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UNITED STATES NUCLEAR REGULATORY COMMISSION

BEFORE THE COMMISSION

In the Matter of	)	
Public Service Company of New Hampshire, et al.	)	Docket No. 50-443 OL-1/444-OL-1
(Seabrook Station, Units 1 & 2)	)	ONSITE EMERGENCY PLANNING & TECHNICAL ISSUES

NEW ENGLAND COALITION ON NUCLEAR POLLUTION'S
PETITON FOR REVIEW OF ALAB-899

I. Introduction The New England Coalition on Nuclear Pollution ("NECNP") hereby petitions for Commission review of ALAB-899 (August 23, 1988), in which the Appeal Board affirmed NECNP's appeal of the Licensing Board's dismissal of NECNP's Contention IV.[1]

In discovery, NECNP presented Applicants with a series of interrogatories regarding the adequacy of Applicants' program to detect and control "microbiologically induced corrosion," or "MIC," a form of biofouling by which microbiological organisms

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1 NECNP Contention IV reads as follows: Contention: The Applicant must establish a surveilance and maintenance program for the prevention of the accumulation of mollusks, other aquatic organisms, and debris in cooling systems in order to satisfy the requirements of GDC 4, 30, 32, 33, 34, 35, 36, 38, and 39, which require the maintenance and inspection of reactor cooling systems. The design, construction and proposed operation of Seabrook fail to satisfy these requirements.

The basis of Contention IV, which is too lengthy to reproduce here given the page limits, is quoted in full in ALAB-899, slip op. at 3-4.

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accumulate in and corrode nuclear power plant cooling systems. In response to NECNP's Second Set of Interrogatories and Request for Production of Documents to Applicants on NECNP Contention IV, dated December 23, 1987, Applicants objected to NECNP's questions on the ground that the literal language of NECNP Contention IV did not specifically identify MIC as an issue.[2] NECNP then filed a motion to compel Applicants to respond to these questions, in which NECNP presented proof, in the form of NRC-sponsored studies,[3] demonstrating that the literal language used in NECNP Contention IV and bases placed Applicants on notice that the issue of "microbiologically induced corrosion" was encompassed by the contention.[4] By order dated February 17, 1988, the Licensing Board denied NECNP's motion to compel, and ruled, inter alia, that the issue of "microbiologically induced corrosion" ("MIC") is not within the scope of NECNP Contention IV. The Licensing

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2 "Applicants' Responses to NECNP's Second Set of Interrogatories and Request for Production of Documents to Applicants on NECNP Contention IV," filed January 14, 1988, at 2.

3 Neitzel, et al, "Improving the Reliability of Open-Cycle Water Systems: An Evaluation of Biofouling Surveillance and Control Techniques for Use at Nuclear Power Plants," NUREG/CR-4724, Vol. 1 (1986).

4 "NECNP's Motion to Compel Applicants to Respond to NECNP's Second Set of Interrogatories and Request for Production of Documents on NECNP Contention IV," dated January 25, 1988. NECNP also moved to compel Applicants to respond to questions seeking information concerning possible biofouling and corrosion in "circulating water systems" at the Seabrook plant. NECNP's subsequent appeals encompassed these discovery rulings as well.

Board reasoned that "NUREG/CR-4724 was issued some four years after Contention IV was proposed," and that NECNP cannot "expand the scope of the contention by reliance upon a document that did not exist at the time Contention IV was submitted."[5]

NECNP then sought and was granted leave to file a motion for reconsideration of the Licensing Board's February 17, 1988 Order, which motion was filed by NECNP on March 1, 1988. In support of its motion, NECNP presented an expert affidavit from Dr. James Bryers, who testified that the scientific meaning of the literal terms of Contention IV encompassed the issue of microbiologically induced corrosion.[6] In addition, NECNP submitted scientific studies contemporaneous to the admission of Contention IV demonstrating that, in 1982, microbiologically induced corrosion was recognized as one of the detrimental effects of biofouling of nuclear power plants. Both the Applicants and the NRC Staff filed responses opposing NECNP's motion, which urged the Licensing Board to disregard the expert affidavit of Dr. Bryers on the

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5 Memorandum and Order of February 17, 1988 Denying NECNP's Motion to Compel, [unpublished] at 6-7.

6 NECNP's affiant, Dr. James Bryers, is a professor in the Center for Biochemical Engineering at Duke University, and is the author of over thirty published articles in scientific journals and treatises on the subject of microbial fouling and its effects in engineered systems, including nuclear power plant heat-exchange systems. Dr. Bryers' affidavit and curriculum vitae are attached in support of the NECNP's appellate brief, as Exhibits A and B, for the convienence of the Commission.

ground that it was "unpersuasive;" however, they failed to provide any expert opinion or studies of their own controverting the voluminous material provided by NECNP.[7] The Licensing Board then denied NECNP's motion for reconsideration, again on the grounds that "the opinion of Dr. Bryer (sic) and the appended scientific studies cannot serve to establish that, in preparing the contention in 1982, the drafter intended to encompass MIC within the scope of the contention."[8]

By letter dated April 22, 1988, NECNP notified the Licensing Board and the parties that it did not choose to litigate Contention IV due to the Licensing Board's restrictive rulings which precluded NECNP from litigating the adequacy of Applicants' program for controlling microbiologically induced corrosion. NECNP further stated that it intended to appeal the Licensing Board s rulings on the scope of NECNP Contention IV at the appropriate

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7 "Applicant's Response to NECNP's Motion for Reconsideration of the Board's Order Denying NECNP's Motion to Compel," dated March 14, 1988, at 3; "NRC Staff Reponse to NECNP Motion for Reconsideration of the Board's Denial of NECNP's Motion to Compel," dated March 11, 1988, at 5 n.3.

8 Memorandum and Order [unpublished], dated March 18, 1988, at 3. The Licensing Board denied NECNP's subsequent request for entry upon land, dated February 19, 1988, on the ground that it concerned the impermissible issue of MIC. ASLB Memorandum and Order [unpublished], dated March 18, 1988, at 4-5. The Board also denied NECNP's March 22, 1988, motion to compel Applicants to answer interrogatories regarding MIC at Seabrook on the ground that it was untimely, and because it concerned matters not within the scope of NECNP Contention IV. ASLB Order [unpublished], dated April 1, 1988.

time. On May 12, 1988, in reaction to this letter, the Licensing Board dismissed NECNP Contention IV as "abandoned." NECNP filed a notice of appeal on June 1, 1988, along with a motion for leave to file the notice of appeal out of time. The Appeal Board, in ALAB-894, granted NECNP's motion.[9] On August 23, 1988, in ALAB-899, the Appeal Board affirmed the Licensing Board's dismissal of Contention IV.

II. Reasons ALAB-899 Should Be Reversed The Appeal Board made several errors in concluding that Contention IV encompassed only "blockage" of reactor coolant systems and not degradation caused by microbiologically induced corrosion. First, the language of the contention, which refers to the "accumulation of mollusks, other aquatic organisms, and debris in cooling systems," logically embraces the effects of such "accumulation," including both blockage and corrosion.[10] The scope of the contention is determined by the language of the contention itself, and not by the contention's title.[11]

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9 ALAB-894.

10 Contrary to the Appeal Board's implication (slip op. at 9), these effects are not mutually exclusive. It would be perfectly possible, for example, for blockage to occur at the same time that corrosive effects took place.

11 The Appeal Board also errs in relying for its conclusion on NECNP's statements at an oral argument, in which counsel referred to blockage of cooling tunnels to illustrate a point about whether the Seabrook cooling tunnels constitute the reactor's ultimate heat sink. Obviously, this colloquoy did not squarely raise the issue of the scope of the contention.

The Appeal Board also incorrectly found that Contention IV lacked specificity with respect to the issue of microbiologically induced corrosion. A contention need only be specific enough to put other parties on notice so that they will know what to defend against or oppose, and to assure that the proposed issues are proper for adjudication. Philadelphia Electric Co. (Peach Bottom Atomic Power Station, Units 2 and 3), ALAB-216, 8 AEC 13, 20 (1974). The fact that the basis of Contention IV fails to specifically use the technical term "MIC" cannot preclude litigation of that issue, as that would establish "secretive and complex technicalities" not intended by the basis and specificity requirements of 10 C.F.R. § 2.714(b). Id. The basis of Contention IV refers, inter alia, to "buildup of fouling organisms" and "fouling by aquatic organisms." As demonstrated in affidavits filed before the Licensing Board[12], these terms are adequate to place Applicants on notice that they encompass the concept of microbiologically induced corrosion.

The Appeal Board did not reach a number of other issues raised in NECNP's appeal. First, the Licensing Board wholly disregarded the voluminous expert and scientific evidence presented by NECNP that the literal language of Contention IV encompassed

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12 See Note 18, infra.

the issue of microbiologically induced corrosion.[13] Instead, the Licensing Board created an entirely novel standard which seeks to determine NECNP's "intent" when its contention was formulated. However, it is well-esablished that the scope of a contention is controlled by an objective standard -- the "literal language" of the contention. Carolina Power and Light Co. (Shearon Harris Nuclear Power Plant), ALAB-852, 24 NRC 532, 545 (1986).

Second, the Licensing Board erred in ruling that NECNP's February 19, 1988 request for entry upon land was outside the scope of the discovery period. The language used in the Licensing Board's December 2, 1987 Scheduling Order implied that February 19, 1988 was the last date on which requests for discovery may be served. The Board's Scheduling Order did not provide a separate deadline by which discovery requests must be served and received. Past NRC practice in the Seabrook proceeding has consistently been that the date by which discovery is to be closed has meant the date on which the last discovery request must be

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13 NECNP presented uncontroverted evidence that microbiologically induced corrosion was recognized as one of the detrimental effects of biofouling as early as 1977, five years prior to the formulation of NECNP Contention IV. Bryers' Affidavit, at 9; See also Norman, G., Characklis, W.G., and Bryers, J.D., "Control of Microbial Fouling in Circular Tubes with Chlorine," 18 Development in Industrial Microbiology, pp. 581-590 (1977), excerpt attached to NECNP's appellate brief as Exhibit E.

filed.[14] Where a Licensing Board has intended to impose on parties a specific deadline by which the last discovery response must be received, and depositions must be taken, it has done so explicitly.[15]

Finally, the Licensing Board erred in denying NECNP's motion to compel Applicants to respond to questions seeking information concerning possible biofouling and corrosion in all "circulating water systems" at the Seabrook plant, on the ground that NECNP Contention IV only concerned "cooling systems."[16] These discovery requests were entirely permissible.

It is well established that "In modern administrative and legal practice, pretrial discovery is liberally granted to enable the parties to ascertain the facts in complex litigation, refine the issues, and prepare adequately for a more expeditious hearing or trial." Pacific Gas and Electric Co. (Stanislaus Nuclear Project, Unit 1, LBP-78-20, 7 NRC 1038, 1040 (1978). In this regard, interrogatories need only have "general relevance, for discovery purposes, to the matters in controversy in the proceed-

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14 "Memorandum & Order - Establishing Hearing Schedule on Offsite Issues Raised By NHRERP," ASLBP No. 82-471-02-OL, dated December 4, 1986; "Memorandum and Order," ASLPBP No. 82-471-02 OL, dated September 13, 1982.

15 "Memorandum and Order," ALBP No. 82-471-02-OL, dated July 25, 1986, at 11-12.

16 "NECNP's Motion to Compel Applicants to Respond to NECNP's Second Set of Interrogatories and Request for Production of Documents on NECNP Contention IV," dated January 25, 1988, at 4-5.

ing." Texas Utilities Generating Co. (Comanche Peak Steam Electric Station, Units 1 and 2), LPB-81-25, 14 NRC 241, 243 (1981).

Here, NECNP sought information about other systems in order to determine the extent to which microbiologically induced corrosion has occurred and is adequately treated in general at Seabrook. These interrogatories seeking information about other systems are designed to lead to information that is relevant to NECNP's Contention IV, which concerns the adequacy of Applicants' surveillance and maintenance program for the prevention of microbiologically induced corrosion in cooling systems. The presence of corrosion in other circulating water systems may well indicate that corrosion may occur in cooling systems. If corrosion has occurred in other circulating water systems, it is necessary to determine whether Applicants have a program designed to prevent or control corrosion in these systems. Obviously, if Applicants' responses showed that these programs are the same as the programs used to prevent or control corrosion in cooling systems, this may be admissible evidence that such programs are also not adequate to treat or control corrosion in cooling systems. Accordingly, these interrogatories were clearly "relevant to the subject matter involved in the proceeding...[or which] appears reasonably calculated to lead to the discovery of admissible evidence." 10 C.F.R. § 2.740(b)(1).

III. Reasons the Commission Should Take Review of ALAB-899 The Commission should take review of this petition because it raises

both significant safety issues and important questions of Commission practice and policy. First, the integrity of the Seabrook reactor coolant systems is of paramount significance to the safe operation of the plant. In their Supplemental Response to NECNP's Second Set of Interrogatories to Applicants on NECNP Contention IV, Applicants, revealed that MIC has been discovered in Seabrook cooling systems. Thus, this petition poses very real, and not just speculative, concerns about the potential effects of microbiologically induced corrosion on cooling systems at Seabrook.

Second, both the Appeal Board and the Licensing Board committed fundamental legal error with respect to the application of the Commission's standards for the admissibility of contentions. These errors, if allowed to stand, could have profound and adverse effects on the public's right to participate in NRC licensing proceedings. For these reasons, the Commission should grant review of this petition for review.

Respectfully submitted,

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CERTIFICATE OF SERVICE

I certify that on September 12, 1988, copies of the foregoing pleading were served by first-class mail on all parties to this proceeding, as designated on the attached service list.

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UNITED STATES NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING APPEAL BOARD

In the Matter of Public Service Company of New Hampshire, et al. (Seabrook Station, Units 1 & 2)	Docket No. 50-443 OL-1 ONSITE EMERGENCY PLANNING & TECHNICAL ISSUES

NEW ENGLAND COALITION ON NUCLEAR POLLUTION'S BRIEF IN SUPPORT OF ITS APPEAL OF THE LICENSING BOARD'S DISMISSAL OF NECNP CONTENTION IV

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July 1, 1988

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UNITED STATES NUCLEAR REGULATORY COMMISSION

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I. INTRODUCTION

The instant appeal concerns the Licensing Board's March 18, 1988, ruling which limited the scope of NECNP Contention IV[1] to only one of the adverse affects of the accumulation of aquatic organisms in cooling systems, namely, the accumulation of macro-organisms resulting in blockage and constriction of coolant flow. As a result of this ruling, as well as other Licensing Board rulings constricting the time and type of allowable discovery for this contention, NECNP was precluded from inquiring into, or litigating, the adequacy of Applicants' program to monitor and

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1 NECNP Contention IV reads as follows: The Applicant must establish a surveilance and maintenance program for the prevention of the accumulation of mollusks, other aquatic organisms, and debris in cooling systems in order to satisfy the requirements of GDC 4, 30, 32, 33, 34, 35, 36, 38, and 39, which require the maintenance and inspection of reactor cooling systems. The design, construction and proposed operation of Seabrook fail to satisfy these requirements.

control microbiologically induced corrosion, a form of biofouling caused by the accumulation of microbiological organisms in cooling systems.

II. BACKGROUND

On March 25, 1987, the Licensing Board issued a Partial Initial Decision ("PID") which authorizes Public Service Co. of New Hampshire ("Applicants") to operate the Seabrook nuclear power plant at power levels up to and including 5% of rated power.[2] NECNP appealed that decision on the merits, arguing, inter alia, that the Licensing Board had wrongly denied NECNP Contention IV. On October 1, 1987, the Atomic Safety and Licensing Appeal Board (the "Appeal Board") issued ALAB-875, reversing and remanding in part the March 25, 1987 Licensing Board decision authorizing a low power license for Seabrook. The Appeal Board ordered, inter alia, that the Licensing Board admit two of NECNP's contention concerning protection against steam generator tube ruptures (NECNP Contention I.V.) and potential degrading of the plant's heat removal capability due to build-up of biological organisms (NECNP Contention IV), and begin the litigation process for these improperly rejected contentions.[3] Discovery upon the remanded

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2 Public Service Co. of New Hampshire, et al. (Seabrook Station, Units 1 and 2), LBP-87-10, 25 NRC 177 (1987). Hereinafter, all administrative decisions in the Seabrook proceeding will be cited only by number and date. The agency's citation system denotes decisions of the Licensing Board Panel as "LBP" decisions, Appeal Board decisions as "ALAB," and Commission decisions as "CLI."

3 ALAB-875, slip op. at 13-20.

contentions began on October 26, 1987, and was to be completed by February 19, 1988.[4]

In response to NECNP's Second Set of Interrogatories and Request for Production of Documents to Applicants on NECNP Contention IV, dated December 23, 1987, Applicants objected to NECNP's questions concerning the adequacy of Applicants' program to detect and control "microbiologically induced corrosion," on the ground that the literal language of NECNP Contention IV did not specifically identify "microbiologically induced corrosion" as an issue.[5] NECNP then filed a motion to compel Applicants to respond to these questions, in which NECNP presented proof, in the form of NRC-sponsored studies,[6] demonstrating that the literal language used in NECNP Contention IV and bases placed Applicants on notice that the issue of "microbiologically induced

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4 Discovery was extended by the Licensing Board Order of December 2, 1987, to take into account the additional obligations placed on counsel as a result of the Appeal Board rulings on low power operation.

5 "Applicants' Responses to NECNP's Second Set of Interrogatories and Request for Production of Documents to Applicants on NECNP Contention IV," filed January 14, 1988, at 2.

6 Neitzel, et al, "Improving the Reliability of Open-Cycle Water Systems: An Evaluation of Biofouling Surveillance and Control Techniques for Use at Nuclear Power Plants," NUREG/CR-4724, Vol. 1 (1986).

corrosion" was encompassed by the contention.[7] By Order dated February 17, 1988, the Licensing Board denied NECNP's motion to compel, and ruled, inter alia, that the issue of "microbiologically induced corrosion" ("MIC") is not within the scope of NECNP Contention IV. The Licensing Board reasoned that "NUREG/CR-4724 was issued some four years after Contention IV was proposed," and that NECNP cannot "expand the scope of the contention by reliance upon a document that did not exist at the time Contention IV was submitted."[8]

NECNP then sought and was granted leave to file a motion for reconsideration of the Licensing Board's February 17, 1988 Order, which motion was filed by NECNP on March 1, 1988. In support of its motion, NECNP presented an expert affidavit from Dr. James Bryers, who testified that the scientific meaning of the literal terms of Contention IV encompassed the issue of microbiologically

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7 "NECNP's Motion to Compel Applicants to Respond to NECNP's Second Set of Interrogatories and Request for Production of Documents on NECNP Contention IV," dated January 25, 1988. NECNP also moved to compel Applicants to respond to questions seeking information concerning possible biofouling and corrosion in "circulating water systems" at the Seabrook plant. Applicants had refused to provide this information with respect to all circulating water systems which Applicants claim are not "cooling systems" based on their view that "Issues concerning circulating water systems generally are outside the scope of Contention IV." "Applicants' Responses to NECNP's Second Set of Interrogatories and Request for Production of Documents to Applicants on NECNP Contention IV," filed January 14, 1988, at 13, 28. The Licensing Board did not address this argument, since it viewed its resolution of the MIC issue as dispositive. ASLB Memorandum and Order [unpublished], dated February 17, 1988, at 3 n. 2.

