF, etc.	2/5	3.6%
23.	Coupling of Fundamental Research in Other etc.	1/3	2.1%
24.	Understanding Silica Crystalline Structures, etc.	1/1	0.7%

APPENDIX D

All Problems (24) Ranked by Design Participants (5)

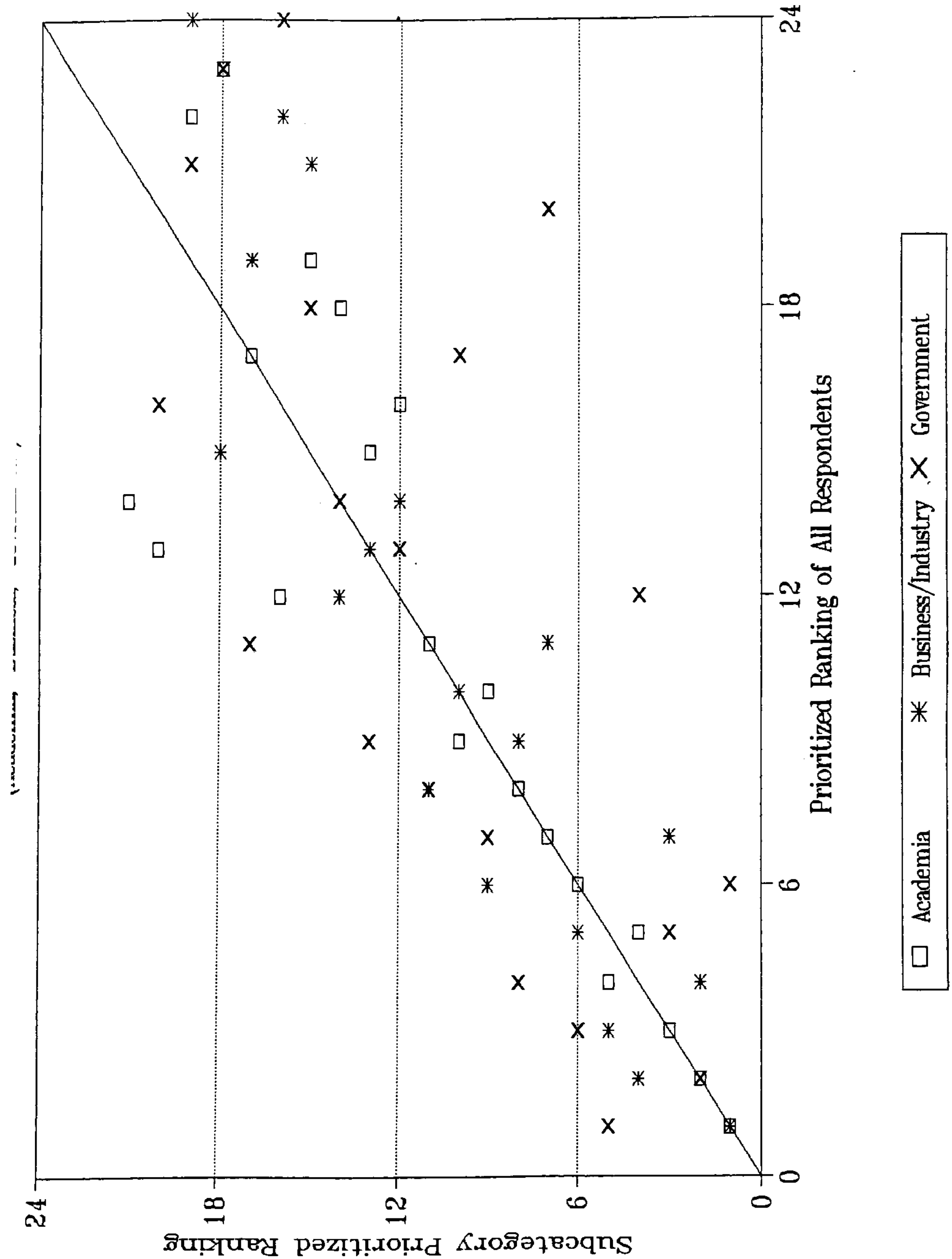
Rank	Abbreviated Title	Times Picked/Points	Strength of Feeling
1.	Taxonomy of Fouling: etc.	4/31	62.0%
2.	Understanding & Reducing Biofouling thru Fluid Mech. & Mass Transfer	4/31	62.0%
3.	Membrane Biofouling: Mechanisms, etc.	4/27	54.0%
4.	Protein Adsorption: A Dynamic Process	4/26	52.0%
5.	Chemical Modification of Membrane Surfaces, etc.	2/22	44.0%
6.	Effective Pretreatment Strategies, etc.	4/20	40.0%
7.	Development of Cost-Effective, High Performance Membrane Modules	3/19	38.0%
8.	Role of Organic-Membrane Interactions & the Impact of Surface Chemistry, etc.	2/17	34.0%
9.	Development & Characterization of Well-Defined Membranes,etc.	3/15	30.0%
10.	Cleaning Techniques for Fouled Membranes	3/13	26.0%
11.	Reduction of Roughness on the Transport Surface, etc.	2/11	22.0%
12.	Fouling by Viscous Particulate Layers, etc	1/10	20.0%
13.	Development of a Flux-Loss Predictable Model, etc	2/7	14.0%
14.	Development of a Chlorine-Stable RO and NF Membranes	2/7	14.0%
15.	Development of Standard Tests for Characterization, etc.	3/6	12.0%
16.	Regenerable Surfaces via Dynamic Membranes	1/4	8.0%
17.	Understanding Silica Crystalline Structures, etc	1/3	6.0%
18.	Removal of Cell Debris from Cell Lysates, etc.	1/3	6.0%
19.	Solute Fractionation with Ultrafiltration Membranes, etc.	1/2	4.0%
20.	Coupling of Fundamental Research in Other Areas, etc.	1/1	2.0%