8 Memorandum and Order of February 17, 1988 Denying NECNP's Motion to Compel, [unpublished] at 6-7.

induced corrosion.[9] In addition, NECNP submitted scientific studies contemporaneous to the admission of Contention IV demonstrating that, in 1982, microbiologically induced corrosion was recognized as one of the detrimental effects of biofouling of nuclear power plants.[10] Both the Applicants and the NRC Staff filed responses opposing NECNP's motion, which urged the Licensing Board to disregard the expert affidavit of Dr. Bryers on the ground that it was "unpersuasive;" however, they failed to provide any expert opinion or studies of their own controverting the voluminous material provided by NECNP.[11] The Licensing Board then denied NECNP's motion for reconsideration, again on the grounds that "the opinion of Dr. Bryer (sic) and the appended scientific studies cannot serve to establish that, in preparing the contention in 1982, the drafter intended to encompass MIC within the scope of the contention."[12]

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9 NECNP's affiant, Dr. James Bryers, is a professor in the Center for Biochemical Engineering at Duke University, and is the author of over thirty published articles in scientific journals and treatises on the subject of microbial fouling and its effects in engineered systems, including nuclear power plant heat-exchange systems. Dr. Bryers' affidavit and curriculum vitae are attached in support of the instant appeal, as Exhibits A and B.

10 Copies of the relevant portions of these studies are attached hereto as Exhibits C through G.

11 "Applicant's Response to NECNP's Motion for Reconsideration of the Board's Order Denying NECNP's Motion to Compel," dated March 14, 1988, at 3; "NRC Staff Reponse to NECNP Motion for Reconsideration of the Board's Denial of NECNP's Motion to Compel," dated March 11, 1988, at 5 n.3.

12 Memorandum and Order [unpublished], dated March 18, 1988, at 3.

On February 19, 1988, NECNP filed a request for entry upon land for inspection and the taking of notes, samples and photographs at Seabrook in the areas containing piping and heat-exchangers that are susceptible to biofouling or microbiologically induced corrosion, and in laboratories where testing for biofouling or microbiologically induced corrosion is performed. The Licensing Board denied NECNP's request on the ground that it was untimely, and because it concerned matters not within the scope of NECNP Contention IV.[13]

On March 22, 1988, NECNP filed a motion to compel Applicants to respond to NECNP's Third Set of Interrogatories and Request for production of documents to Applicants on NECNP Contention IV, which were served on February 19, 1988. The Licensing Board denied this motion, again, on the ground that the issue of microbiologically induced corrosion was not encompassed within the scope of NECNP Contention IV.[14]

By letter dated April 22, 1988, NECNP notified the Licensing Board and the parties that it did not choose to litigate the Contention IV due to the Licensing Board's restrictive rulings which precluded NECNP from litigating the adequacy of Applicants' program for controlling microbiologically induced corrosion. NECNP further stated that it intended to appeal the Licensing Board's

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13 ASLB Memorandum and Order [unpublished], dated March 18, 1988, at 4-5.

14 ASLB Order [unpublished], dated April 1, 1988.

rulings on the scope of NECNP Contention IV at the appropriate time. On May 12, 1988, in reaction to this letter, the Licensing Boarddismissed NECNP Contention IV as "abandoned." NECNP filed a notice of appeal on June 1, 1988, along with a motion for leave to file the notice of appeal out of time. The Appeal Board, in ALAB-894, granted NECNP's motion.[15]

III. THE LITERAL LANGUAGE OF CONTENTION IV ENCOMPASSES THE ISSUE OF "MICROBIOLOGICALLY INDUCED CORROSION" AND OTHER DETRIMENTAL EFFECTS OF "FOULING" OF COOLING SYSTEMS.

It is important, at the outset, to understand the scientific definitions of the phenomenon of "biofouling" and "microbiologically induced corrosion," and the scientific meaning of the terms employed in NECNP Contention IV. NECNP Contention IV asserts simply that "the Applicant must establish a surveillance and maintenance program for the prevention of the accumulation of mollusks, other aquatic organisms, and debris in cooling systems..." This contention does not specifically identify the problem as either "fouling" or "biofouling," nor does it identify any of the detrimental effects of this process. However, this language in fact broadly identifies the process commonly known as "fouling," which has a number of detrimental effects, including blockage, constriction and/or mechanical deterioration of the

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15 ALAB-894.

operating characteristics of valves and pumps, fluid resistance, and corrosion.[16]

The Licensing Board determined that NECNP Contention IV was limited to only one particular detrimental effect of fouling, that of blockage of piping in heat exchange systems, which is generally caused by the build-up of macro-organisms (such as clams and mussels) and debris on the inside of piping, resulting in the degradation of heat removal capability of cooling water systems. In reaching this conclusion, the Licensing Board appropriately relied on the literal language of the contention, which referred to "the accumulation of mollusks, other aquatic organisms, and debris."[17] However, the Licensing Board erred in reaching the conclusion the word "accumulation" was intended to refer only to the detrimental effect of blockage caused by fouling. Rather, the term "accumulation" clearly refers to the process of fouling itself, which is the accumulation of organisms

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16 See Bryers' Affadivit, Exhibit A, at 7; see also Bryers, J.D., Characklis, W.G., Zelver, N., and Nimmons, M.G., "Microbial Film Development and Associated Energy Losses," at 12.14-1, Paper No. 12-15 presented at the Proc. 6th OTEC Conference, "Ocean Thermal Energy for the '80's," Washington, D.C., June 19-20, 1979, which defines "fouling" as follows:

> The term fouling refers to the formation of inorganic and/or organic deposits on surfaces. In cooling systems, these deposits form on condenser tube walls increasing fluid frictional resistance, accelerating corrosion and impairing heat transfer.

An excerpt of this study is attached hereto as Exhibit C.

17 ASLB Memorandum and Order, dated February 17, 1988, at 5 (emphasis in original).

(both macro and micro) and debris on pipes. The accumulation of macro-organisms can cause blockage, and the accumulation of biofilms on heat-exchange systems can ultimately interact with bacteria to cause the phenomenon of microbiologically induced corrosion.[18] Thus, the use of the word "accumulation" in the Contention reinforces a broad, rather than limited construction of Contention IV.

It is well settled that a party is bound by the literal terms of its own contention. Carolina Power and Light Co. (Shearon Harris Nuclear Power Plant), ALAB-852, 24 NRC 532, 545

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18 Perhaps the clearest explanation of the process, and different types of fouling, appears in a 1981 article by W.G.Characklis, entitled "Bioengineering Report -- Fouling Biofilm Development: A Process Analysis:"

> The term fouling refers to the formation of inorganic and/or organic deposits on surfaces. These deposits can impede the flow of heat across the surface, increase the fluid frictional resistance at the surface, and increase the rate of corrosion at the surface. In any case energy losses result.
>
> Several types of fouling and their combinations may occur in heat exchangers: 1) crystalline or precipitation fouling, 2) corrosion fouling, 3) particulate fouling, 4) chemical reaction fouling, and 5) biological fouling. Biological fouling results from a) development of a biofilm consisting of microorganisms and their products (microbial fouling), b) deposition and growth of macroorganisms such as barnacles (macrobial fouling), and c) assorted detritus.

Biotechnology and Bioengineering, Vol. XIII, pp. 1923-1960 (John Wiley & Sons, Inc. 1980), excerpt attached as Exhibit D. See also Bryers, J.D., Characklis, W.G., Zelver, N., and Nimmons, M.G., "Microbial Film Development and Associated Energy Losses," at 12.14-1, Paper No. 12-15 presented at the Proc. 6th OTEC Conference, "Ocean Thermal Energy for the '80's," Washington, D.C., June 19-20, 1979, excerpt attached hereto as Exhibit C; Bryers Affidavit, at 8.

(1986). Here, the literal terms of the contention broadly identify the process of fouling, which has a number of detrimental effects, including microbiologically induced corrosion. Accordingly, microbiologically induced corrosion is within the scope of NECNP Contention IV.

The Licensing Board, in part, apparently based its decision on the fact NECNP Contention IV did not specifically identify the issues of "biofouling" or "microbiologically induced corrosion." However, a contention need only be specific enough to put other parties on notice so that they will know what to defend against or oppose, and to assure that the proposed issues are proper for adjudication. Philadelphia Electric Co. (Peach Bottom Atomic Power Station, Units 2 and 3), ALAB-216, 8 AEC 13, 20 (1974). The fact that the contention fails to identify specifically the issues encompassed by the contention by their technical names cannot preclude litigation of those issues, as that would establish "secretive and complex technicalities" not intended by the basis and specificity requirements of 10 C.F.R. § 2.714(b). Id. In case of doubt, Applicants "may fill any gaps in their knowledge of the intervenors' case through discovery against intervenors." Texas Utilities Co. (Comanche Peak Steam Electric Station, Unit 1, ALAB-868, 25 NRC 912, 933 (1987).[19]

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19 We note that Applicants here chose not to undertake any discovery against NECNP; in any event, however, they were quickly put on notice through NECNP's discovery that NECNP regarded microbiologically induced corrosion as within the scope of its contention.

Here, NECNP Contention IV, by broadly identifying the process of fouling of nuclear power plant heat-exchange systems, clearly put Applicants on notice that the contention encompassed all the detrimental effects of this process, including microbiologically induced corrosion. Thus, the issue of microbiologically induced corrosion was identified with sufficient specificity to satisfy the pleading requirements of 10 C.F.R. § 2.714(b).[20]

IV. THE LICENSING BOARD ACTED ARBITRARILY AND CAPRICIOUSLY IN RESTRICTING THE SCOPE OF NECNP CONTENTION IV.

A. The Licensing Board Applied an Incorrect Legal Standard in Determining the Scope of NECNP Contention IV.

As noted above, the scope of a contention is defined by the literal terms of the contention. Carolina Power and Light Co. (Shearon Harris Nuclear Power Plant), ALAB-852, 24 NRC 532, 545 (1986). However, the Licensing Board wholly disregarded the voluminous expert and scientific evidence presented by NECNP that the literal language of Contention IV encompassed the issue of microbiologically induced corrosion. Instead, the Licensing

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20 While microbiologically induced corrosion is not specifically discussed in the bases for the contention, the bases for a contention cannot be relied on to alter the contention's actual language. Texas Utilties Co. (Comanche Peak Steam Electric Station, Unit 1), 25 NRC 912, 932 n. 83 (1987). And, as noted above, the contention's literal language was sufficient to identify the issue of microbiologically induced corrosion. Likewise, the use of the word "blockage" in the caption of NECNP Contention IV cannot be construed as limiting the scope of the contention to only that detrimental effect of fouling, to the exclusion of others. Like the interpretion of statutes, titles or captions cannot be used to alter or vary the plain meaning of provisions. See e.g. Pike v. U.S., 340 F.2d 487 (9th Cir. 1974).

Board created an entirely novel standard which seeks to determine NECNP's "intent" when its contention was formulated. Applying this new standard, the Licensing Board determined that NECNP did not "intend" for its contention to encompass the issue of microbiologically induced corrosion in 1982, when the contention was first formulated.

This subjective standard for determining the scope of a contention is without any support in past NRC precedent.[21] Further, it is flatly contradicted by the numerous cases setting forth an objective test for determining the scope of a contention, namely, that the literal language employed by the contention controls. See Philadelphia Electric Co. (Limerick Generating Station, Units 1 and 2), 22 NRC 681, 709 (1985), in which the Appeal Board held the intervenors to the literal terms of its contention, despite their assertion that the "sought to litigate something else."

More importantly, the subjective standard applied by the Licensing Board runs contrary to the principle purpose of 10 C.F.R. § 2.714(b), which is to provide notice to Applicants of so that they will know what to defend against or oppose. Philadelphia Electric Co. (Peach Bottom Atomic Power Station, Units 2 and 3), ALAB-216, 8 AEC 13, 20 (1974). Indeed, as the Limerick case

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21 Ironically, the Licensing Board was forced to confine its search for "NECNP's then (1982) intent" to the language and basis of the contention itself, since this contention was wrongly rejected by the Board at the outset, thereby precluding any opportunity to develop this contention. As noted above, the literal language of the contention itself encompasses the issue of microbiologically induced corrosion.

cited above recognizes, it would be fundamentally unfair to Applicants if subjective intent could be used to guide litigation of contentions and to protect Applicants from surprises.

Indeed, NECNP presented evidence that microbiologically induced corrosion was recognized as one of the detrimental effects of biofouling as early as 1977, five years prior to the formulation of NECNP Contention IV.[22] Thus, the literal language of the contention was sufficient to provide adequate notice to Applicants that microbiologically induced corrosion was one of the issues to be litigated within the scope of NECNP Contention IV in 1982, when the contention was drafted, as well as in 1987 -- the more relevant time period -- when the contention was actually admitted and litigation begun. Despite the fact that this evidence was uncontroverted, the Licensing Board disregarded this evidence, again on the premise that these studies did not indicate what NECNP "intended" in preparing the contention in 1982.[23] Clearly, the focus should not be on what NECNP "intended" but on whether Applicants objectively had adequate notice. We submit that the literal language of the contention provided this notice.

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22 Bryers' Affidavit, at 9; See also Norman, G., Characklis, W.G., and Bryers, J.D., "Control of Microbial Fouling in Circular Tubes with Chlorine," 18 Development in Industrial Microbiology, pp. 581-590 (1977), excerpt attached as Exhibit E.

23 ASLB Memorandum and Order [unpublished], dated March 18, 1988, at 3.

Moreover, the facts here show that NECNP did intend that microbiologically induced corrosion be encompassed within the scope of its contention. This intent is apparent in the contention's literal language, which broadly identified the issue of fouling, and in NECNP discovery requests, in which NECNP consistently sought to acquire information about the Applicants' program to control microbiologically induced corrosion. The Licensing Board erred in basing its finding of NECNP's "1982 intent" on the very general information provided to satisfy the basis and specificity requirements of 10 C.F.R. § 2.714(b), and in ignoring the more persuasive evidence of NECNP's intent consistently evidenced in NECNP's discovery requests and pleadings, which were filed as soon as NECNP was permitted to litigate the contention. Again, to confine the search for NECNP's "intent" to only those documents filed in 1982, and to ignore the clear evidence of NECNP's intent contained in its discovery requests, would unfairly penalize NECNP for the Licensing Board's action in wrongly rejecting the contention at the outset.

B. The Licensing Board Erred in Ruling Contrary to the Uncontroverted Expert Affidavit and Scientific Studies Provided by NECNP.

In addition to applying an incorrect legal standard, the Licensing Board erred in disregarding the expert affidavit and scientific studies presented by NECNP. NECNP presented an expert affidavit from Dr. James Bryers, one of the nation's foremost experts on the issue of microbiologically induced corrosion and fouling of heat-exchange systems, who stated that the literal

language of the contention encompassed the issue of microbiologically induced corrosion,[24] and that the problem of corrosion in engineered systems caused by the interaction between microorganisms and biofilms on pipe-liquid surfaces was recognized by the scientific community as early as 1977.[25] Neither the Applicants nor the Staff offered any controverting affidavits or studies. Rather, Applicants rested merely on the bald assertions of counsel that Dr. Bryers' testimony is "unpersuasive;"[26] and the NRC Staff merely stated, again without submitting any controverting evidence or expert opinion, that Dr. Bryers' opinion "is entitled to little, if any weight."[27] Despite the absence of any controverting evidence, the Licensing Board disregarded Dr. Bryers' testimony. The Licensing Board's ruling was based on its view that Dr. Bryers' statements, by necessity made six years after the contention was formulated, "cannot serve to establish that, in preparing the contention in 1982, the drafter intended

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24 Bryers' Affidavit, at 5.

25 Bryers' Affidavit, at 9; See also Norman, G., Characklis, W.G., and Bryers, J.D., "Control of Microbial Fouling in Circular Tubes with Chlorine," 18 Development in Industrial Microbiology, pp. 581-590 (1977), excerpt attached as Exhibit E.

26 "Applicant's Response to NECNP's Motion for Reconsideration of the Board's Order Denying NECNP's Motion to Compel," dated March 14, 1988, at 3.

27 "NRC Staff Reponse to NECNP Motion for Reconsideration of the Board's Denial of NECNP's Motion to Compel," dated March 11, 1988, at 5 n. 3.

to encompass MIC within the scope of the contention."[28]

Where expert opinion evidence is submitted by only one side, as is the case here, an agency may disregard it only under three circumstances: where the agency possesses the expertise to 'substitute its judgment in the place of the experts'; where their is contrary evidence already in the record; and where the expert's testimony has minimum credibility. Stein, Mitchell, and Mezines, Administrative Law, § 28.06 (Mathew-Bender, 1987). None of these circumstances is present here.

First, the issue at hand involves the interpretation of technical, scientific terms used in the field of microbiology and biochemical engineering, which is not an area in which the Commission possesses expertise. Where the testimony of a witness is in an area in which the agency lacks knowledge or technical skill, it may not arbitrarily substitute its judgment for that of an expert witness. Culler v. Commissioner of Internal Revenue, 237 F.2d 611, 616 (8th Cir. 1956).

Second, there was no contrary evidence in the record, other than the unsupported "lay' opinion of Applicants' and the Staff's legal counsel. Finally, as noted above, Dr. Bryers is one of the

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28 ASLB Memorandum and Order [unpublished], dated March 18, 1988, at 3. This reasoning is particularly ironic, in light of the fact that Dr. Bryers' "post hoc" interpretation of this Contention is necessitated by the fact that the contention was wrongfully dismissed at an earlier stage in this proceeding. To disallow expert opinion as to the scientific meaning of the plain langauge of the Contention because it could not, due to an error not of NECNP's making, be made contemporaneously, is blatantly unfair and prejudicial to NECNP.

country's foremost experts on the subject of the effects of biological fouling on engineered safety systems. His opinion as to the meaning and scope of the plain language of NECNP Contention IV is clearly entitled to great weight.[29] Accordingly, the Licensing Board abused its discretion in ruling contrary to the uncontroverted and entirely credible evidence presented by NECNP that microbiologically induced corrosion was within the scope of NECNP Contention IV.

V. THE LICENSING BOARD ERRED IN DISALLOWING NECNP'S DISCOVERY REQUEST SERVED PRIOR TO THE TIME DISCOVERY CLOSED.

The Licensing Board denied NECNP's Motion for Leave to Enter Applicants' Land, filed on February 19, 1988, and its alternative motion to extend the deadline for discovery,[30] on two grounds: first, that the motion sought discovery on matters not within the scope of NECNP Contention IV; and second, that the motion was untimely.[31] This ruling was in error on both counts.

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29 While Dr. Bryers' opinion as to "the scope of NECNP Contention IV" is, admittedly, the ultimate issue of this case, Dr. Bryers' expert opinion of the technical, scientific meaning of the terms used in the contention, and his expert opinion as to the range of detrimental effects that are caused by the process referred to in the contention, are entirely appropriate and admissible.

30 "NECNP's Reply to Applicants' Response to NECNP's Request for Entry Upon Land," dated March 3, 1988, at 4.

31 ASLB Order [unpublished], dated March 18, 1988, at 4-5. According to the Licensing Board, its December 2, 1988 Scheduling Order, which provided that 'Applicants,' NECNP and the Staff shall ... complete discovery by February 19, 1988," meant that all responses to discovery must be received by February 19, 1988.

First, as noted above, microbiologically induced corrosion and biofouling are within the scope of NECNP Contention IV. Therefore, NECNP's motion was clearly "relevant to the subject matter involved in the proceeding...[and] appears reasonably calculated to lead to the discovery of admissible evidence." 10 C.F. § 2.740(b)(1).

Second, the language used in the Licensing Board's December 2, 1987 Scheduling Order implied that February 19, 1988 was the last date on which requests for discovery may be served. The Board's Scheduling Order did not provide a separate deadline by which discovery requests must be served and received. Past NRC practice in the Seabrook proceeding has consistently been that the date by which discovery is to be closed has meant the date on which the last discovery request must be filed.[32] Rather, where a Licensing Board has intended to impose on parties a specific deadline by which the last discovery response must be received, and depositions must be taken, it has done so explicitly.[33]

NECNP relied in good faith on the Board's previous practice of providing explicit guidelines and deadlines in such instances where it intended for the deadline for service of discovery requests to be different and earlier from deadline for completion

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32 "Memorandum & Order - Establishing Hearing Schedule on Offsite Issues Raised By NHRERP," ASLBP No. 82-471-02-OL, dated December 4, 1986; "Memorandum and Order," ASLPBP No. 82-471-02 OL, dated September 13, 1982.

33 "Memorandum and Order," ALBP No. 82-471-02-OL, dated July 25, 1986, at 11-12.

or closure of discovery. Given the serious consequences in terms of NECNP's ability to effectively litigate the important, remanded safety issue of NECNP Contention IV, and the reasonableness of NECNP's reliance on past practice regarding discovery scheduling, the Board should have allowed NECNP's motion, or granted NECNP's request in the alternative for an extension of the discovery deadline. See Cincinnati Gas and Electric Co. (William H. Zimmer Nuclear Station), 12 NRC 231, 232 n.1 (1980) (ASLB considered untimely filed response because reluctant to take position which might preclude litigation of safety or environmental issues without giving every party an opportunity to be heard).

VI. THE LICENSING BOARD ERRED IN DISALLOWING DISCOVERY INTO CIRCULATING WATER SYSTEMS THAT WERE NOT "COOLING SYSTEMS."

The Licensing Board also erred in denying NECNP's motion to compel Applicants to respond to questions seeking information concerning possible biofouling and corrosion in all "circulating water systems" at the Seabrook plant, on the ground that NECNP Contention IV only concerned "cooling systems."[34] These discovery requests were entirely permissible.

It is well established that "In modern administrative and legal practice, pretrial discovery is liberally granted to enable the parties to ascertain the facts in complex litigation, refine

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34 "NECNP's Motion to Compel Applicants to Respond to NECNP's Second Set of Interrogatories and Request for Production of Documents on NECNP Contention IV," dated January 25, 1988, at 4-5.

the issues, and prepare adequately for a more expeditious hearing or trial." Pacific Gas and Electric Co. (Stanislaus Nuclear Project, Unit 1, LBP-78-20, 7 NRC 1038, 1040 (1978). In this regard, interrogatories need only have "general relevance, for discovery purposes, to the matters in controversy in the proceeding." Texas Utilities Generating Co. (Comanche Peak Steam Electric Station, Units 1 and 2), LPB-81-25, 14 NRC 241, 243 (1981).

Here, NECNP sought information about other systems in order to determine the extent to which microbiologically induced corrosion has occurred and is adequately treated in general at Seabrook. These interrogatories seeking information about other systems are designed to lead to information that is relevant to NECNP's Contention IV, which concerns the adequacy of Applicants' surveillance and maintenance program for the prevention of microbiologically induced corrosion in cooling systems. The presence of corrosion in other circulating water systems may well indicate that corrosion may occur in cooling systems. If corrosion has occurred in other circulating water systems, it is necessary to determine whether Applicants have a program designed to prevent or control corrosion in these systems. Obviously, if Applicants' responses showed that these programs are the same as the programs used to prevent or control corrosion in cooling systems, this may be admissible evidence that such programs are also not adequate to treat or control corrosion in cooling systems. Accordingly, these interrogatories were clearly "relevant to the subject matter involved in the proceeding...[or which] appears reasonably

calculated to lead to the discovery of admissible evidence." 10 C.F.R. § 2.740(b)(1).

VII. CONCLUSION

For the foregoing reasons, the Licensing Board's erred in ruling that microbiologically induced corrosion was not within the scope of NECNP Contention IV, and by restricting the time and type of allowable discovery under this contention. Therefore, the Licensing Board's decisions of February 17, 1988, March 18, 1988, and April 1, 1988, should be reversed.

Respectfully submitted,

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CERTIFICATE OF SERVICE

I certify that on July 1, 1988, copies of the foregoing pleading were served by first-class mail, or as otherwise indicated, on all parties listed on the attached service list.

Andrea Ferster

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UNITED STATES NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

In the Matter of Public Service Company of New Hampshire, et al. (Seabrook Station, Units 1 & 2)	Docket No. 50-443 OL-1 ONSITE EMERGENCY PLANNING & TECHNICAL ISSUES

AFFIDAVIT OF DR. JAMES BRYERS

I, James Bryers, being on oath, depose and say as follows:

1. I am a Professor in the Center for Biochemical Engineering at Duke University. My curriculum vitae, which describes my academic and professional experience, publications, and research, is attached hereto as Exhibit B.

2. My area of expertise in the field of chemical engineering is in the physical, chemical and biological processes governing biofilm formation, and the detrimental effects of these biofilms in engineered systems, including nuclear power plant heat-exchangers.

3. I have reviewed the text and bases of Contention IV, "Blockage of Coolant Flow to Safety-Related Systems and Components by Buildup of Biological Organisms," sponsored by New England Coalition on Nuclear Pollution ("NECNP") in the above-captioned proceeding. It is my opinion that, while Contention IV's identification of the problem as "the accumulation of mollusks and other aquatic organisms in reactor cooling systems" does not specifically identify any particular type or detrimental

effect of fouling, it broadly identifies the process of fouling.

4. The term "fouling" refers to the formation of inorganic and/or organic deposits on surfaces, and includes that form of fouling caused by the attachment of macro-organisms and particulate matter on pipe-liquid interfaces, and corrosion fouling, resulting from the interaction of biological organisms and biofilms or slime layers on surfaces. "Microbiologically induced corrosion," also referred to as "microbiologically mediated corrosion," is one detrimental effect of fouling, which can be caused by the interaction between aerobic and anaerobic bacteria and biofilms in pipe-liquid interfaces.

5. It is my opinion that, because the identification of the issues in NECNP Contention IV broadly identifies the process that causes "fouling" and "corrosion," microbiologically induced corrosion is within the scope of this Contention.

6. "Biofouling" refers to fouling that results from the development of a biofilm consisting of of microorganims and their products (microbial fouling), the deposition and growth of macro-organisms such as barnacles (macrobial fouling), and the accumulation of assorted detritus. Biofouling can be very extensive, even with very minute levels of biofilm. Similarly, flow or heat inefficiencies can occur even with minute coverage of fouling organisms on surfaces.

7. There are several detrimental effects of biofouling in heat-exchange systems. One effect is blockage of cooling systems, and subsequent impairment of the system's heat transfer

capabilities. Blockage can be caused by the accumulation of macro-organisms (mussels, barnacles). Another detrimental effect of fouling is contriction and/or mechanical deterioration of the operating characteristics of valves and pumps, which is caused by the accumulation of a biofilm or "slime" on pipe-liquid interfaces.. Another detrimental effect of fouling is fluid frictional resistance, whereby fluid as pumped ineffeciently through pipes. Finally, corrosion and degradation of pipes and heat-exchange systems, as a result of the accumulation of micro-organisms (microbial fouling) on surfaces.

8. The identification of microbiologically induced corrosion can be seen in Contention IV's use of two words -- "aquatic organisms," and "accumulation." The term "aquatic organisms" refers both to macro-organism such as mussels, clams, and other bivalves and bivalve larvae, and micro-organisms, including aerobic and anaerobic bacteria. "Accumulation" is used in the bio-chemistry field to refer to the accumulation of biofilms on heat-exchange systems, which are the result of aerobic or anaerobic bacteria depositions, as well as the accumulation of macroorganisms. See Dryers, J.D., Characklis, W.G., Ze'ver, N., and Nimmons, M.G., "Microbial Film Development and Associated Energy Losses," at 12.14-1, Paper No. 12-15 presented at the Proc. 6th OTEC Conference, "Ocean Thermal Energy for the '80's," Washington, D.C., June 19-20, 1979. This detrimental biofilm or slime can ultimately interacts with bacteria to cause corrosion of heat-exchangers. Thus, "the accumulation of aquatic

organisms" refers equally to the accumulation of microorganisms and the formation of biofilms, as well as the accumulation of macroorganisms.

9. The problem of corrosion in engineered systems caused by the interaction between microorganisms and biofilms on pipe-liquid surfaces is not a new one. As early as 1977, the corrosive effects associated with microbial fouling and biofilm formation have been the subject of studies by the scientific community, and have been identified as a detrimental effect of "biofouling." See Norman, G., Characklis, W.G., and Bryers, J.D., "Control of Microbial Fouling in Circular Tubes with Chlorine," 18 Development in Industrial Microbiology, pp. 581-590 (1977), attached as Exhibit E, and studies cited above.

10. Fouling by macro-organisms, such as barnacles and mussels, should not be thought of as independent of microbial fouling. Microbial fouling often precedes colonization of heat-exchanger surfaces by macro-organisms, since the microbiological organisms which cause the corrosion are a food source for bivalves, permitting and encouraging their settlement and colonization, and the sedimentation caused by and causing microbiologically induced corrosion enables mussels and oysters to attach more firmly to piping surfaces. Therefore, control of microbial fouling results in control of macrobial fouling. Conversely, controlling macro-fouling will not necessaryily control microbial fouling or microbiologically induced corrosion. See Characklis, W.G., "Bioengineering Report -- Fouling Biofilm

Development: A Process Analysis," Biotechnology and Bioengineering, Vol. XIII, pp. 1923-1960 (John Wily & Sons, Inc. 1980), attached as Exhibit D.

James D Bryers
Dr. James D. Bryers

Subscribed and sworn before me
this 29th day of February, 1988.

Blanca M. Perry
Notary Public

My Commission Expires April 30, 1992

Ex. B

COPY

October, 1987

CURRICULUM VITAE

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EDUCATION

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Dynamics of Early Biofilm Formation in a Turbulent Flow System, Ph.D. Dissertation.

M.Sc., Chemical Engineering, University of Idaho, 1976.
The Effects of Chain Transfer on Molecular Weight Distributions in an Emulsion Polymerization, M.Sc. Thesis

B.Sc. Chemical Engineering, University of Houston, Graduation with Honors, 1974.

PROFESSIONAL EXPERIENCE

A. Teaching and Research

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Research Scientist (Mitarbeiter), Abteilung Technische Biologie, Institut für Biotechnologie und die Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz (EAWAG), Eidgenössische Technische Hochschulen (ETH), Zürich Switzerland (May,1980 - May,1985).

Research Fellow, Departments of Chemical Engineering and Biology, University of Calgary, Calgary, Alberta, Canada (August,1979 - August, 1980).

B. Consulting

Oregon Graduate Center, Beaverton, OR - 1986
BIORESPONSE, Inc., Haywood, CA - 1986
Cetus Corporation, Emeryville, CA - 1986
Nestle' Corporation, Vevey, Switzerland - 1985
Shell Exploration & Production, Aberdeen, Scotland - 1985
Ciba-Geigy, Bern, Switzerland - 1983-1985
Shell Oil Company, Westhollow Research Center, Houston, Tx - 1984
Institute of Paper Chemistry, Appleton, WI - 1980
British Petroleum, London, England - 1980-1981
Shell Oil Company, Calgary, Alta, CAN - 1980
Mobil Oil Company, Edmonton, Alta, CAN - 1980

C. Directed Thesis Research

Microbiological events in aerobic/anaerobic fouling biofilms, Ph.D. research of W.F. McCoy, Department of Biology, University of Calgary, Calgary, Alta, CAN - 1982.

Transport of groundwater pollutants during peak flood events in the Glatt River, Kanton Zurich, M.Sc. Thesis, EAWAG, 1982.

Particulate Effects on the anaerobic production of methane, Ph.D. research of J. Berger, EAWAG 1983.

Use of dynamic tracer methods to evaluate performance of biomass support particles in wastewater treatment systems, M.Sc. research project, EAWAG, 1983.

Mass transport within biofilms, Ph.D. research of H. Siegrist, EAWAG, 1985.

Death, Lysis, and Cryptic Growth in Microbial Cultures, Ph.D. research of C.A. Mason, EAWAG/ETH, 1986.

JOURNAL EDITORSHIP

Regional Editor, BIOFOULING, Gordon & Breach Science Publ., Beginning 1987 until 1990.

PROFESSIONAL SOCIETIES

American Institute of Chemical Engineers
Society of Industrial Microbiologists
American Chemical Society - Microbial and Biochemical Technology

AWARDS, HONORS, SCHOLARSHIPS

Charles P. Schaufus Fellowship from the Parenteral Drug Association and the Millipore Corporation for research on cell recycle in fermentation systems, Nov. 1985. Award value: $30'000.

PUBLICATIONS

A. Articles in Refereed Journals

Bryers, J. D., Biologically Active Surfaces: Processes Governing the Formation and Persistence of Biofilms, Biotechnol. Prog., 3 (2): 57-68, 1987.

Bryers, J. D. and Mason, C. A. Biopolymer Particulate Turnover in Biological Waste Treatment Systems: a Review Bioprocess Engineering, 2: 95-109, 1987.

Mason, C. A., Hamer, G., and Bryers, J. D., The Death and Lysis of Microorganisms in Environmental Processes, FEMS Microbiological Reviews, 39: 373-401, 1986.

Mason, C. A., Bryers, J. D., and Hamer, G., Activity, Death and Lysis during Microbial Growth in a Chemostat. Chemical Engineering Communications, 45: 163-176, 1986.

Bryers, J. D., Stability Analysis of a Binary Culture Chemostat Experiencing Biofilm Formation, Bioprocess Engineering, 1, 3-11, 1986.

Hamer, G., Bryers, J. D., and Berger, J. Thermophilic Anaerobic Digestion for Sewage Sludge Digestion, ACTA. BIOTECHNOL., 5 213-222, 1985.

Bryers, J. D. A Structured Model of the Anaerobic Digestion of Biomass Particulates. Biotechnology and Bioengineering, 27(5): 638-649, 1985.

Bryers, J. D. Biofilm Formation and Chemostat Dynamics: Pure and Mixed Culture Considerations, Biotechnology and Bioengineering, 26(8): 948-958, 1984.

Bryers, J. D. and Characklis, W. G. Processes Governing Early Biofilm Formation. Biotechnology and Bioengineering, 24 (11): 2451-2476, 1982.

Characklis, W. G., Trulear, M. G., Bryers, J. D., and Zelver, N. Dynamics of Biofilm Processes: Methods. Water Research, 16(7): 1207-1216, 1982.

McCoy, W. F., Bryers, J. D., Robbins, J., and Costerton, J. W. Observations of Fouling Biofilm Formation. Canadian J. Microbiology, 27(9): 910-917, 1981.

Bryers, J. D. and Characklis, W. G. Early Fouling Biofilm Formation in a Turbulent Flow System: Overall Kinetics. Water Research, 15(4): 483-491, 1981.

B. Other Professional Publications

Bryers, J. D. A Structured Model of Hansenula polymorpha Diauxic Growth in Continuous Culture, Proceedings 1987 ASME Winter Meeting, Bioprocessing Colloquium, Boston, MA. December, 1987.

Bryers, J. D. Effects of Cell Recycle on Cell Viability and Metabolism, Proceedings 1987 ASME Winter Meeting, Bioprocessing Colloquium, Boston, MA. December, 1987.

Banks, M. K. and Bryers, J. D. Biopolymeric Particulate Turnover in Biofilm Systems, Proceedings A.I.Ch.E. 1987 Annual Meeting - Colloidal Phenomena in Biofilm Systems, New York, NY, November, 1987.

Mason, C. A., Bryers, J. D., and Hamer, G. Mikrobielles Wachstum in Chemostaten: Ein Tod, Lyse und kryptisches Wachstum inkorporierendes Modell, 3. Dechema Proc., Jahrestagung der Biotechnologen, Frankfurt, BRD. 1985.

Bryers, J. D., Hamer, G. and Moo-Young, M. (Eds.). Third International Waste Treatment and Utilization Symposium. Conservation and Recycling, 8 (1/2), 1985.

Hamer, G. and Bryers, J. D., "Aerobic thermophilic sludge treatment: some biotechnological concepts," Proceedings Third International Waste Treatment Symposium, Conservation and Recycling, 8, (1/2, 1985).

Bryers, J. D., Berger, J. and Hamer, G. Interpretation of Thermophilic Anaerobic Digestion Experiments Using a Dynamic Structural Model. Proceedings, Third International Waste Treatment and Utilization Symposium - IWTUS3. Resources and Recycling 8 (1/2), Pergamon, 1985.

Bryers, J. D., Characklis, W. G., Zelver, N., and Nimmons, M. J. Biofouling Film Development and Associated Energy Losses, Proceedings, 6th OTEC Conference, G. L. Dugger (Ed.), Washington, D. C., 1979.

Bryers, J. D. and Characklis, W. G. The Mathematical Simulation of Microbial Film Growth. Proceedings 97th Annual AWWA Conference, Anaheim, CA, 1977.

Norrmann, G., Characklis, W. G., and Bryers, J. D. The Control of Microbial Films in Circular Tubes with Chlorine, Developments in Microbiology, 18, Chapter 48, 1977.

C. Contributions to Books

Characklis, W. G. and Bryers, J. D. Biofilms in Wastewater Treatment, Chapter 17, in BIOFILMS, W. G. Characklis and K. C. Marshall. (Eds.), John Wiley, (in press).

Bryers, J. D. and Characklis, W. G. Biofilms in Biotechnology, Chapter 19. IN: BIOFILMS, W. G. Characklis and K. C. Marshall. (Eds.) John Wiley Publication (in press).

Bryers, J. D. Mathematical Models of Bacterial Attachment and Subsequent Biofilm Formation. IN: Mathematical Models in Microbial Physiology, Michael Bazin (ed) CRC Review Series, Boca Raton, FL. (in press).

Bryers, J. D. and Hamer, G. Use of Artificially Captured Microorganisms in Water Purification. Chapter IN: Methods in Enzymology Series; Enzyme and Whole Cell Technology. K. Mosbach (Vol. Ed) Academic Press, Inc., New York. (in press).

Bryers, J. D. Application of Captured Cell Systems to Biological Treatment Processes. Chapter 2 in Bioenvironmental Systems, Vol. I, D. L. Wise (Ed) CRC Review Series, Boca Raton, FL. (1987).

Bryers, J. D. and R. L. Irvine. Structured Modelling of Biological Treatment Processes. Chapter 6 in Bioenvironmental Systems, Vol. II, D. L. Wise (Ed) CRC Review Series, Boca Raton, FL. (1987).

Irvine, R. L. and Bryers, J. D. Stoichiometry and Kinetics of Biological Treatment Processes. IN: Comprehensive Biotechnology, Volume IV - Principles of Biotechnology: Engineering Considerations, M. Moo-Young, C. L. Cooney, and A. E. Humphrey, Chapter 41, pp 757-772, (Eds.), Pergamon Press, London (1986).

Bryers, J. D. Biofilm Formation and Its Consequences. Group Two Report. IN: Microbial Adhesion and Its Consequences. K. C. Marshall (Ed.) Dahlem Konferenzen. Berlin, West Germany. January, 1984.

Bryers, J. D. Processes Contributing to Biofilm Formation: A Review. Proceedings First International Conference on Fixed Film Biological Processes, Y. C. Wu et al (Eds.), Kings Island, OH, pp. 155-183, 1982.

Characklis, W. G., Bryers, J. D., Trulear, M. G., and Zelver, N. Biofouling Film Development and Its Effects on Energy Losses: A Laboratory Study, in Chapter 5, Condenser Biofouling Control, J. F. Garey (Ed) Ann Arbor Science, Inc., Ann Arbor, MI, pp. 49-76, 1980.

Bryers, J. D. and Characklis, W. G. Measurement of Primary Biofilm Formation, in Chapter 11, Condenser Biofouling Control J. F. Garey (Ed) Ann Arbor Science, Inc., Ann Arbor, MI, pp. 169-183, 1980.