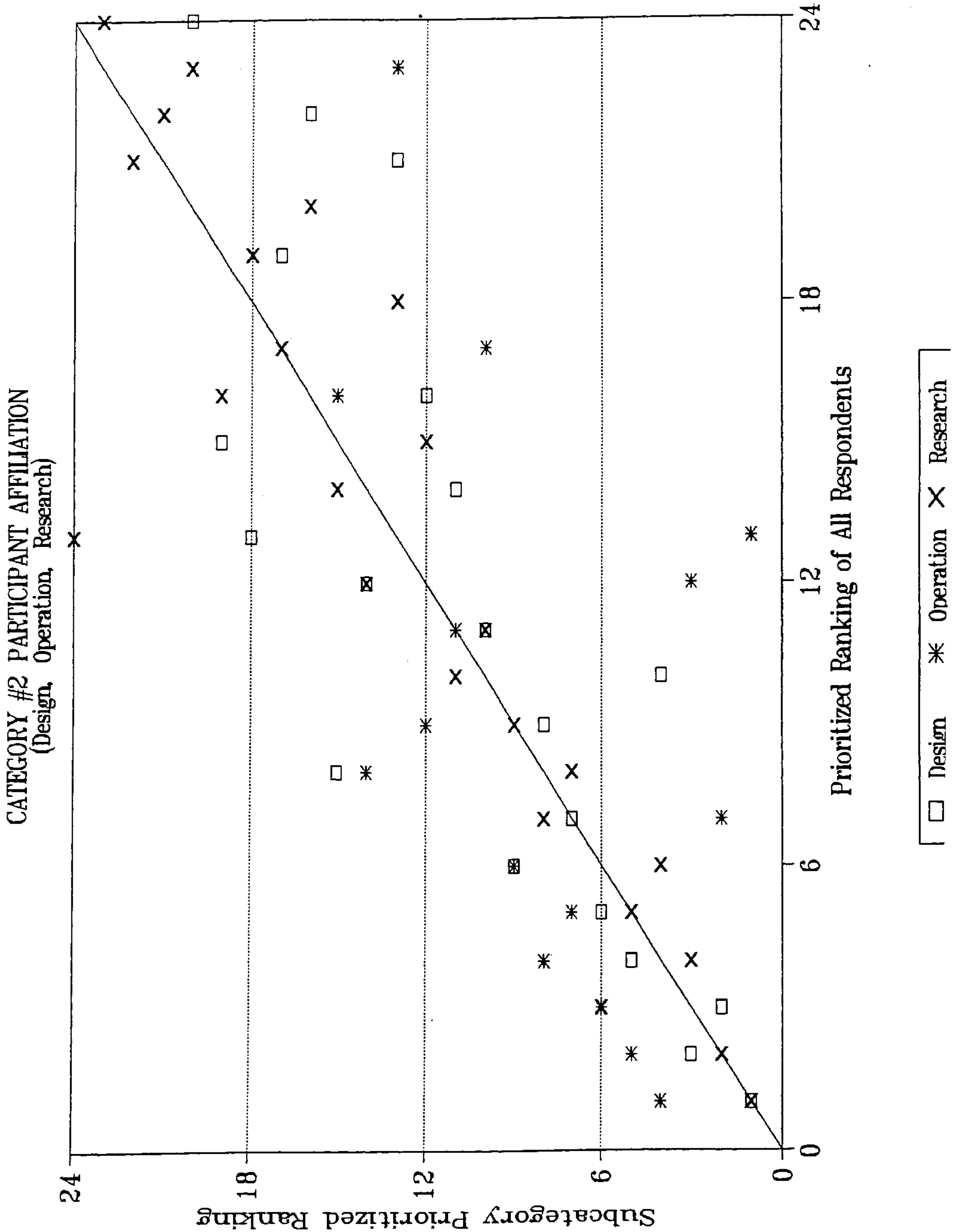
APPENDIX E

All Problems (24) Ranked by Operations Participants (3)

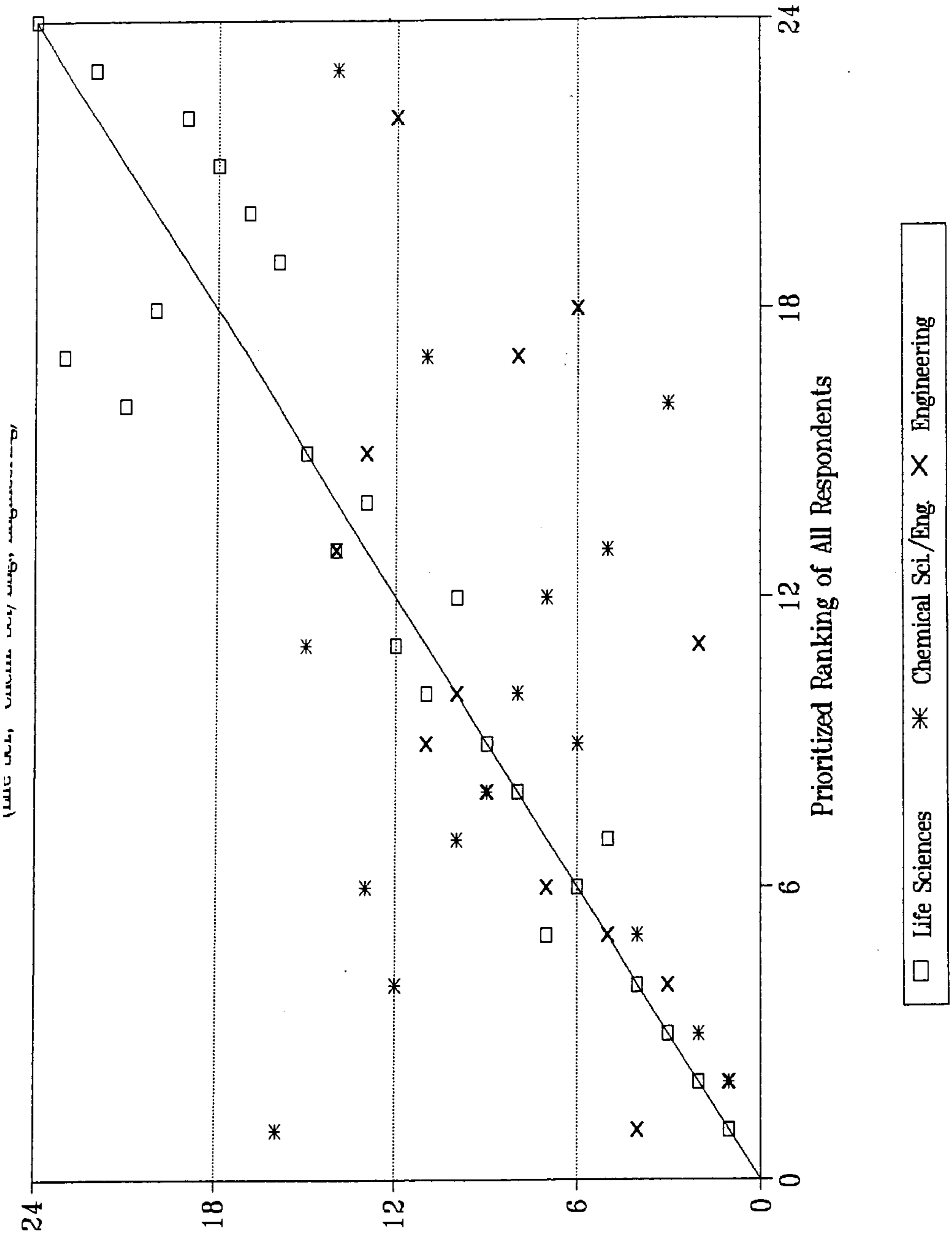
Rank	Abbreviated Title	Times Picked/Points	Strength of Feeling
1.	Understanding Silica Crystalline Structures and Their Attachment	3/24	80.0%
2.	Development of Cost-Effective, High Performance Membrane Modules	3/21	70.0%
3.	Development of a Flux-Loss Predictable Model, etc.	2/16	53.3%
4.	Taxonomy of Fouling: etc.	2/15	50.0%
5.	Membrane Biofouling: Mechanisms, etc.	2/15	50.0%
6.	Understanding & Reducing Biofouling thru Fluid Mech. & Mass Transfer	3/14	46.7%
7.	Development of Effective Pretreatment Strategies, etc.	3/14	46.7%
8.	Chemical Modification of Membrane Surfaces, etc.	2.12	40.0%
9.	Development & Characterization of Well-Defined Membranes, etc.	3/9	30.9%
10.	Cleaning Techniques for Fouled Membranes	1/7	23.3%
11.	Develop a Handbook that will Organize & Parameterize, etc.	1/7	23.3%
12.	Role of Organic-Membrane Interactions & Impact, etc.	1/4	13.3%
13.	Assess Mechanical Cleaning Techniques, etc.	1/3	10.0%
14.	Fouling by Viscous Particulate Layers, etc.	1/2	6.7%
15.	Development of Standard Tests for Characterization, etc.	2/2	6.7%