Bryers, J. D. and Characklis, W. G. Kinetics of Primary Biofilm Formation within a Turbulent Flow System, in Fouling of Heat Transfer Equipment, E.F.C. Somerscales and J. G. Knudsen (Eds.), Hemisphere Publishing Corporation, Washington, D. C., pp. 313-333, 1981.

D. Invited Seminar/Conference Speaker:

"Biotechnology in Environmental Engineering - Introduction" and "Fate of Genetically Engineered Microorganisms in Natural and Envineered Systems," Invited Lecture, American Environmental Engineering Professors (AEEP) Workshop, Philadelphia, Pennsylvania, October 1987.

"Modelling of Biological Wastewater Treatment," an IAWPRC Specialized Seminar, August 28-30, 1985. Copenhagen, Denmark. Session Chairman on Basic Kinetics.

"Microbial Adhesion and Its Consequences," Dahlem Conference Scheduled January, 1984, Berlin, invited guest speaker.

"First International Conference on Fixed Film Biological Processes," invited Session Chairman on Fundamental Biofilm Processes, Kings Island, Ohio, April, 1982.

"First International Conference on Fouling of Heat Transfer Equipment," session Co-chairman on Biofouling, Rensselaer Polytechnic Institute, Troy, New York, 1979.

RESEARCH PROJECTS AND ACQUIRED FUNDING

DATE	INSTITUTION	PROJECT TITLE	FUNDING SOURCE	AMOUNT (in US $)
1978	Rice University, Houston, TX	Equipment Grant-Ph.D Research Supplement	Sigma Xi Research Society	1'000.
1979 to 1981	University of Calgary, Calgary, Alberta, CAN	Anaerobic Biofilm Formation in Secondary Oil Recovery Systems	Province of Alberta, Dept. of Natural Resources & Energy	150'000.
1981 to 1983	Swiss Federal Institute for Water Resources & Water Pollution Control, EAWAG, Dübendorf, Switzerland	Mixed Culture Biofilm Development: Carbon Oxidation and Nitrification (Co-Investigator: W. Gujer)	Swiss National Science Funds, Water Quality Division	200'000.
1983 to 1985	EAWAG, Dübendorf, Switzerland	Thermophilic Anaerobic & Aerobic Digestion of Sludge (Co-Investigator: G. Hamer)	Swiss National Science Fund, Refuse & Recycle Division	180'000.
1985 to 1987	EAWAG, Dübendorf, Switzerland	Physiology of Transient Conditions in Microbial Cultures	Swiss National Scierce Funds, Microbiology Division	150'000.
1985	Duke University Durham, NC	Research Initiation Grant	School of Engineering	15'000.

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1985	Duke University	Research Equipment Grant	Graduate School and the Richard Leach Research Endowment	12'000.
1985	Duke University	Research Equipment Grant	Academic Research Council, Duke University	5'000.
1985 to 1986	Duke University	Research Development Grant	NIH Biomedical Research Grant	50'000.
1985 to 1986	Duke University	Biofilm Formation within Cell Recycle Fermentation Systems	Parenteral Drug Association & Millipore Corp. C.P. Schaufus Award	30'000.
1986	Duke University	Biochemical Engineering Research Laboratory Development (Co-Investigator: H. Clark)	North Carolina Biotechnology Center	406'000.
1986 to 1987	Duke University	Enhanced Enzyme Productivity via Substrate Compositional Transients	North Carolina Biotechnology Center	15'000.
1987	Duke University	1987 Triangle University Conference: Biotechnology Applied to the Environment	North Carolina Biotechnology Center and the Millipore Corp.	5'700.
1987	Duke University	Research Equipment Grant: Liquid Scintillation Counter	National Science Foundation	29'450.

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c o n t i n u e d

1987	Duke University	Fate of Biopolymeric Particles in an Aerobic Biofilm System	North Carolina Biotechnology Center	16'500.
1987	Duke University	Effects of Exo-Polysaccharide Production on Biofilm-Bound Bacterial Metabolism	Duke University Research Council	5'000.
1987-1990	Duke University	Enhanced Enzyme Productivity in Microorganisms Experiencing Prolonged System Transients	NSF-Biochemical & Biomass Engrg. CBT-8711612	210'000.
1987	Duke University	Workshop on the Commercialization of Cellular Adhesion & Biofilm Processes	North Carolina Biotechnology Technology (H.Smith-CoPI)	15'000.

Total (as of Sept,1987) **$ 1'495'650.**

MICROBIAL FILM DEVELOPMENT AND ASSOCIATED ENERGY LOSSES

J. D. Bryers**, W. G. Characklis*, N. Zelver†, and M. G. Nimmons†

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George R. Brown School of Engineering
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Houston, Texas 77001

EX. C

Abstract

Microbial fouling in power plant condensers increases heat transfer and fluid frictional resistance resulting in energy losses. Biofouling control is generally by chlorine addition creating potential toxicity problems in receiving waters. A better understanding of biofouling film development and destruction (i.e., stoichiometry and kinetics) is necessary to maintain effluent water quality while minimizing biofouling effects.

This paper reviews research progress in the following areas:

1. Development of various sensitive biofilm detection methods for monitoring the extent of biofouling.

2. Determination of effects of certain variables on the kinetics and stoichiometry of biofilm accumulation.

3. Correlation of biofilm development to increases in both heat transfer and fluid frictional resistance.

4. Determination of the effects of chlorine applications on established biofilms.

Introduction

The term fouling refers to the formation of inorganic and/or organic deposits on surfaces. In cooling systems, these deposits form on condenser tube walls increasing fluid frictional resistance, accelerating corrosion and impairing heat transfer. Four types of fouling, alone or in combinations, may occur:

1. crystalline fouling caused by precipitation of $CaCO_3$, $CaSO_4$ or silicates

2. corrosion fouling resulting from formation of insulating layers of metal oxides on the tubes

3. fouling due to adherence of particulate matter on tube surfaces

4. biological fouling resulting from attachment and growth of microbial organisms

This investigation was restricted to the study of biological fouling.

The Problem

The most common method for controlling the fouling biofilm development and maintaining condenser performance is periodic chlorination. However, concern over residual toxicity from hypochlorous acid or its reaction products has resulted in federal regulations which limit the allowable concentrations of free available chlorine in cooling water discharges. At the present time, there is no sound basis for assessing the impact of the regulations.

This investigation stems from the apparent need for a more basic understanding of fouling biofilm development and fouling biofilm destruction.

Project objectives included the following:

1. Develop a better understanding of fouling biofilm development, with particular emphasis on the effects of fluid flow rate, bulk water temperature, wall surface temperature and limiting nutrient concentration.

2. Determine the effectiveness of fouling biofilm destruction by chemical oxidants, primarily chlorine.

3. Develop a practical, reliable, sufficiently sensitive device for monitoring biofouling and for effectively operating and controlling biofouling destruction processes at operating power plants.

Laboratory experiments and a limited number of field tests were conducted with two reactor configurations:

1. a tubular reactor

2. an annular reactor consisting of a stationary outer cylinder and a rotating inner cylinder.

The tubular reactor geometry and its turbulent flow regime are identical to those existing in cooling water condensers. The annular reactor was tested as a biofouling monitor because it is very sensitive to fouling and is easy to operate and maintain. The annular reactor has the potential of being used in a sidestream from the cooling water supply to continuously monitor biofouling for control of the addition of oxidant. Biofouling in the experimental reactors was measured by observing changes in the following parameters:

1. biofilm thickness

2. attached biomass

3. fluid frictional resistance

4. heat transfer resistance

Processes in Fouling Biofilm Development

Microbial fouling is the combined result of phys-

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**,†,†Graduate Assistant, Environmental Science and Engineering Dept., Rice University.

Proc. 6th OTEC Conference, "Ocean Thermal Energy for the 80's", Wash. D.C. June 19-24 1977
Paper No 12-15

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EX. D

BIOENGINEERING REPORT

Fouling Biofilm Development: A Process Analysis

W. G. CHARACKLIS, *College of Engineering, Montana State University, Bozeman, Montana 59717*

Summary

Biofilm development at a surface is the net result of several physical, chemical, and microbial processes including the following: 1) transport of dissolved and particulate matter from the bulk fluid to the surface; 2) firm microbial cell attachment to the surface; 3) microbial transformations (growth, reproduction, etc.) within the biofilm resulting in production of organic matter; 4) partial detachment of the biofilm due primarily to fluid shear stress. This report presents a framework for analyzing the interrelated processes contributing to biofilm development. Some of the available rate and composition data are presented so that the relative process rates can be compared.

INTRODUCTION

The term fouling refers to the undesirable formation of inorganic and/or organic deposits on surfaces. These deposits can impede the flow of heat across the surface, increase the fluid frictional resistance at the surface, and increase the rate of corrosion at the surface. In any case, energy losses result.

Several types of fouling and their combinations may occur in heat exchangers: 1) crystalline or precipitation fouling, 2) corrosion fouling, 3) particulate fouling, 4) chemical reaction fouling, and 5) biological fouling or biofouling. Biological fouling results from a) development of a biofilm consisting of microorganisms and their products (microbial fouling), b) deposition and growth of macroorganisms such as barnacles (macrobial fouling), and c) assorted detritus. Although many different macroorganisms such as barnacles and mussels have been identified in fouling communities, this report will concentrate on microbial fouling on the controversial premise that it always precedes colonization of the surface by macroorganisms. Consequently, control of microbial fouling results in control of macrobial fouling.

Development of a systematic understanding of biofouling from field observations has been limited because of the interaction of several con-

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TABLE 1
Effect and Relevance of Biofilms on Various Rate Processes

Effects	Specific process and result	Concerns
Heat transfer reduction	Biofilm formation on condenser tubes and cooling tower fill material, *energy losses*	Power industry, chemical process industry, U.S. Navy, solar energy systems
Increase in fluid frictional resistance	Biofilm formation in water and wastewater conduits as well as condenser and heat exchange tubes. Causes increased power consumption for pumped systems or reduced capacity in gravity systems, *energy losses*	Municipal utilities, power industry, chemical process industry, solar energy systems
	Biofilm formation on ship hulls causing increased fuel consumption, *energy losses*	U.S. Navy, shipping industry
Mass transfer and chemical transformations	Accelerated corrosion due to processes in the lower layers of the biofilm. Results in *material deterioration* in metal condenser tubes, sewage conduits, and cooling tower fill	Power industry, U.S. Navy, municipal utilities, chemical process industry
	Biofilm formation on *remote sensors, submarine periscopes, sight glasses, etc.*, causing *reduced effectiveness*	U.S. Navy, water quality data collection
	Detachment of microorganisms from biofilms in cooling towers. Releases *pathogenic organisms* (e.g., *Legionella* in aerosols)	Public health
	Biofilm formation and detachment in drinking water distribution systems. Changes *water quality* in distribution system	Municipal utilities, public health
	Biofilm formation on teeth, causes *dental plaque and caries*	Dental health
	Attachment of microbial	Human health

TABLE 1 *(continued from previous page)*

Effects	Specific process and result	Concerns
	cells to animal tissue, causes *disease* of lungs, intestinal tract, and urinary tract	
	Extraction and oxidation of organic and inorganic compounds from water and wastewater (e.g., rotating biological contactors, biologically aided carbon adsorption and benthal stream activity), *reduced pollutant load*	Wastewater treatment, water treatment, stream analysis
	Biofilm formation in industrial production processes *reduces product quality*	Pulp and paper industry
	Immobilized organisms or community of organisms for conducting *specific chemical transformations*	Chemical process industry
	Fouling biofilm accumulation *reduces effectiveness* of ion exchange and membrane processes used for high quality water treatment	Desalination, industrial water treatment

tributing rate processes. Mechanistically, fouling biofilm accumulation may be described as the net result of the following:

Transport of material from the bulk fluid to the surface and attachment to the surface. Materials can be soluble (microbial nutrients and organics) or particulate (viable microorganisms, their detritus, or inorganic particles). Also, suspended particles of sufficient mass may control films by "scouring" action.

Microbial metabolism within the film. Microbial growth in the biofilm and extracellular polymers produced by the microorganisms contribute to the biofilm deposit and promote adherence of inorganic suspended solids.

Fluid shear stress at the surface of the film. Such forces can limit the overall extent of the fouling deposit by reentraining attached material.

Surface material and roughness. Surface properties can influence micromixing near the surface and corrosion processes. Some metal surfaces may release toxic components into the biofilm inhibiting growth and/or

attachment. Some metals produce loosely held oxide films under the biofilms. When the oxide film sloughs, the biofilm is also removed.

Fouling control procedures. Chlorine, the most commonly used chemical, oxidizes biofilm polymers causing disruption and partial removal. Inactivation of a portion of the microbial population also occurs. Altered biofilm "roughness" and decreased viable cell numbers will influence "regrowth" rates of the biofilm. Mechanical cleaning can physically remove portions of the attached film.

The most common method of controlling biofilm accumulation is periodic or continuous chlorination. Chlorine dosage and application schedules are governed typically by observation of back pressure in a steam condenser, operator experience, or visual observation.

Recently in the United States, concern over toxicity from hypochlorous acid, or its reaction products, has resulted in federal regulations which limit the allowable concentration of free available chlorine in cooling water discharges. The impact of the limitations is unknown but will vary significantly with location. At present, there is no sound basis for assessing the impact of these regulations. This dilemma along with a host of other biofilm problems and applications has stimulated research in biofilm processes (Table 1).

PROPERTIES AND COMPOSITION OF BIOFILMS

Microorganisms, primarily bacteria, adhere to surfaces ranging from the human tooth and intestine to the metal surface of condenser tubes exposed to turbulent flow of water. The microorganisms "stick" by means of extracellular polymer fibers, fabricated and oriented by the cell, that extend from the cell surface to form a tangled matrix termed a "glycocalyx" by Costerton, Geesey, and Cheng.[4] The fibers may concentrate extracellular enzymes necessary for preparing substrate molecules for ingestion, especially high molecular weight or particulate substrate frequently found in natural waters.

The biofilm surface is highly adsorptive, partially due to its polyelectrolyte nature, and can collect significant quantities of silt, clay, and other detritus in natural waters.

Physical, chemical, and biological properties of biofilms are dependent on the environment to which the attachment surface is exposed. The physical and chemical microenvironment combine to select the prevalent microorganisms which, in turn, modify the microenvironment of the surface. As colonization proceeds and a biofilm develops, gradients develop within the biofilm and average biofilm properties change. Changes in biofilm properties that occur during biofilm development must be considered when attempting to predict the effect of biofilms on fluid and heat

transport in turbulent flow systems. These changes have been largely ignored in past studies.

Physical Properties

Relevant *thermodynamic properties* of biofilm are its volume (thickness) and mass. In turbulent flow systems, wet biofilm thickness (Th) seldom exceeds 1000 μm.[2] The biofilm dry mass density (ρ_{Db}) can be determined from the wet biofilm thickness if the biofilm mass (ρ_{Db}) is known. ρ_{Db} reflects the attached dry mass per unit wet biofilm volume and measured values in turbulent flow systems range from 10 to 50 mg/cm^3. ρ_{Db} increases with increasing turbulence[2] and increasing substrate loading[3,4] as indicated in Figures 1 and 2. The increase in ρ_{Db} with increasing turbulence may be caused by one of the following phenomena: 1) selective attachment of only certain microbial species from the available population; 2) microbial metabolic response to environmental stress; 3) fluid pressure forces "squeeze" loosely bound water from the biofilm.

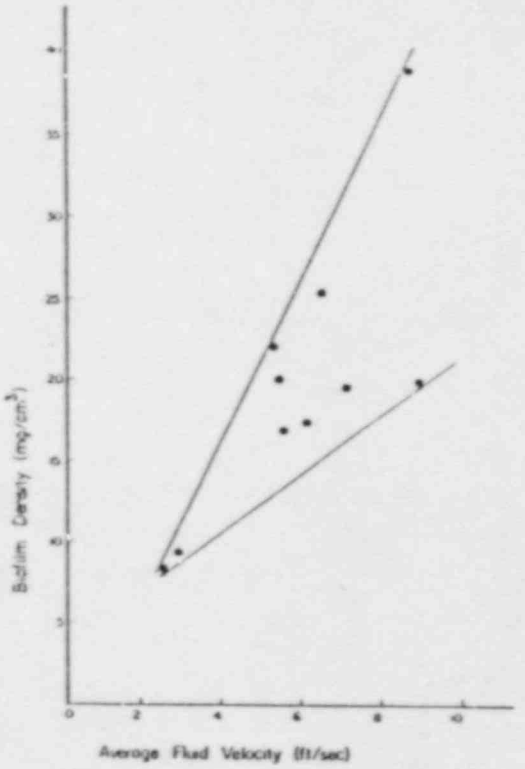


Fig. 1. Influence of fluid shear stress on biofilm density. [•] Ref. 2.

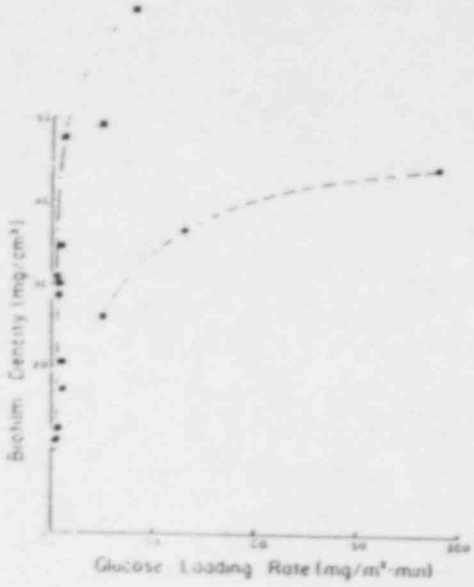


Fig. 2. Influence of glucose loading rate on biofilm density. (•) Ref. 2; (▪) Ref. 31.

The relatively low biofilm mass densities compare well with observed water content of biofilm.[4,6]

The *transport properties* of biofilm are of critical importance in quantifying effects of biofilms on mass, heat, and momentum transfer. Diffusion coefficients for various compounds through microbial aggregates have been reported in the literature,[7] mostly for floc particles (Table II). Matson and Characklis[7] report variation in the diffusion coefficient for glucose and oxygen with growth rate and carbon-to-nitrogen ratio. In biofilms, the diffusion coefficient is most probably related to biofilm density. *In situ* theological measurements indicate that the biofilm is viscoelastic, with a relatively high viscous modulus as indicated in Table III.[5] Reported biofilm thermal conductivities are presented in Table IV. As expected from reported water content, biofilm thermal conductivity is not significantly different from water.

Chemical Properties

Inorganic composition of biofilms undoubtedly varies with the chemical composition of the bulk water and probably affects the physical and biological structure of the film. Calcium, magnesium, and iron affect intermolecular bonding of biofilm polymers which are primarily responsible for the structural integrity of the deposit. In fact, EDTA is effective in detaching biofilm.[7] In heat exchangers, corrosion products [illegible] ment

TABLE II
Experimental Diffusion Coefficient Measurements from the Literature (Ref. 7)

Reactant	Diffusivity (10^{-5} cm²/s)	Bio-Film Thickness ($\times 10^{4}$ cm)	Biomass type	Growth system	Procedure	Reference
Oxygen	1.5	70	Bacterial slime	Rotating tube	Reaction products analysis	10
Oxygen	0.21	8	Fungal slime *Zoogloea ramigera*	Fluidized reactor	Nonlinear curve fit	11
Glucose	0.048	8	*Zoogloea ramigera*	Fluidized reactor	Nonlinear curve fit	12
Glucose	0.18–0.8	10–100	Mixed culture	Fluidized reactor	Two chamber	13
Oxygen	2.2	90	Nitrifier culture	Fluidized reactor	Two chamber	14
Ammonia	1.3	80				
Nitrate	1.4	90				
Oxygen[a]	0.4–2.0	20–100	Mixed culture	Fluidized reactor	Two chamber	15
Glucose[a]	0.08–0.21	10–30				15

[a] Tests were conducted under a variety of experimental conditions.