APPENDIX F

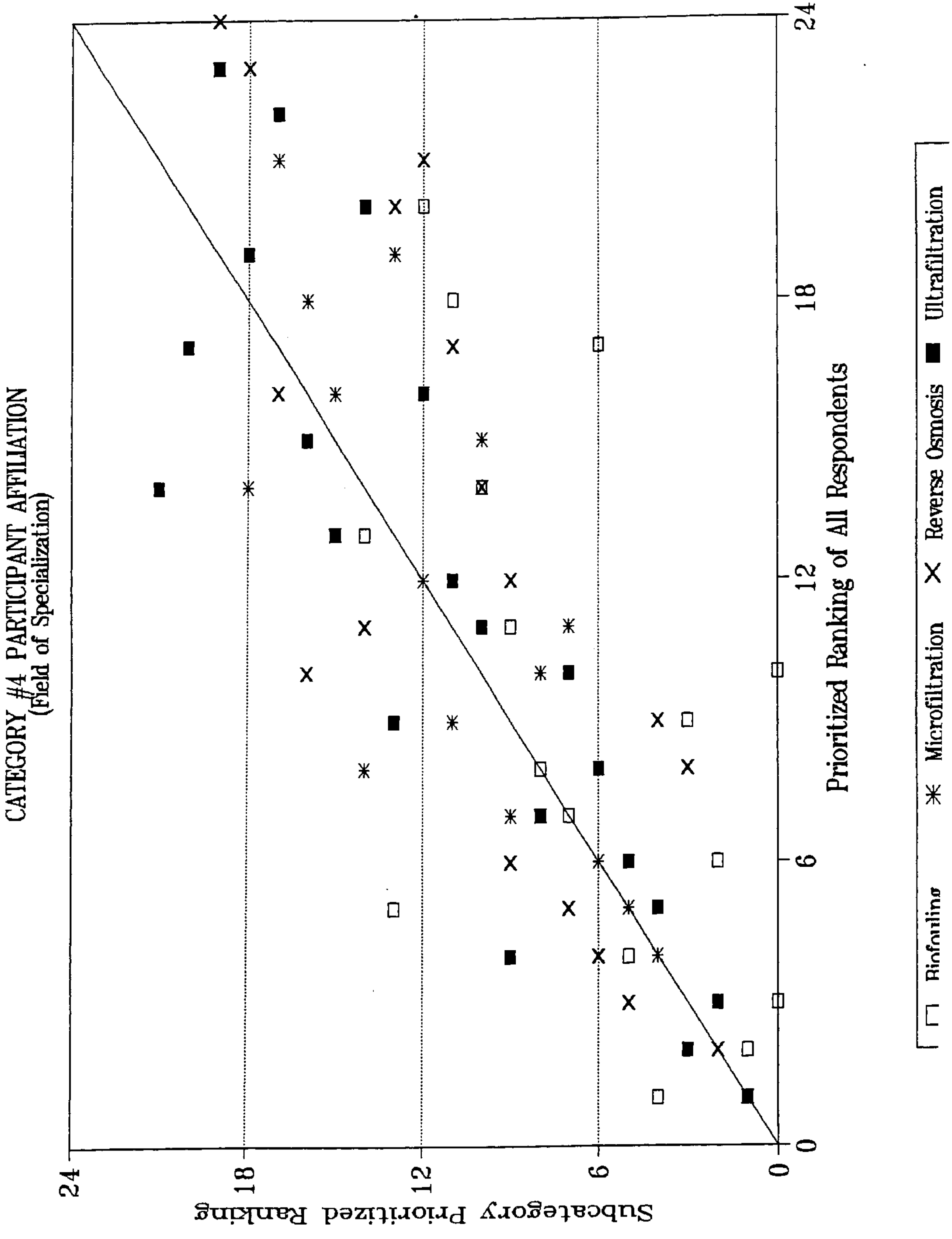

Subcategory Prioritized Ranking
Prioritized Ranking of All Respondents
0
6
12
18
24
Academia
Business/Industry
Government

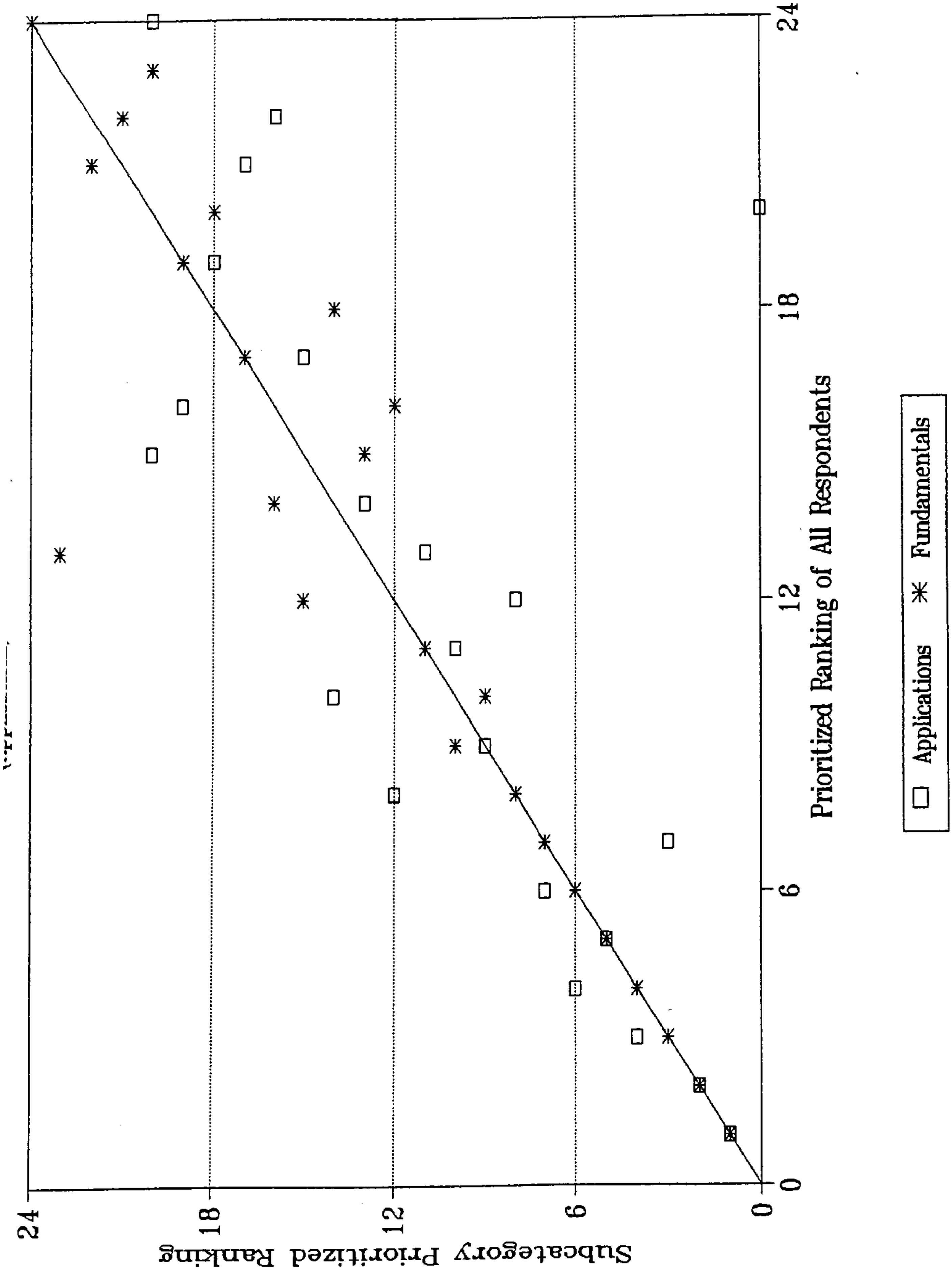

CATEGORY #2 PARTICIPANT AFFILIATION
(Design, Operation, Research)
Subcategory Prioritized Ranking
0
6
12
18
24
Prioritized Ranking of All Respondents
0
6
12
18
24
Design
Operation
Research