TABLE III
Viscoelastic Properties of Biofilm Developed at 40°C at a Fluid Shear Stress of 3.3 N/m², Glucose Was Growth-Limiting and Was Applied at 6.2 mg/m² min (Ref. 5)

Elastic (storage) modulus	99.5 N/m²
Viscous (loss) modulus	118 N/m²

suspended solids can adsorb to the biofilm matrix and influence its chemical composition. Table V reports the range of inorganic composition observed in selected biofilms.

The organic composition of the biofilm is strongly related to the energy and carbon sources available for metabolism. Classical papers[8,9] have demonstrated the effect of environment and microbial growth rate on the composition of the cells and their extracellular products. For example, nitrogen limitation can result in production of copious quantities of microbial extracellular polysaccharides. Table VI presents data on the composition of biofilms developed in the field and in the laboratory. In terms of macromolecular composition, Bryers[25] has measured protein-to-polysaccharide mass ratios ranging from 0 to 10 (polysaccharide concentration in terms of glucose and protein concentration based on casein) with increasing biofilm accumulation. Other chemical analyses of biofilm have been reported by Bryers and Characklis.[26]

TABLE IV
Thermal Conductivity of Biofilm and Other Selected Materials Relevant to Biofouling of Heat Exchangers

Material	Thermal conductivity (W/m K)	Temperature (°C)	Reference
Biofilm	0.68 ± 0.27	28.3 ± 0.3	4
	0.71 ± 0.39	26.7 ± 0.3	
	0.57 ± 0.10	28.3 ± 0.3	
Water	0.61	26.7	16
	0.62	28.3	
Carbon steel	51.92	0–100	17
Steel	46.86	18	18
Stainless steel type 316	16.30	0–100	17
Mononium 505	138.46	20	17
	205.85	100	18
Cupronickel 10%, 30%	44.71	0–100	17
Copper	384	18	18
Titanium (commercial pure)	16.44	0–100	17
Glass	0.6–0.9	—	16

TABLE V
Chemical Properties of Biofilms Obtained from Fouled Surfaces Experiencing Excessive Frictional Losses (Ref. 6)

	Reference				
	19	20	20	21	5
Water	87	85.6	90	95	96
Volatile fraction	2.5	2.7	1.9	2.4	3.2
Fixed fraction	10.5	11.7	8.1	2.6	0.8
Si (as percent fixed fraction)		7.0	11.8	12.5	
Fe		18.5	7.9	1.4	
Al		7.5		3.9	
Ca		1.0	5.6		
Mg		2.5		3.2	
Mn		59.5	56.3	4.9	

Biological Properties

The organisms which colonize the attachment surface will strongly influence biofilm development rate and biofilm chemical and physical properties. However, organism–organism and organism–environment interactions undoubtedly shift population distributions during biofilm accumulation. Several investigators have observed succession during biofouling.[27,28]

The first visible signs of microbial activity on a surface are usually small "colonies" of cells distributed randomly on the surface. As biofilm development continues, the colonies grow together forming a relatively uniform biofilm. The viable cell numbers are relatively low in relation to

TABLE VI
Chemical Composition of Biofilms Obtained in the Field and Laboratory Emphasizing the Primary Constituents (C,N,P)

Source	Percent dry weight						
	Carbon (C)	Nitrogen (N)	Phosphorus (P)	Fixed solids	C/N	C/P	Reference
Biofilm power plant condenser	6.4–13.8	0.5–3.0	—	—	2–27	—	22
Biofilm laboratory reactor	42.8	10.0	—	—	4.3	—	23
Biofilm laboratory reactor	19.0	9.2	1.8	20	2.1	10.5	5
E. coli	50.0	14.0	3.0	—	3.6	16.7	24

the biofilm volume (10^4–10^6/cm^3 biofilm) occupying only 1–10% of the biofilm in dilute nutrient solutions.[4] Costerton[29] and Jones, Roth, and Sanders[30] present photomicrographs which corroborate these data in natural and laboratory systems.

In many cases, filamentous forms emerge as the biofilm develops further. *Hyphomicrobium*, *Sphaerotilus*, and *Beggiatoa* are frequently identified. The filamentous forms may gain an ecological advantage as the biofilm develops since their cells can extend into the flow to obtain needed nutrients or oxygen which may be depleted in the deeper portions.

Major questions remain unanswered regarding biofilm properties and their influence on processes of interest and include the following:

1) Are the physical and chemical properties of the biofilm dependent on the microbial species in the biofilm? To what extent? How specific is the relationship between the predominant microbial species and the immediate environment of the surface?

2) How much do biofilm properties influence the effect of biofilms on energy losses (i.e., fluid frictional resistance and heat transfer resistance)?

3) How do biofilm properties change when biocides are applied on a continuing basis?

4) How does inorganic content of the water influence biofilm properties?

RATE PROCESSES CONTRIBUTING TO BIOFILM DEVELOPMENT

The physical, chemical, and biological transformations of interest in biofilm development are completed in a certain period of time. For biofilm development, a specified change may signal the shutdown of manufacturing operations and the beginning of cleaning operations. The time required for this specified change is inversely proportional to the *rate* at which the process occurs. Thus the rate is the most important quantity

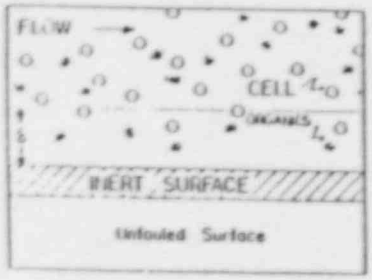


Fig. 3. A clean surface exposed to a turbulent flow of fluid containing dispersed microorganisms, nutrients, and organic macromolecules. δ refers to the viscous sublayer thickness.

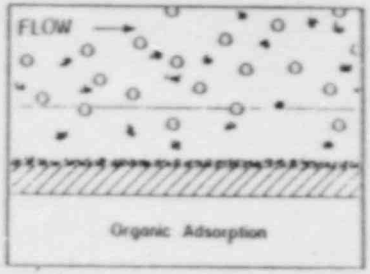


Fig. 4. Transport and adsorption of organic molecules on a clean surface.

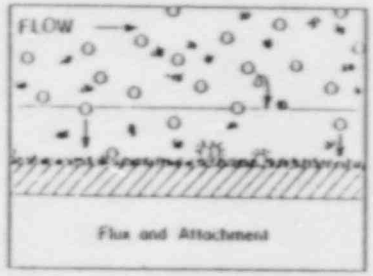


Fig. 5. Transport and adhesion of microbial cells to the conditioned surface.

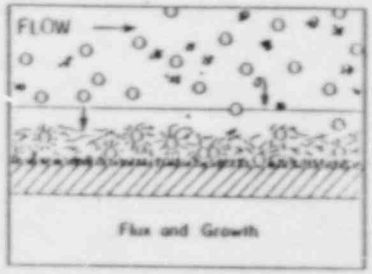


Fig. 6. Continued transport and adhesion of microbial cells as well as growth and other metabolic processes within the biofilm.

in process analysis. If the process consists of a number of processes in series, the slowest step of the sequence exerts the greatest influence and *controls* the overall process rate. This step is called the "rate-determining step" or "rate-controlling step."

In this discussion, biofilm development will be considered to be the net result of the following physical, chemical, and biological processes: transport of organic molecules and microbial cells to the wetted surface (Fig. 3); adsorption of organic molecules to the wetted surface resulting in a

"conditioned" surface (Fig. 4); adhesion of microbial cells to the conditioned surface (Fig. 5); metabolism by the attached microbial cells resulting in more attached cells and associated material (Fig. 6); detachment of portions of the biofilm (Fig. 12).

Transport to the Wetted Surface

When a clean surface is immersed in natural water, transport controls the initial rate of deposition (Fig. 3). In very dilute suspensions of microbial cells and nutrients, transport of microbial cells to the surface may be the rate-controlling step for long periods of time. Biofilm development in open ocean waters or distilled water storage tanks may be illustrative of these cases. Transport of molecules and particles smaller than 0.01–0.1 μm is described satisfactorily in terms of diffusion. In turbulent flow, the diffusion equation must be modified to include turbulent eddy transport. Transport of such small molecules and particles is relatively rapid compared to transport of larger particles. Consequently, adsorption of an organic film is reported to occur "instantaneously" in many cases, as schematically illustrated in Figure 4.

Larger particles develop a sluggishness with respect to the surrounding fluid. As the particle approaches the wetted surface, eddy transport diminishes and the viscous boundary layer exerts a greater influence. For soluble matter and small particles, diffusion can adequately describe transport in the viscous sublayer.[31–33] For larger particles, other mechanisms must be considered to explain experimental observations.

Within a turbulent flow regime, larger particles suspended within the fluid are transported to the solid surface primarily by fluid dynamic forces. Particle flux to the surface increases with increasing particle concentration. However, particle flux is also strongly dependent on the physical properties of the particles (e.g., size, shape, and density) and is influenced by many other forces near the attachment surface.

Microbial cells (0.5–10.0 μm effective diameter) can be transported from the bulk fluid to the wetted surface by several processes including the following: diffusion (Brownian), gravity, thermophoresis, taxis, fluid dynamic forces: inertia, lift, drag, drainage, and downsweeps.

Transport mechanisms

Particles in turbulent flow are transported to within short distances of the surface by eddy diffusion. Particles are propelled into the viscous (or laminar) sublayer under their own momentum. Turbulent eddies supply the initial impetus and frictional drag slows down the particle as it penetrates the viscous sublayer.[34,35] For microbial cells, the inertial forces are very small because of their small diameter and density (in relation to water).

If the particle is traveling faster than the fluid in the region of the wall, the *lift force* directs the particle toward the wall.[36] This would normally be the case if particle density is greater than fluid density and the particle is moving toward the wall. *Frictional drag forces* can be significant, especially in the viscous sublayer region. The drag force slows down the particle as it approaches the surface and is proportional to difference between particle velocity and fluid velocity.

If the mass density of the particle, ρ_p, differs substantially from the fluid density ρ, the *gravity force* may be significant. For microbial cells in turbulent flow, the gravity force is generally negligible. *Thermophoresis* is only relevant when particles are being transported in a temperature gradient.[37] If the surface is hot and the bulk fluid is cold, the thermophoretic force will repel the particle from the surface. *Eddy diffusion* may be instrumental in dispersing particles in the turbulent core region, thus maintaining a relatively uniform concentration in that region. However, eddy diffusion will not be significant in transporting particles to the wall. *Brownian diffusion* contributes little to the transport of microbial cells (> 1.0 μm diam) in turbulent flow. Certain microbes are capable of *motility* or *taxis* through their own internal energy. Velocities as high as 4×10^{-4} cm/s[1] have been observed. Taxis could possibly be a significant transport process within the viscous sublayer. For particles in liquids, the *fluid drainage force* is significant.[31] The drainage force describes the resistance the particle encounters near the wall due to the pressure in the draining fluid film between the two approaching surfaces. This force is quite large for a microbial cell as it approaches the wall.

Recent published research on the structure of the viscous sublayer in turbulent flow indicates that "*downsweeps*" of fluid from the turbulent core penetrate all the way to the wall.[32,38] Particles in the bulk fluid are transported all the way to the wall by these convective downsweeps. Aside from lift, this is the only fluid mechanic force directing the particle to the wall. Downsweeps are apparently quite important in terms of particle transport to the wall in turbulent flow.

For a Reynolds number of 30,000 in tube flow, the bursts resulting from the downsweeps have the following characteristics: burst diameter, 0.11 cm; average axial distance between bursts, 0.50 cm; and mean time between bursts, 0.006 s. Minimum transport rate of particles would be observed when particle diameter approximates 0.1×10^{-4} cm under constant fluid flow conditions. At this diameter, *Brownian diffusion* starts exerting a significant effect. Particle flux in the pipe for a bulk fluid particle concentration of 10^4 particles/cm^3 is approximately 0.1 particles/cm^2 s.

Influence of surface roughness

Surface roughness significantly influences *transport rate* and *microbial cell attachment* for several reasons including the following: (1) increases

convective mass transport near the surface, 2) provides more "shelter" from shear forces for small particles, and 3) increases surface area for attachment. If surface roughness elements are larger than the viscous sublayer, the roughness can be measured quantitatively by hydraulic methods. If surface roughness elements are smaller than the viscous sublayer (i.e., microroughness), measurements of roughness are difficult to quantify and interpret. Browne[39] reports that particle deposition from gases is very sensitive to roughness too small to affect fluid frictional resistance.

Consequences of transport rates on biofilm development

When a "clean" surface first contacts water with biological activity, organic substances and microbial cells must be transported to the surface before biofilm development can begin. Consequently, the rate of transport determines the length of the "induction" period, i.e., the initial period during which no macroscopic effects of the biofilm are evident. In very dilute solutions (e.g., open ocean), the rate of transport may control the overall rate of biofilm development for long periods. Rate of transport is proportional to the concentration difference between the bulk fluid and the surface. In dilute solutions, this difference is small. The flow regime (zero, laminar, or turbulent) also significantly influences transport rates and should be defined carefully in any experimental system used for biofilm studies. Surface characteristics are also critical to the repeatability and applicability of the results because a rough surface will increase transport and attachment rates. Which rate controls—rate of transport or rate of adhesion?

Summary

There is a need for more information on transport of particulate material from a turbulent fluid to a wall. Especially relevant to this discussion is the rate of transport of microbial cells in aquatic systems where inertial forces are relatively small. Other questions that might be addressed include the following:

1) How do microbial cell properties influence transport rate?

2) How does particle flocculation influence transport rate?

3) At what concentration do particle interactions influence transport rate?

4) Does surface roughness influence particle transport rate? Can this influence be predicted from friction factor measurements?

Adsorption of Organic Molecules to the Wetted Surfaces

Figure 3 illustrates an initially clean surface exposed to turbulent flow of a fluid containing dispersed microorganisms, nutrients, and organic

TABLE VII

Maximum Rate and Extent of Molecular Fouling

Maximum rate (nm/min)	Maximum accumulation (nm)	Maximum accumulation (μg COD/cm²)	Surface	Reference
0.15–0.45	30–60		Pt[a]	40
0.004 – 7.4			Ge[b]	41
0.044	77.3		Ti[b]	
0.07[c]	13.5[c]	1.5	glass[c]	25
0.22[c]	22.5[c]	2.5	glass[d]	

[a] Immersed in quiescent Chesapeake Bay water (3–4°C) containing 2.3 mg carbon/L, salinity between 9 and 16‰, and pH between 7.9 and 8.2.

[b] Gulf of Mexico water (22°C) flowing past the surface at a fluid shear stress of 7.1 N/m². Salinity was 34‰. Carbon concentration not reported.

[c] Medium consisted of sterile 1:1 w/w trypticase soy broth–glucose mixture (34°C; pH 8). The glass surfaces were immersed in tubes placed in a mechanical shaker. Carbon concentration was approximately 80 mg carbon/L.

[d] Medium was effluent (30°C; pH 8) from a chemostat (40–20 mg/l. COD, 3 mg/l. polysaccharide) with no primary substrate remaining. Microorganisms were present (approximately 10^6 cells/mL) but no cells attached during the period of interest. Fluid shear stress was 3.8 N/m².

[e] Estimated from measurements of chemical oxygen demand (COD) adsorbed per unit area. Assumed COD of protein is 0.855 mg COD/mg protein and protein density is 1.3 g protein/cm³.

macromolecules. Microorganisms select their habitats on the basis of many factors, including the nature of the wetted surface (material of construction and surface roughness). Adsorption of an organic monolayer occurs within minutes of exposure as shown in Figure 4 and changes the properties of the wetted surface. Investigations have shown that materials with diverse surface properties (e.g., wettability,[7] surface tension, electrophoretic mobility) are rapidly conditioned by adsorbing organics when exposed to natural waters with low organic concentrations. These organic molecules are usually polysaccharides or glycoproteins. Loeb and Neihob[40] and DePalma, Goupil, and Akers[41] have measured adsorption rates of organic molecules in seawater, and Bryers[25] has observed adsorption rates in a laboratory system. Rates and extent of adsorption in these investigations are presented in Table VII. Maximum accumulation from molecular fouling is less than 0.1 μm. The rate of molecular fouling can be considered instantaneous since it is much greater than the rate of microbial fouling. Based on "thickness" measurements, molecular fouling can have no significant effect on fluid flow or heat transfer. Nevertheless, the surface properties resulting from adsorption of an organic film may affect the sequence of microbial events which follow.

Costerton, Geesey, and Cheng[4] have discussed the pronounced specificity of some bacteria that attack only a particular animal host tissue and suggest that specificity may be explained by the specificity of the

host-tissue glycocalyx. It remains to be seen whether a surface, wetted by the absorption of organic molecules indigenous to that environment will be initially colonized by a *specific* microbial cell.

Brash and Samak[42] present experimental evidence that significant turnover occurs in molecular (protein) adsorbed fouling films on polyethylene. Protein molecules in the bulk fluid are continuously exchanging with adsorbed proteins. This suggests that dispersed microbial cells and their associated extracellular material may be continually exchanging with biofilm material at the wall.

Adhesion of Microbial Cells to the Wetted Surface

Previous research[27, 43] suggests the existence of a two-stage adhesion process: 1) reversible adhesion followed by 2) an irreversible adhesion. Reversible adhesion refers to an initially weak adhesion of a cell which can still exhibit Brownian motion but is readily removed by mild rinsing. The adhesive forces which hold the cell at the wall during reversible adhesion probably include the following: a) electrostatic, b) London–van der Waals, c) interfacial tension, and d) covalent bonding. Conversely, irreversible adhesion is a permanent bonding to the surface, usually aided by the production of extracellular polymers. Cells attached in this way can only be removed by rather severe mechanical treatment. Marshall[2] and Corpe[44] have implicated polysaccharides and glycoproteins in irreversible adhesion (Fig. 5).

Most of the research on cell adhesion has been conducted at very low fluid shear stress or in quiescent conditions.[30] These conditions suggest that sedimentation or diffusion may control the rate of adhesion. Also, there is yet to be a demonstration of reversible adhesion in turbulent flow.

In turbulent flow, the *net* rate of adhesion is the quantity most easily measured. The net rate of adhesion is the difference between the rate of adhesion and rate of detachment. Detachment results from several forces including the following: fluid dynamic forces, shear forces, lift (upsweeps), and taxis. Upsweeps are analogous to the downsweeps discussed above. Upsweeps result in turbulent bursts which move away from the surface into the bulk flow. Upsweeps generate a lift force normal to the surface which can influence detachment. Drag or viscous shear forces act in the direction of flow on attached cells and are approximately 1000 times greater than the lift forces acting on attached cells. Note that although viscous shear may dislodge a particle, unless a lift force is present, the particle will presumably roll along the surface until another surface adhesion site is found.

The nature of the surface is an important factor affecting adhesion. Wettability or critical surface tension, is the property used most frequently to describe surface characteristics in microbial attachment studies.[4, 30] In seawater, cell attachment increases with increasing critical surface tension of the surface (including glass, copper, polyethylene, Teflon) with the exception of the copper surface on which fewer cells attached.[45] The copper may inhibit cell attachment by inhibiting a metabolic process necessary for attachment. Even so, there are many examples of biofouling on cupronickel condenser surfaces.[46]

The presence of multivalent cations (especially Ca^{2+}, Mg^{2+}, and Fe^{3+}) also influences the attachment process, possibly by altering surface characteristics or by bridging cellular anionic polyelectrolytes to anionic polyelectrolytes adsorbed on the wetted surface.

Other questions of relevance still remain including the following:

1) Is an adsorbed organic layer a prerequisite for cellular attachment to a surface?

2) Is there a significant interchange between cells on the surface and cells in the bulk fluid?

3) What types of compounds serve as "glue" for firm cellular attachment?

4) Is the adsorption process "species specific", i.e., is there a high degree of specificity in the organism–surface interaction?

5) How does the attachment process differ after the formation of a "monolayer" of cells?

Metabolism by the Attached Microbial Cells

Restricting our discussion to chemosynthetic organisms, the attached microbial cells assimilate reduced organic or inorganic compounds, nutrients, and oxygen or some other electron acceptor. The process yields energy with which the cells reproduce, maintain their internal structure, and form extracellular products. Therefore, *growth*, *maintenance*, and *product formation* are *fundamental processes* carried out by microbial cells in the presence of sufficient nutrients (Table VIII). If nutrients are depleted, or toxic substances are present, *death* and *lysis* may occur.

The rates of the fundamental microbial processes are difficult to measure. Consequently, the *observed rates* (last row, Table VIII) are usually rate of substrate (the growth-limiting nutrient) removal, electron-acceptor (usually oxygen) removal, biomass production, or product formation.

The stoichiometry of each fundamental process can be measured in certain laboratory systems (e.g., chemostats). The rows in Table VIII qualitatively represent the stoichiometry of each fundamental process (– refers to reactant and + refers to product).

Analysis of rate and stoichiometry of processes within a biofilm are frequently complicated by significant mass transfer resistances in the liquid or diffusional resistances within the biofilm.

Trulear and Characklis[4] have observed substrate removal rate in an experimental biofilm reactor. The substrate removal rate increases in proportion to biofilm thickness up to a critical thickness beyond which

TABLE VIII
A Matrix Representation for the Fundamental Microbial Rate Processes

Fundamental process		Reactants			Stoichiometry			Products		
		Substrate	Nutrient	Electron acceptor	Biomass		Product		Metabolite
Process	Rate	S	N	E	X_V	X_D	P_1	P_2	M
Growth	μ	-	-	+	+		+	[illegible]	+
Maintenance									
exogenous	m	-	-	-			+		+
endogenous	k_e	+	+	+	-	[illegible]	+	-	+
Product formation	k_{p_1}	+	+	+			+		+
Death									
loss of viability	k_d	[illegible]			+				
lysis	k_l	[illegible]	[illegible]	[illegible]	+	[illegible]	+		
Observed rate		q_s	q_n	q_e	r_{x_v}	r_{x_D}	r_{p_1}	r_{p_2}	r_m

q = specific production or removal rate (time^{-1})
μ = specific growth rate or specific biomass production rate (time^{-1})
k_d = total biomass concentration (mass/length^3)
k_e = inert solids concentration (mass/length^3)
β_1 = extracellular microbial product concentration (mass/length^3)
β_2 = intracellular microbial product concentration (mass/length^3)
Δ = substrate concentration (mass/length^3)
Σ = nutrient concentration (mass/length^3)
ε = electron-acceptor concentration (mass/length^3)
r_m = net solids production rate (time^{-1})

Fig. 7. The influence of biofilm thickness and glucose loading rate on glucose removal rate by a biofilm. Glucose loading rate was 9.9 mg/m^2 min^1 for AFR-19 and 2.0 mg/m^2 min^1 for AFR-21 (Ref. 54).

removal rate remains constant (Fig. 7). The critical, or "active," thickness is observed to increase with substrate concentration. This behavior is confirmed by other investigators[2,23,50] and is attributed to nutrient diffusional limitations within the biofilm. Once the biofilm thickness exceeds the depth of substrate (or oxygen) penetration into the biofilm (Fig. 8), the removal rate is unaffected by further biofilm accumulation.

Observed substrate removal rate cannot be used to distinguish between growth, maintenance, product formation, and death. It seems clear from other data[25] that product formation (primarily polysaccharide) is significant in the early stages of biofilm formation. Maintenance requirements or biomass decay become important as the biofilm gets thicker and substrate does not entirely penetrate the biofilm. These other process rates

Fig. 8. As biofilm thickness increases, beyond the depth of substrate (or oxygen) penetration, substrate (or oxygen) removal rate becomes independent of biofilm thickness.

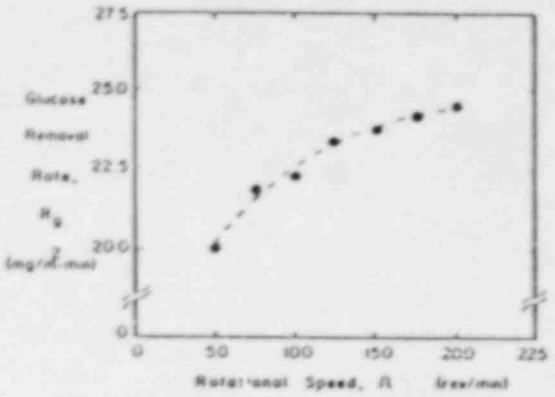


Fig. 9. Influence of rotational speed on glucose removal rate by a biofilm in an annular reactor (Rcf. 51). MR-18. L_f = 112 μm.

have not been measured and are critical for determining stoichiometric coefficients and predicting biofilm development rates.

The substrate removal rate is also dependent on fluid velocity (Fig. 9). At low fluid velocities, a relatively thick mass transfer boundary layer (δ_m) can cause a liquid phase diffusional resistance which decreases substrate concentration at the liquid–biofilm interface and thereby decreases substrate removal rate (Fig. 10).

A general mathematical model for microbial processes in a continuous stirred tank reactor (CSTR), based on material balances, is presented in Table IX. The model considers microbial activity in the bulk fluid as well as the reactor surfaces. Figure 11 is a diagrammatic representation of the model.

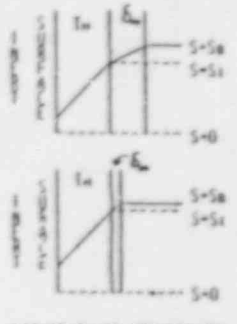


Fig. 10. The mass transfer boundary layer that decreases with increasing fluid velocity past the biofilm interface resulting in a higher effective substrate concentration at the biofilm–fluid interface (S_1).

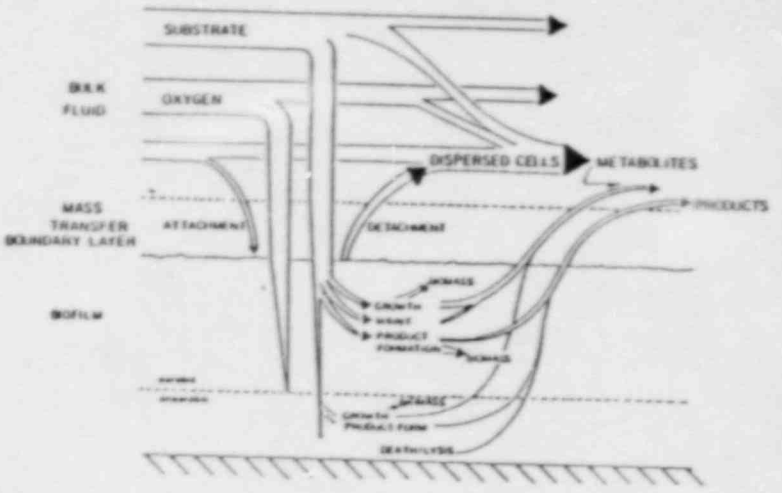


Fig. 11. Diagrammatic representation of the mathematical model for biofilm development described in Table IX.

TABLE IX

Mathematical Representation of Microbial Processes, Including Biofilm Formation, Occurring in a CSTR (see Fig. 11)

Substrate material balance

$$V\,ds/dt = Fs_i - sI - NA - (\mu - m)cVT_c$$

Suspended biomass material balance

$$Vdx/dt = Fx_i - xI + \mu xV - R_aA + R_{sa}A$$

Accumulation of biofilm

$$dB/dt = NAY_m - R_{sa}A + R_aA - R_dB$$

Accumulation of total reactor biomass

$$dM_t/dt = Vdx/dt + dB/dt = Fx_i - xI + \mu xV + NAY_m - R_dB$$

A = wetted surface area (length^2)
B = biofilm mass (M_m)
F = volumetric flow rate (length^3/time)
m = maintenance coefficient (time^{-1})
M_t = total reactor biomass (mass)
N = substrate flux into the biofilm (M/length^2 time)
R_a = rate of suspended biomass adsorption onto the biofilm (M/length^2 time)
R_{sa} = rate of biofilm detachment (M_m/length^2 time^{-1})
R_d = rate of biofilm decay (e.g., lysis, endogenous respiration) (time^{-1})
$s(x_i)$ = (input) substrate concentration (M/length^3)
t = time (time)
$x(x_i)$ = (input) suspended biomass concentration (M/length^3)
Y_m = yield coefficient for biofilm (M_m/M_s)
Y_c = yield coefficient for suspended biomass (M_c/M_s)
V = reactor volume (length^3)
μ = specific growth rate of suspended biomass (time^{-1})

Other questions of concern regarding microbial processes in the biofilm include the following:

1) Are the observed high biofilm yields in the early stages of biofilm development due to extracellular polymer production? What type of polymer predominates (polysaccharide, protein)? This point may be critical in assessment of biofouling control measures (e.g., chlorination) if they are to be used in the early stages of biofilm formation.

2) Is the Frank–Kamenetskii relationship[14] useful as a criterion for determining the "critical" biofilm thickness at which diffusion of oxygen in the biofilm becomes rate-limiting for substrate removal? When oxygen limitation occurs, do sulfate-reducing bacteria, strongly implicated in corrosion, become prominent?

3) Can an effectiveness factor model adequately describe substrate removal in a time-varying (i.e., dynamic) system? Can the parameters in the model be quantified?

4) Do biofilm transport properties (i.e., diffusion coefficient, rheological properties, thermal conductivity) and physical properties (density) change significantly as the biofilm develops?

Detachment of Biofilm

As the biofilm grows thicker, the fluid shear stress at the biofilm interface generally increases. Also, as biofilms grow thicker, the potential for substrate, oxygen, or nutrient limitation in the deeper portions is great. These limitations may weaken the biofilm matrix and cause detachment (Fig. 12). Trulear and Characklis[8] report that the biofilm detachment rate increases with increasing biofilm mass (Fig. 13). Trulear[51] also reports that detachment rate increases with fluid shear stress (Fig. 14).

Techniques for determining strength of adhesion and strength of deposit are necessary to further understanding of the detachment process. Other questions regarding detachment also arise including the following:

1) Is there detachment of cells from the surface simply as a result of cell reproduction, i.e., the daughter cells peel off into the fluid?

2) How is the strength of deposit affected by anaerobic layers deep in the biofilm?

3) How does detachment rate change with fluid shear stress and biofilm thickness? Can detachment rate (i.e., cells in suspension) be used to monitor biofilm accumulation? Under what circumstances?

4) How do biocides influence strength of deposit or detachment rate?

Overall Rate of Biofilm Development

In summary, biofilm development is the net result of several processes occurring in series and parallel (Fig. 15). The development of a biofilm is adequately described by a sigmoidal-shaped curve (Fig. 16). The slope

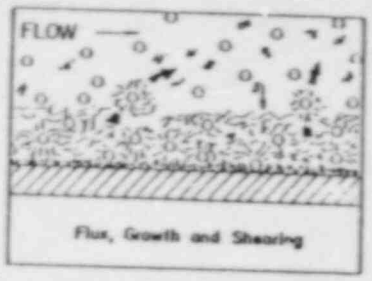


Fig. 12. Transport, adhesion, and growth increase the accumulated mass of the biofilm while detachment processes decrease the attached mass.

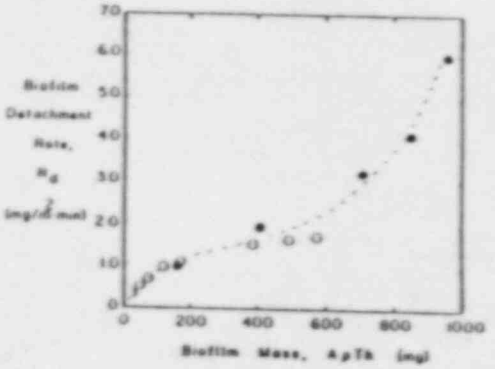


Fig. 13. Influence of biofilm mass on biofilm detachment rate at a constant fluid shear stress (Ref. 51). (●) AFR-23, (○) AFR-26.

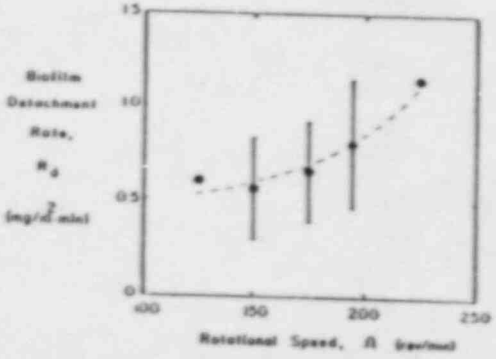


Fig. 14. Influence of fluid shear stress on biofilm detachment rate at a constant attached biomass (Ref. 51). Mass = 150–160 mg.

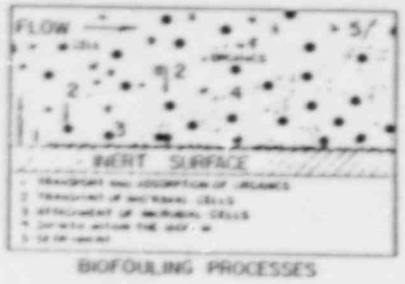


Fig. 15. A summary diagram of processes contributing to biofilm accumulation.

of this curve at a particular time is the *net biofilm development rate* and is also plotted in Figure 16. The rate increases to a maximum value corresponding to the sigmoidal inflection point and then decreases to zero. Net biofilm development rate is expressed as follows (Table IX):

$$dB/dt = \lambda A Y_n - R_{dt} A + R_a A - R_e B \qquad (1)$$

where $\lambda A Y_n$ is the attached biomass production rate and $R_{dt}A$ is the biofilm detachment rate. R_aA is the adsorption rate of cells, and R_eB is the endogenous respiration rate. At steady state, thickness remains constant.

The effect of fluid velocity on the plateau (or steady state) biofilm thickness is illustrated in Figure 17 for various substrate loadings. At high substrate loadings, increasing fluid velocity increases biofilm detachment rate which minimizes the plateau biofilm thickness. However, at low

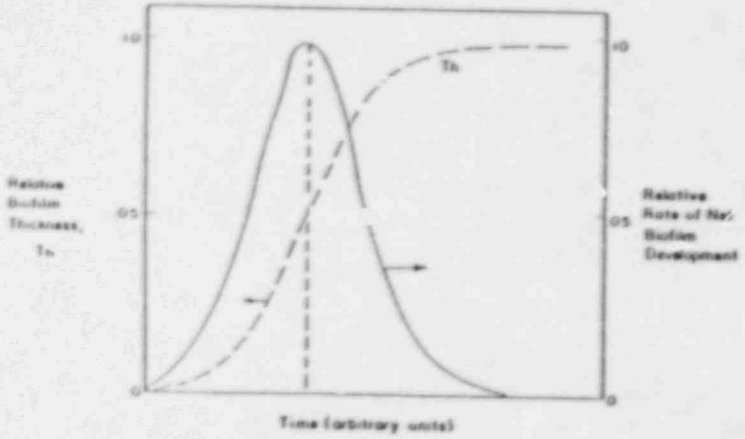


Fig. 16. Progression of net biofilm development is described by a sigmoidal-shaped curve. Net biofilm development rate is the slope of the sigmoidal-shaped curve at any time.

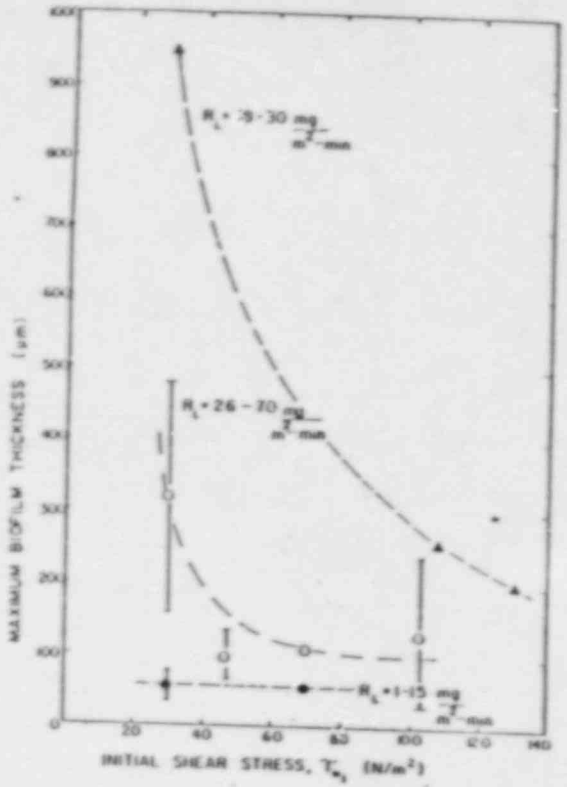


Fig. 17. Influence of fluid shear stress and substrate loading on plateau (or maximum) biofilm thickness (Ref. 2).

substrate loadings, fluid velocity seems to have no measurable effect on the plateau thickness. Trulear and Characklis[3] have demonstrated that plateau biofilm mass exhibits a maximum when fluid velocity is increased. At low fluid velocities, mass transfer limits the rate of biofilm production. Therefore, increasing fluid velocity increases substrate flux into the biofilm and net biofilm development rate increases. As fluid velocity continues to increase, biofilm detachment rate becomes the dominant process and net biofilm development begins to decrease.

EFFECTS OF BIOFILMS ON FLUID FRICTIONAL RESISTANCE

Increase in fluid frictional resistance due to biofilm accumulation when flow rate is maintained constant causes an increase in pressure drop and power requirements for pumping as shown in Figure 18.[2] Conversely, if pressure drop is held constant, flow capacity is reduced. Figure 19 in-

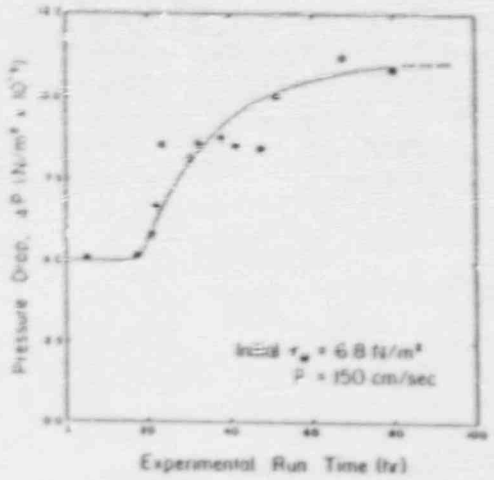


Fig. 18. Change in pressure drop with time due to biofilm formation. Experiment conducted at constant fluid velocity (Ref. 2).

dicates that flow capacity was reduced to 42% of the original capacity in a 100-h laboratory experiment.[2]

Frictional resistance can be represented by a dimensionless friction factor given by

$$f = 2.0 \frac{d}{L} \frac{\Delta p}{\rho_s V^2}$$

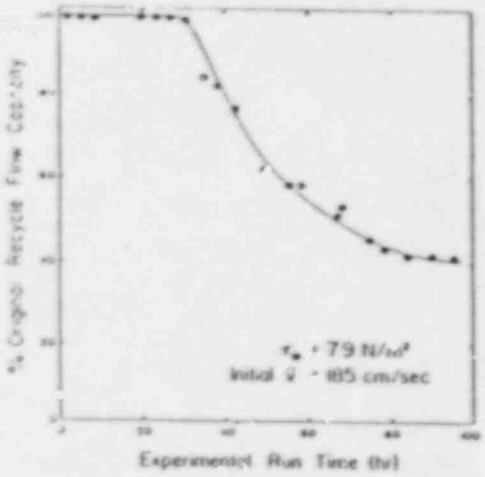


Fig. 19. Change in volumetric flow rate with time due to biofilm formation. Experiment was conducted at constant pressure drop (Ref. 2).