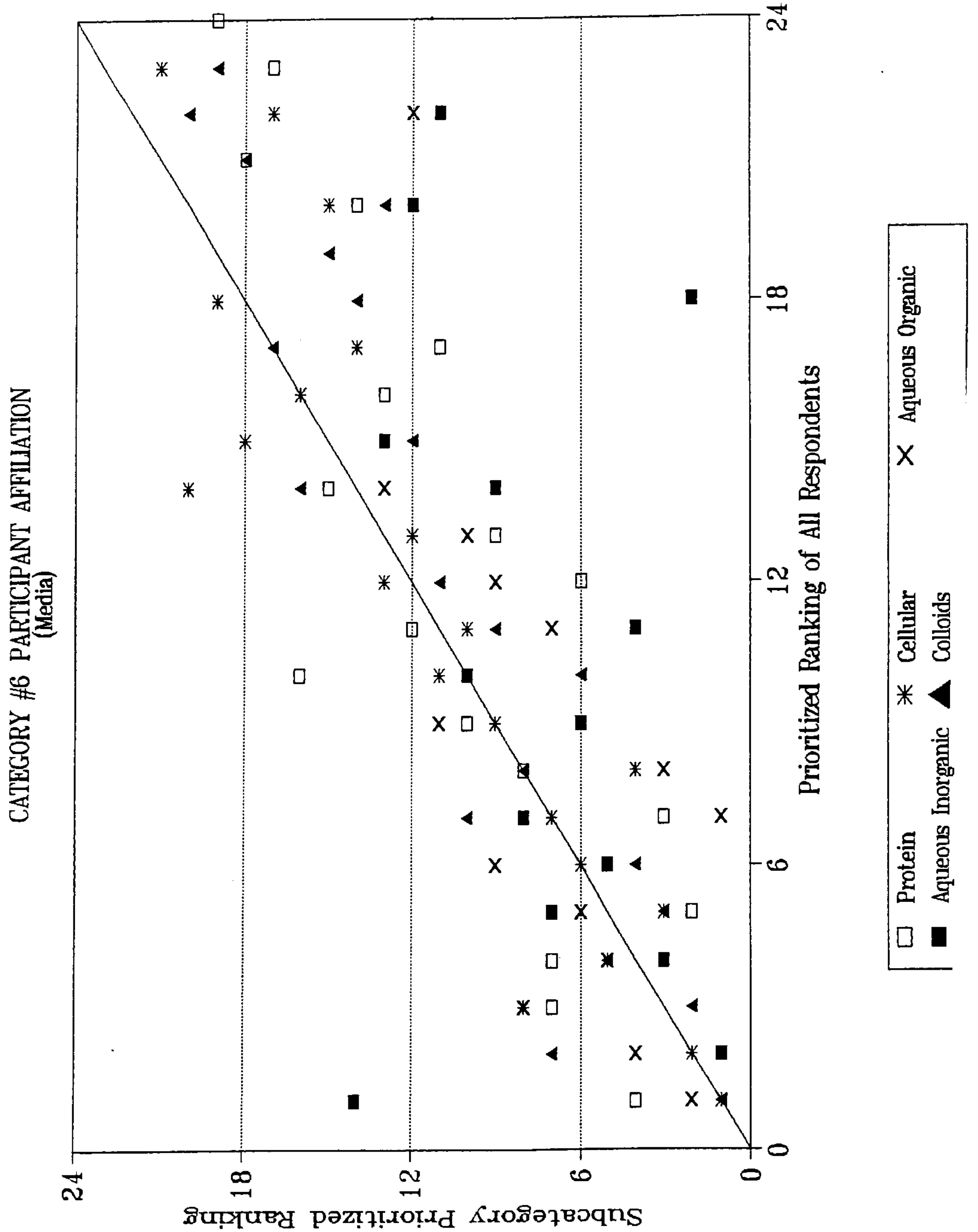
APPENDIX H



Subcategory Prioritized Ranking
Prioritized Ranking of All Respondents
0
6
12
18
24
Life Sciences
Chemical Sci./Eng.
Engineering


CATEGORY #4 PARTICIPANT AFFILIATION
(Field of Specialization)
Subcategory Prioritized Ranking
Prioritized Ranking of All Respondents
0
6
12
18
24
Biofoulin
Microfiltration
Reverse Osmosis
Ultrafiltration