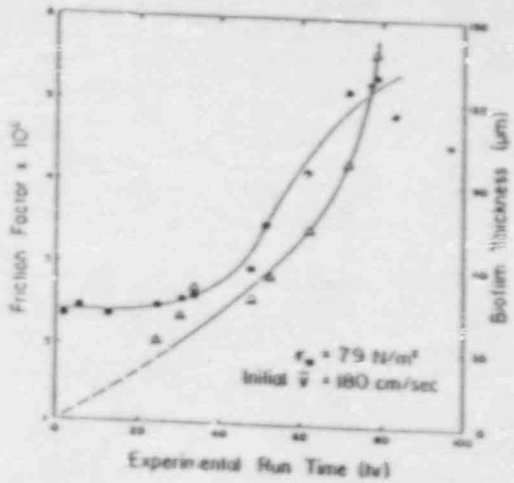


Fig. 20. Change in (•) friction factor and (△) biofilm thickness with time for an experiment conducted at constant pressure drop (Ref. 2).

where f = friction factor (dimensionless), d = tube diameter (length), ρ = fluid density (mass/length^3), $\bar{V}$ = average fluid velocity (length/time), Δp = pressure drop along length L (mass/length time^2), and L = length between pressure ports (length).

The change in friction factor and biofilm thickness with time is shown in Figure 20 for a laboratory tubular reactor. Dehart[52] has observed similar behavior in a tubular reactor in the field (Fig. 21).

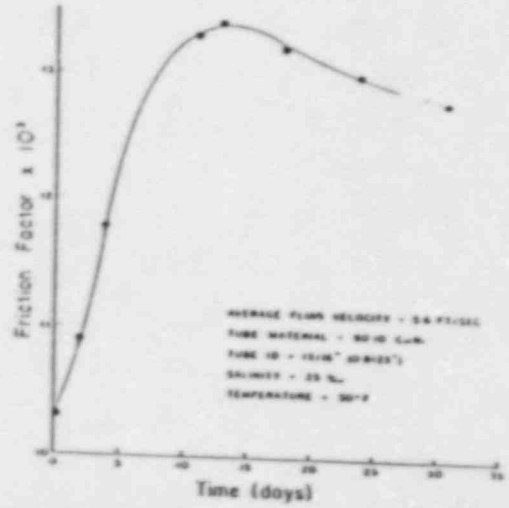


Fig. 21. Change in pressure drop due to biofilm formation at a field location (Ref. 52).

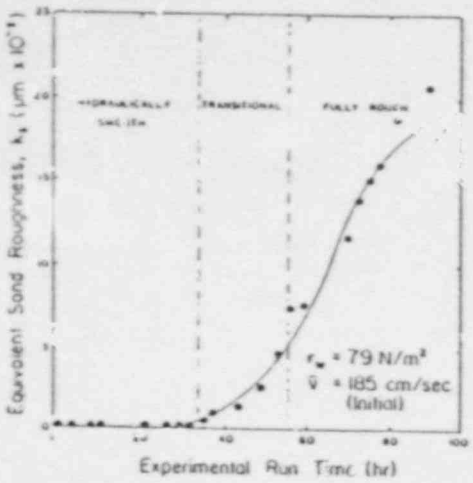


Fig. 22. Change in equivalent sand roughness with time due to biofilm formation. Experiment was conducted at constant pressure drop (Ref. 2).

The friction factor is related to the Reynolds number and the equivalent sand roughness k_s through the empirical Colebrook–White relation. This equation correlates friction factor to Reynolds number for various "commercially rough" pipes throughout the hydraulically smooth, transition and fully rough regimes. The Colebrook–White equation solved for the equivalent sand roughness k_s yields

$$k_s = \left(\frac{\varepsilon d}{3}\right) 10^{\left(\frac{1.14}{\sqrt{f}} - \left(\frac{18.76}{\mathrm{Re}\sqrt{f}}\right)\right)} \quad (3)$$

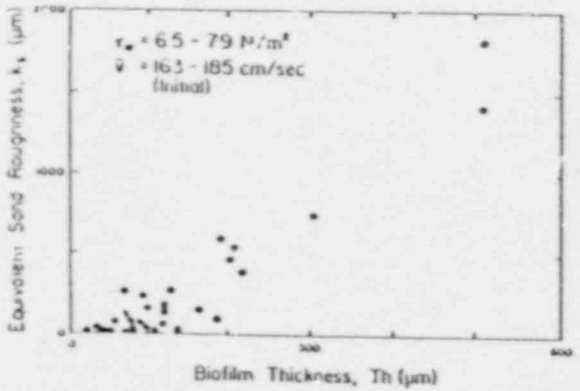


Fig. 23. Change in calculated equivalent sand roughness with biofilm thickness for several experiments conducted at constant pressure drop (Ref. 2).

where d = tube diameter (length), $\mathrm{Re} = \bar{V}d/\nu$ = Reynolds number (dimensionless), and ν = kinematic viscosity (length²/time). This expression can be used to compute an equivalent sand roughness for the biofilm from measurement of the flow rate and pressure drop. Figure 22 indicates the progression of k_s with time and Figure 23 presents the change in k_s with biofilm thickness for the range of shear stress investigated by Zelver.[2]

Determination of the flow regime (smooth, transitional, or fully rough) depends on the magnitude of k_s relative to the size of the viscous sublayer (δ_1):

$$\delta_1 = (10d/\mathrm{Re})\left(f^{1/2}\right) \quad (4)$$

More specifically, when $k_s < \delta_1$, the [illegible] considered hydraulically smooth; when $14\delta_1 > k_s > \delta_1$ the flow [illegible] transitional regime; when $k_s > 14\delta_1$ the flow is in the fully rough [illegible].

Frictional resistance of biofilms grown [illegible] constant pressure drop (i.e., constant shear stress) have been compared to the frictional resistance of pipes with a rigid roughness as given by the Colebrook–White equation. The following was observed:

1) Frictional resistance due to biofilms shows a similar dependency on Reynolds number as frictional resistance due to commercially rough pipe surface.

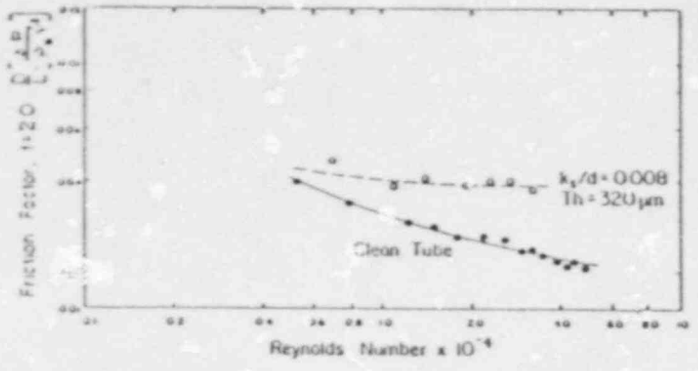
2) Frictional resistance is dependent on biofilm thickness.

3) Frictional resistance does not increase above the hydraulically smooth pipe value until a critical biofilm thickness is attained.

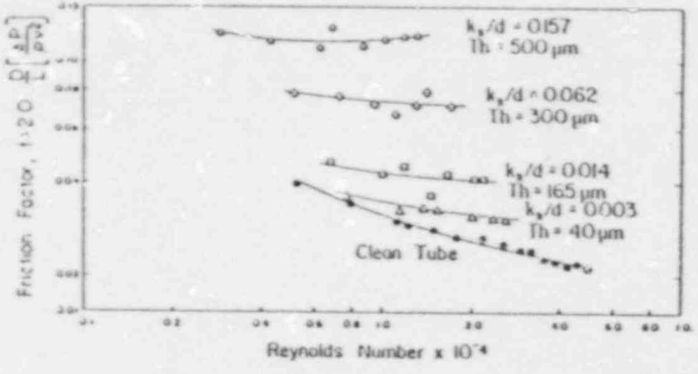
The Blasius–Stanton or Moody diagram[54] can be used to compare frictional resistance due to biofilm with frictional resistance of rigid rough surfaces. The Blasius–Stanton diagram is a plot of friction factor versus Reynolds number for a series of pipes with different equivalent sand roughness; the friction factor in a pipe with a rigid rough surface depends on both the relative roughness and the Reynolds number.

The relationship between friction factor and Reynolds number for a coiled circular tube is presented in Figure 24(a). The friction factors and Reynolds numbers presented have not been corrected for the pipe contribution resulting from the biofilm. This figure shows the dependency of friction factor on Reynolds number is the same as for a tube with a rigid rough surface within the range of Reynolds number investigated (8000–48,000). These data were obtained by reducing, in steps, the shear stress from its initial value in a given experiment and calculating friction factor and Reynolds number at each step. The shear stress was reduced from the initial condition to minimize detachment of biofilm during the experiment.

Figure 24(b) indicates the relationship between friction factor and Reynolds number within a single experiment at different stages of biofilm development; friction factor increases with biofilm thickness. The rela-



(a)



(b)

Fig. 24. Change in friction factor as function of Reynolds number and roughness due to biofilm formation: (b) at different stages of biofilm development (Ref. 23).

tionship between biofilm thickness and friction factor for all of Zelv experiments at a wall shear stress from 6.5 to 7.9 N/m² is shown in Fig 25. Friction factor is dependent on biofilm thickness after a critical thi ness (Th_c) approximately equal to the thickness of the viscous subla (δ_v) is attained.

Conceptually, Th_c corresponds to the stage of biofilm development which surface irregularities protrude through the viscous sublayer. U this stage, the biofilm lies completely within the viscous sublayer ($k_s < \delta_v$) and friction factor does not increase (the tube is hydraulically smoo For a wall shear stress of 6.5–7.9 N/m², the viscous sublayer is appr imately equal to 40 μm; this compares well with the observed Th_c = 30 μm for the same wall shear stress range.

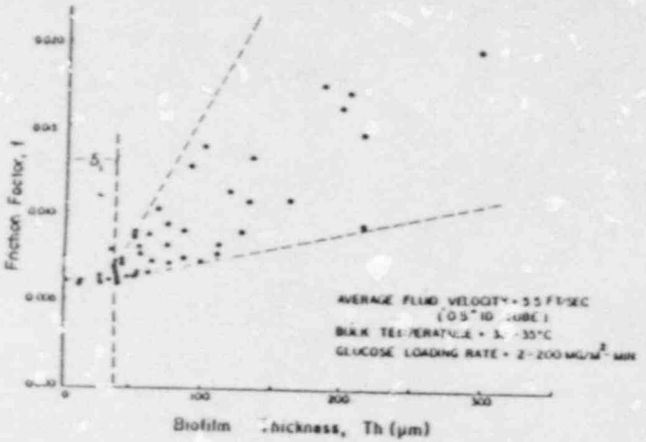


Fig. 25. Influence of biofilm thickness on friction factor in a circular tube 1.27 cm i.d. (cf. 23). Results of several experiments at widely varying glucose loading rates indicating viscous sublayer thickness.

Although the frictional resistance effects of biofilm can be adequately scribed by formulas and concepts suitable for rigid rough surfaces, the nclusion should not be drawn that indeed the biofilm presents a rigid ugh surface to the flow. Such a notion is an oversimplification and annot account for all experimental observations.[55]

Finally, frictional resistance measurements provide a relatively simple ethod for determining liquid mass transfer resistance in some biofilm stems since frictional resistance and liquid mass transfer resistance are lated.[56]

EFFECTS OF BIOFILM ON HEAT TRANSFER RESISTANCE

Biofilm development and resulting fluid frictional resistance have been scussed and both influence heat transfer. Changes in heat transfer re- stance arise from the combined effects of increased biofilm thickness nductive heat transfer) and increased frictional resistance (convective at transfer).

Conductive heat transfer can be related to biofilm thickness and its fective thermal conductivity. Experimental biofilm thermal conductiv- determinations indicate no significant difference from that of water at e same temperature (see Table IV). This is not surprising since biofilm approximately 98–99% water.

Convective heat transfer results from fluid mixing or motion and can related to momentum transfer or frictional resistance. Colburn[57] cor- lated convective heat transfer in tubes to friction factor and properties

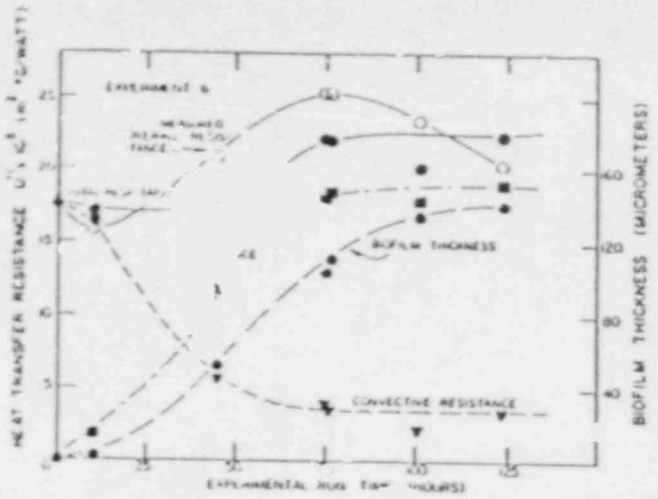


Fig. 26. Changes in convective and conductive heat transfer resistance as a result of biofilm development (Ref. 4).

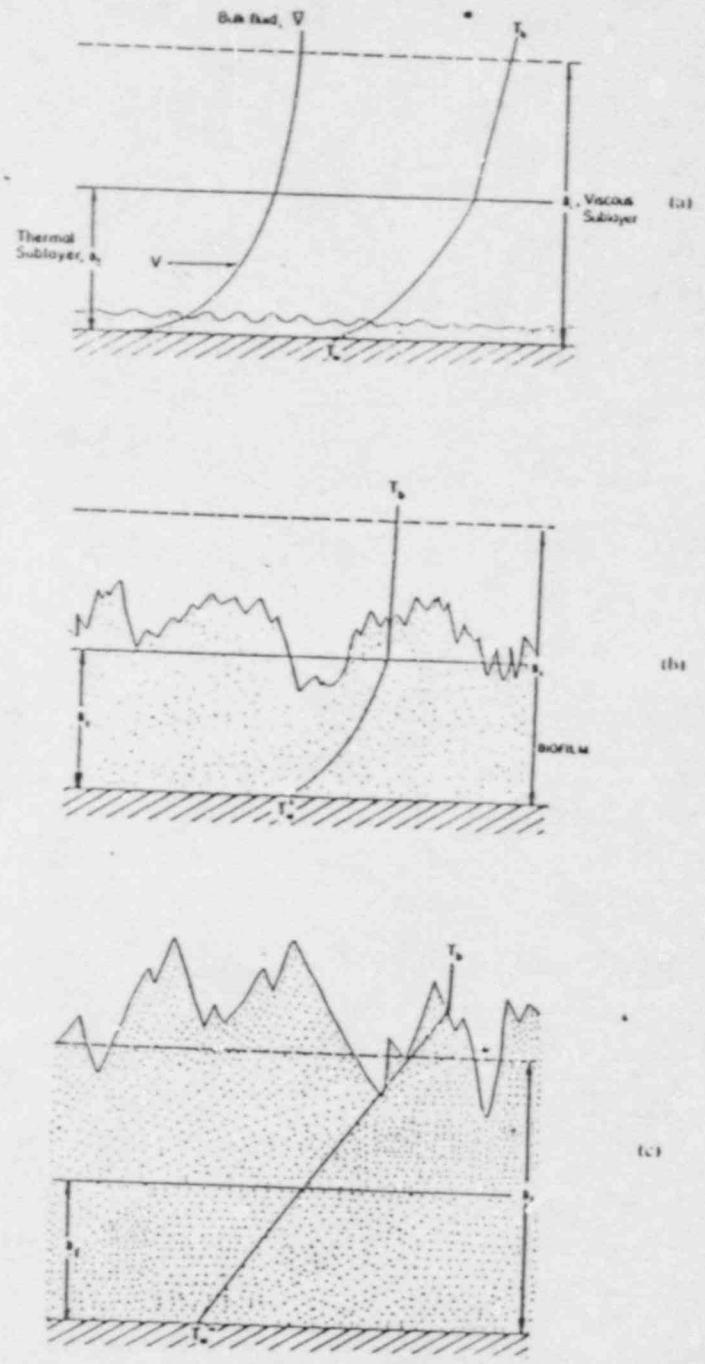
of the fluid. The Colburn relationship is only useful when the biofilm is thicker than the viscous sublayer.

Overall heat transfer resistance due to biofouling film development can then be calculated if the following are known: 1) biofilm thickness and biofilm thermal conductivity, 2) frictional resistance, and 3) wall temperature and bulk temperature.

Figure 26 describes a typical experiment conducted by Nimmons[4] in a tubular reactor and illustrates the relative effects of conductive and convective heat transfer resistance on overall heat transfer resistance.

Heat transfer resistance was consistently observed to decrease upon initial exposure to the fouling fluid in Nimmon's experiments. He hypothesized the following sequence of events to explain his observations. As a clean heat exchanger [Fig. 27(a)] is exposed to the fluid, a microlayer of organics and microbial cells forms. The conductive thermal resistance is relatively insignificant for a thickness of a few micrometers and the fouling layer remains within the viscous and thermal boundary layers. However, the biofilm layer produces a microroughness increasing convective heat transfer. Assuming the biofilm thermal conductivity is equal to that of water, the effect of the biofilm on conductive heat transfer would be equal to a stagnant water film of the same thickness. As long

Fig. 27. Hypothesized thermodynamic changes occurring near a heat transfer surface as biofilm develops. (a) Thin biofilm causes no changes in friction factor but "microroughness" decreases convective heat transfer resistance; (b) biofilm becomes thick enough to significantly influence conductive heat transfer but not friction factor; (c) biofilm is sufficiently thick to increase friction factor and Colburn relationship is valid.



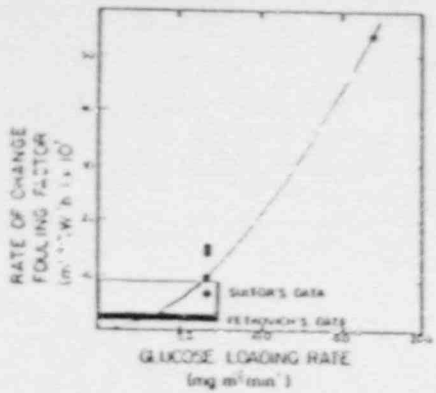


Fig. 28. Influence of substrate loading rate on heat transfer fouling factor (Ref. 4). The ranges measured by others are indicated for comparison (see Table X).

as the biofilm thickness is less than the viscous sublayer thickness, changes in convective heat transfer are not accompanied by changes in friction factor [Fig. 27(b)]. When the roughness elements are of sufficient height to project beyond the viscous sublayer and into the turbulent zone, an increase in friction factor and a further decrease in convective heat transfer resistance are observed. At this point the Colburn relationship may be used to determine the convective heat transfer coefficient [Fig. 27(c)]. Based on this hypothesis and his experimental data, Nimmons estimated the thermal boundary layer to be approximately 10–15 μm. The expected value is 22 μm. The viscous sublayer thickness calculated from hydrodynamic considerations was 44 μm as compared to 40 μm based on the observed onset of increased frictional resistance.