Subcategory Prioritized Ranking
Prioritized Ranking of All Respondents
0
6
12
18
24
Applications
Fundamentals


CATEGORY #6 PARTICIPANT AFFILIATION
(Media)
Subcategory Prioritized Ranking
Prioritized Ranking of All Respondents
0
6
12
18
24
Protein
Cellular
Aqueous Organic
Aqueous Inorganic
Colloids

'RI National Water Research Institute

Ellis Avenue, P.O. Box 20865, Fountain Valley, CA 92728-0865 (714) 378-3278 Fax (714) 378-3373

October 7, 1993

Dr. Joseph Henry
Department of Chemical, Biological and
Materials Engineering
Arizona State University
Tempe, AZ 85287

Dear Dr. Henry:

Thank you for taking time from your busy schedule to participate in the Nominal Group Technique Fouling and Module Design Workshop. The workshop will be held October 31-November 1, 1993 at the Virden Retreat Center at the University of Delaware located in the seaport town of Lewes, Delaware. The workshop will be facilitated by the National Water Research Institute in cooperation with the National Science Foundation.

This folder contains information which will help you be a more effective workshop participant. Please allow yourself at least two hours to review this material and to prepare for the workshop before arriving. **It is important that you attend the entire workshop and do not depart before we are finished.**

Please read the description of the guidelines and procedures we will follow at the workshop. We need to adhere to these so that we can complete our work before adjournment time. Of particular importance is the Problem Identification Form. Please prepare a full write-up on each topic which you plan to propose. You may propose as many topics as you wish.

As I mentioned in my earlier letter, you have the option of participating in one of two tours on Sunday, or remaining at Virden Center. Please consult the attached tour schedule and if you are interested in participating in one of the tours, please FAX the enclosed RSVP form, no later than **October 20, 1993.**

APPENDIX M

Please Print or Type

Problem Identification Form

FOULING AND MODULE DESIGN WORKSHOP

Name:____

Organization:____________________________________

Workshop question: *What research is needed to understand the underlying phenomena of fouling and their relative importance in membrane module design for aqueous separations?*

Limit to space provided below and to a three minute presentation at the workshop.

Problem Title: (20 word maximum)

Importance: (What is your rationale? Why is solving this problem important?)

Objective: (Define clearly so that a useful result can be obtained.)

Suggested Approach: (How would you attack this problem?)

APPENDIX N

Participant Categorization Sheet

Name:____

Please Print

Below are listed several categories of participant affiliation. Please indicate which subcategory (within each category) you are comfortable being associated with.

Category #1

Academia [ ]
Business/Industry [ ]
Government [ ]

Category #2

Research [ ]
Design [ ]
Operation [ ]

Category #3

Life Sciences [ ]
Chemical Sci./Eng. [ ]
Engineering-Other [ ]

Category #4 (Field of Specialization, eg. Ultrafiltration, RO, etc.

____

Category #5

Applications [ ]
Fundamentals [ ]

Category #6 (Media)

Protein [ ]
Cellular [ ]
Aqueous Organic [ ]
Aqueous Inorganic [ ]
Gas [ ]
Colloids [ ]
Other (Specify [ ] ______________

APPENDIX O

Consolidation Worksheet

FOULING AND MODULE DESIGN WORKSHOP

YOUR PROBLEM #______________________________

OTHER PROBLEMS WHICH COULD BE CONSOLIDATED WITH YOUR PROBLEM:

Problem #:________________ Originator:__________________________

Problem #:________________ Originator:__________________________

Problem #:________________ Originator:__________________________

Problem #:________________ Originator:__________________________

APPENDIX P

PROBLEM RANKING SHEET

FOULING AND MODULE DESIGN WORKSHOP

(1 = Highest to 10 = Lowest)

Your Problem Rank	Problem Number
1	______________
2	______________
3	______________
4	______________
5	______________
6	______________
7	______________
8	______________
9	______________
10	______________

Signed:______________________________ and ____
(Please Print) (Signature)