Nimmons computed the fouling factor R_f for his system and Figure 28 indicates its strong dependence on input substrate (glucose) concentration. Ranges of R_f measured in natural seawater systems are also included in Figure 28 for comparison purposes. Table X describes the experimental systems for Nimmons (data points), Ritter and Suitor,[58] and Fetkovich et al.[59] Neither carbon nor nutrient concentrations were determined in

TABLE X
Description of Experimental Systems for R_f Measurements Reported in Fig. 28

	Nimmons (Ref. 4)	Ritter and Suitor (Ref. 58)	Fetkovich et al. (Ref. 59)
Surface	Al 6061-T6	Titanium	Cupronickel
Surface temperature, (°C)	39–45	26–38	21
Fluid velocity (cm/s)	81	60–120	90–180

the latter two studies. However, carbon concentrations are estimated at between 0.5 and 10 mg/L.

Kirkpatrick, McIntire, and Characklis[60] have modeled the heat and mass transfer occurring in a heat exchange tube as a biofilm develops. In a typical heat exchanger, results indicate a significant decrease in heat transfer. For systems of interest, the biofilm is relatively uniform over the length of the heat exchange tube. In tubes with combined heat and mass transfer, the biofilm thickness varies appreciably with fluid temperature. The assumed relationships between temperature and biofilm development rates in their model have been partially verified by Stathopoulos.[61]

SUMMARY

Biofilm processes have been discussed in terms of the more fundamental physical, chemical, and biological processes which contribute to the biomass accumulation at a surface. The purpose was twofold:

1) to present a framework for analysis of the rate of biofilm development, extent of biofilm development, and influence of biofilms on energy losses;

2) to stimulate fundamental investigations on topics related to biofilm processes.

Biofilms are emerging as a most critical factor affecting natural aquatic systems, water distribution systems, wastewater treatment systems, heat exchangers, fuel consumption by ships, and even human disease. More attention must be directed to their behavior. Some topics that require more attention include the following:

1) Physical, chemical, and biological properties and structure of biofilms as a function of water quality and hydrodynamic characteristics.

2) Mathematical models relating process rates to bulk water concentrations, surface characteristics, and microbial species.

3) Population dynamics within the biofilm and its relationships to the microbial populations in the bulk water as well as water quality.

4) Methods to inhibit, control, or prevent biofilm accumulation which are compatible with environmental quality.

5) Methods to enhance biofilm accumulation and activity in terms of substrate removal for fixed-film wastewater treatment systems.

Numerous conversations with Dr. J. D. Bryers, Dr. W. Gujer, Dr. B. F. Picologlou, Dr. L. V. McIntyre, M. G. Trulear, and N. Zelver were helpful during the organization and preparation of this article. Dr. R. E. Baier provided helpful suggestions on aspects of molecular fouling. Conversations with Dr. W. A. Corpe and Dr. K. C. Marshall have provided valuable insight into microbiological aspects of the fouling process. Much of the

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References

1. J. W. Costerton, G. G. Geesey, and K. J. Cheng, *Sci. Am.*, **238**, 86 (1978).

2. N. Zelver, "Biofilm Development and Associated Energy Losses in Water Conduits," M.S. thesis, Rice University, Houston, TX, 1979.

3. M. G. Trulear and W. G. Characklis, "Dynamics of Biofilm Processes," in *34th Annual Purdue Industrial Waste Conference, West Lafayette, Indiana, May 8–10, 1979* (Ann Arbor Publishers, Ann Arbor, MI, 1979).

4. M. J. Nimmons, "Heat Transfer Effects in Turbulent Flow Due to Biofilm Development," M.S. thesis, Rice University, Houston, TX, 1979.

5. W. G. Characklis, "Biofilm Development and Destruction," Final Report, Electric Power Research Inst., No. RP 902-1, Palo Alto, CA, 1979.

6. W. G. Characklis, *Water Res.*, **7**, 1249 (1973).

7. J. V. Matson and W. G. Characklis, *Water Res.*, **10**, 877 (1976).

8. D. Herbert, *Symp. Soc. Gen. Microbiol.*, **11**, 391 (1961).

9. M. Schaechter, O. Maaloe, and N. O. Kjeldgaard, *J. Gen. Microbiol.*, **19**, 592 (1958).

10. J. G. Tomlinson and D. M. Snaddon, *Int. J. Air Water Pollut.*, **10**, 865 (1966).

11. J. A. Mueller, W. C. Boyle, and E. N. Lightfoot, *Proceeding of the 21st Annual Purdue Industrial Waste Conference* (Purdue University Press, West Lafayette, IN, 1966), pp. 962–985.

12. R. D. Bullod and W. C. Boyle, *J. San. Eng. Div., ASCE*, **96**, 525 (1970).

13. D. M. Pipes, "Variation in Glucose Diffusion Coefficient through Biological Floc," M.S. thesis, Rice University, Houston, TX, 1974.

14. K. J. Williamson and P. L. McCarty, "Verification Studies of the Biofilm Model for Bacterial Substrate Utilization," presented at Water Pollution Conference Federated Meeting, Cincinnati, OH, 1974.

15. J. V. Matson, "Diffusion through Microbial Aggregates," Ph.D. thesis, Rice University, Houston, TX, 1975.

16. R. C. Weast, Ed., *Handbook of Chemistry and Physics* (CRC, Cleveland, OH, 1973).

17. R. H. Perry and C. H. Chilton, Eds., *Chemical Engineers Handbook* (McGraw-Hill, New York, 1973).

18. Atomic Energy Commission, *Reactor Handbook* (U.S. GPO, Washington, D.C., 1955), Vol. 2, AECD-3646.

19. A. L. Pollard and H. F. House, *J. Power Div., ASCE*, **85**, 163 (1959).

20. A. J. Minkus, *J. New Engl. Water Works Assoc.*, **68**, (1954).

21. G. J. Arnold, *Eng. News Rec.*, **116**, 774 (1936).

22. M. R. Anderson, R. F. Vaccaro, and R. C. Toner, "A New Concept in Power Plant Operation to Control Slime Bacteria in Steam Electric Condenser Cooling Systems," presented at the Symposium on Biological Fouling in Power Plants, Johns Hopkins University, Baltimore, MD, 1976.

23. B. H. Kornegay and J. F. Andrews, *Characteristics and Kinetics of Biological Film Reactors* (U.S. GPO, Washington, D.C., 1967), final report, FWPCA, research grant No. WP-01181.

24. I. C. Gunsalus and R. Y. Stanier, *The Bacteria, Volume I* (Academic, New York, 1960).

25. J. D. Bryers, "Rates of Initial Biofouling in Turbulent Flow Systems," Ph.D. thesis, Rice University, Houston, TX, 1979.

26. J. D. Bryers and W. G. Characklis, "Measurement of Primary Biofilm Formation," in *Condenser Biofouling Control*, J. F. Garey, Ed. (Ann Arbor Science, Ann Arbor, MI, 1979), pp. 169–184.

27. K. C. Marshall, *Interfaces in Microbial Ecology* (Harvard U. P., Cambridge, MA, 1976).

28. W. A. Corpe, "Ecology of Microbial Attachment and Growth on Solid Surfaces," *Proceedings of the Microbiology of Power Plant Thermal Effluents*, R. M. Gerhold, Ed. (University of Iowa, Iowa City, IA, 1978), pp. 57–66.

29. J. W. Costerton, "The Mechanism of Primary Fouling of Submerged Surfaces by Bacteria," presented at Condenser Biofouling Control Symposium, Atlanta, GA, March 25–29, 1979.

30. H. C. Jones, I. L. Roth, and W. M. Sanders, *J. Bacteriol.*, **99**, 316 (1969).

31. D. H. Lister, "Corrosion Products in Power Generating Systems," presented at the International Conference on the Fouling of Heat Transfer Equipment, Rensselaer Polytechnic Institute, Troy, NY, 1979.

32. C. S. Lin, R. W. Moulton, and G. L. Putnam, *Ind. Eng. Chem.*, **45**, 636 (1953).

33. A. C. Wells and A. C. Chamberlain, *Br. J. Appl. Phys.*, **18**, 1793 (1967).

34. S. K. Friedlander and H. F. Johnstone, *Ind. Eng. Chem.*, **49**, 1151 (1957).

35. S. K. Beal, *Nucl. Sci. Eng.*, **40**, 1 (1970).

36. P. O. Rouhiainen and J. W. Stachiewicz, *J. Heat Transfer*, **92**, 169 (1970).

37. J. W. Cleaver and B. Yates, *Chem. Eng. Sci.*, **30**, 983 (1975).

38. J. W. Cleaver and B. Yates, *Chem. Eng. Sci.*, **31**, 147 (1976).

39. L. W. B. Browne, *Atmos. Environ.*, **8**, 801 (1974).

40. G. I. Loeb and R. A. Neihof, "Marine Conditioning Films," in *Applied Chemistry at Protein Interfaces, Adv. Chem. Ser. No. 145* (Am. Chem. Soc., Washington, D.C., 1975), pp. 319–335.

41. V. A. DePalma, D. W. Goupil, and C. K. Akers, "Field Demonstration of Rapid Microfouling in Model Heat Exchangers: Gulf of Mexico, November, 1978," presented at 6th OTEC Conference, Washington, D.C., 1979.

42. J. L. Brash and Q. M. Samak, *J. Colloid Interface Sci.*, to appear.

43. K. C. Marshall, R. Stout, and R. Mitchell, *J. Gen. Microbiol.*, **68**, 337 (1971).

44. C. E. Zobell, *J. Bacteriol.*, **46**, 39 (1943).

45. W. A. Corpe, *Dev. Ind. Microbiol.*, **11**, 402 (1970).

46. M. Fletcher, *Can. J. Microbiol.*, **23**, 1 (1970).

47. S. C. Dexter, "Influence of Substrate Wettability on the Formation of Bacterial Slime Films on Solid Surfaces Immersed in Natural Sea Water," Proceedings of 4th International Congress on Marine Corruption and Fouling, Juan-les-Pins, Antibes, France, 1976.

48. M. Fletcher and G. I. Loeb, *Appl. Environ. Microbiol.*, **37**, 67 (1979).

49. J. Garey, Marine Research, Inc., Sandwich, MA, personal communication, 1979.

50. E. J. LaMotta, "Evaluation of Diffusional Resistances in Substrate Utilization by Biological Films," Ph.D. thesis, University of North Carolina, Chapel Hill, NC, 1974.

51. M. G. Trulear, "Rate of Biofilm Development in a Turbulent Flow Field," M.S. thesis, Rice University, Houston, TX, 1979.

52. R. Dehart, Marine Research, Inc., Sandwich, MA, personal communication, 1979.

53. H. Schlichting, *Boundary Layer Theory* (McGraw-Hill, New York, 1968).

54. L. F. Moody, *Trans. Am. Soc. Mech. Eng.*, **66**, 671 (1944).

55. B. F. Picologlou, N. Zelver, and W. G. Characklis, *J. Hydraul. Div. ASCE*, **106**, 733 (1979).

56. T. K. Sherwood, R. L. Pigford, and C. R. Wilkie, *Mass Transfer* (McGraw-Hill, New York, 1975).

57. A. F. Colburn, *Trans. AIChE*, **29**, 174 (1933).

58. R. B. Ritter, J. W. Suitor, and G. A. Cypher, "Thermal Fouling Rates of 90-10 Copper-Nickel and Titanium in Seawater Service," report to INCRA, HTRI, Alhambra, CA, 1977.

59. J. G. Fetkovich, G. N. Granneman, L. M. Mahalingam, and D. L. Meier, "Meas-

[illegible] of Bonding in OTEC Heat Exchangers [illegible] Miami Beach, FL, 1978.
(50) T. P. Kirkpatrick, L. V. McIntire and W. G. [illegible], [illegible] 14, [illegible] (1980).
(51) N. [illegible] Stathopoulos, "Influence of Temperature on Biofilm Processes," M.S. Thesis, Rice University, Houston, TX, 1981.

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PAPER NUMBER

Ex. E

The International Corrosion Forum Sponsored by the National Association of Corrosion Engineers / March 22-26, 1982 / Albert Thomas Convention Center, Houston, Texas

MICROBIAL FACILITATION OF CORROSION

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ABSTRACT

Newly developed sensitive biochemical methods make possible the quantitative study of microbes that facilitate corrosion. At least 3 mechanisms for facilitation of corrosion can now be examined. The uneven distribution of microbes and their extracellular polymers can create concentration cells that differ in cathodic activity. The metabolic activities of aerobic microbes can create anaerobic niches in highly aerobic environments and from these niches organic acids can be generated by the activities of fermentative bacteria. In the presence of sulfate or organic sulfate esters, the oxidation of organic acids can lead to generation of hydrogen sulfide by the sulfate reducing anaerobes. Hydrogen sulfide is capable of cathodic depolarization and of oxidation by aerobic Thiobacteria with the formation of sulfuric acid. The detection and validation of "signature" lipids in these microbes can now allow the use of ^{13}C enrichment

experiments which can provide correlation between corrosion rates and specific microbial activities so that more rational countermeasures can be developed as has been begun for the microfouling community and the problems of heat transfer efficiency.

INTRODUCTION

With the increasing necessity to recycle both fresh and saltwater, problems of microfouling and subsequent microbially facilitated corrosion become more important. Not only do microbial films increase resistance to efficient heat transfer, increase the resistance to fluid flow and provide the conditions for facilitation of corrosion, but they may provide the ideal growth conditions for the dissemination of the human pathogen Legionella. Simple antifouling treatments with biocides are increasingly expensive and potentially damaging to the environment so research towards a new strategy to interdict microfouling led to the development and validation of biochemical methods by which the biomass and community structure of the microbial films could be examined. These methods can now be applied to increase the basic understanding of microbial corrosion facilitation.

Microbes can facilitate or initiate corrosion by their activities by at least three mechanisms. Concentration cells differing in cathodic activity can be generated by the uneven distribution of microbial and extracellular biomass and community compositon. Microbes can generate corrosive metabolites such as the organic acids that are important in the weathering process by which soils are replenished or by the generation of mineral acids under the proper

conditions of growth. The sulfate reducing bacteria generate hydrogen sulfide with subsequent cathodic depolarization and metalic sulfide formation.

With newly developed methodology for "signature" lipids of various physiological groups of organisms, the microbial ecology of these organisms can be studied to provide a rationale for countermeasures.

EXPERIMENTAL PROCEDURE

A flow diagram of the experimental procedures utilized in the study of microbial fouling and corrosion is illustrated in Figure 1.

Patchy distribution

A coupon of the exposed surface is recovered and stained with aqueous acridine orange. The acridine orange is then washed off and the relative distribution of intensity of fluorescence measured with an epifluorescent microfluorimeter can give a quantitative estimate of the patchiness as the specimen is moved across the microscope stage (1). Other coupons can be fixed with glutaraldehyde, dehydrated, coated and examined by scanning electron microscopy (2). A typical micrograph of the fouling community developing on titanium exposed to seawater is shown in Figure 2.

Lipid extraction

The samples are extracted by the one phase Bligh and Dyer method and after inducing phase separation the lipids are recovered from the organic phase (2). The residue remaining after extraction is removed from the surface by abrasion and analyzed after acid hydrolysis. The aqueous portion of the lipid extraction is also analyzed for the adenine nucleotides as illustrated in Figure 1.

Ex. F

TITLE: Effect of Biofilm Growth on Hydraulic Performance

KEY WORDS: Biofouling; Frictional resistance; Hydraulic Energy Losses; Microbial Films, Pipelines, Slime Layers, Wall Roughness, Water Supply

ABSTRACT: An experimental investigation of the deleterious effect of microbial slime layers on the hydraulic performance of water conduits is presented. The underlying mechanisms that lead to an increase of frictional losses in the conduit are explored and their relative importance is discussed. It is shown that although the slime layer is viscoelastic and filamentous, its effect on frictional resistance can be adequately represented through an increase in rigid equivalent sand roughness of the conduit wall.

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Effect of Biofilm Growth on Hydraulic Performance

By B. F. Picologlou,[1] N. Zelver,[2] and W. G. Characklis[3]

INTRODUCTION

Biofouling in water conduits causes pronounced increases in fluid frictional resistance. The resulting energy losses are of major concern to the water supply and power industries.

Biofouling is a general term referring to undesirable effects due to attachment of microorganisms at liquid-solid interfaces. The microorganisms produce a polysaccharide slime layer (5,6,8) which, when formed on the inside surface of water conduits, increases frictional resistance in flow systems resulting in energy losses or losses in pipeline capacity.

Deterioration of pipeline capacity attributed to biofilm development can be substantial. Seifert and Kruger (14) report a 55% reduction of original capacity in a 50 mile (80 km) long water supply pipeline 23.62 inches (60 cm) ID due to a thin slimy layer approximately 0.026 inches (650 μm) thick. Table 1 documents other case histories of biofouling in water supply lines (3).

Biofouling is not limited to microbial activity. The term includes the interaction of the microorganisms and the slime layer with both the chemistry of the solid surface and the bulk

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TABLE 1. Data Summary from Case Histories of Closed Conduits Experiencing Frictional Losses Due to Biofilms

Reduction in Design Flow Capacity (1)	Biofilm Thickness (micrometers) (2)	Conduit Diameter (centimeters) (3)	Conduit Length (kilometers) (4)	Conduit Surface (5)	Reference (6)
12% in 2 years	800	105	13	Cement	(9)
23%	1600	90	13	Concrete	(9)
16% in 3 weeks	3000	90	41	Steel	(1)
55% in 3 years	635	60	93	Steel	(15)
3.5% in 1 year	-	36	2.5	Steel	(7)

Note: 1 micrometer = 3.94×10^{-5} inches
1 centimeter = .3937 inches
1 kilometer = .6215 miles

fluid. These interactions can enhance some of the more commonly known fouling phenomena such as precipitation or crystallization (scaling) and corrosion. In these latter cases, the wall layer attains a much more rigid structure and the pronounced increase in frictional resistance can be successfully explained by the increase in the equivalent sand roughness of the pipe wall. In the case of microbial slime layers, the situation is more complex. The thickness and morphology of the slime layers are functions of the operating conditions. A change in operating conditions, such as an increase in wall shear stress, can cause significant changes in the morphology and thickness of the biofilm, thus changing the value of the equivalent sand roughness. In addition, the viscoelastic nature of the slime layer and its filamentous morphology suggest that perhaps additional dissipation mechanisms contribute significantly to the increased frictional resistance. Consequently, description of the biofilm effect by a unique value of equivalent sand roughness may be inadequate over the entire range of the operating conditions.

The purpose of this study is to explore some of these possibilities. This paper will only be concerned with microbial slime layers and, therefore, the term biofouling will be used for microbial fouling and the term biofilm for the microbial slime layer.

EXPERIMENTAL METHODS

Only the salient features of the system employed are given here. For additional information, see references (16) and (4).

The experimental system was designed so that important

Ex. G

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CHAPTER 48

Control of Microbial Fouling in Circular Tubes with Chlorine

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Microbial fouling is a major cause of energy loss in water pipelines, heat exchangers, and power-plant condensers. Chemical control is usually by chlorine addition. New restrictions on effluent chlorine residuals require that chlorine be added judiciously. The work described is the basis for a methodology to determine optimum chlorine dosing rates for fouling control. Tubular reactor experiments were conducted for turbulent conditions (Reynolds number 13,000-19,000). Microbial film thickness (T) was monitored by electrical conductivity (±2.5 μm) and correlated well with increases in frictional resistance measured by pressure drop (Δp). Observed Δp was significantly higher than predicted based on reduction of cross-sectional area available for flow, and Δp increases of 200% were observed for T>100 μm. Chlorine addition caused partial film removal with consequent increases in effluent particulates. A mathematical description of microbial film growth and its control by chlorine is offered.

INTRODUCTION

Microbial fouling is a major cause of energy losses in water pipelines and heat exchangers. Thin microbial films attach to the inside of water conduits causing large increases in both fluid frictional and heat transfer resistance. Characklis (1973a,b) and Norrman (1976) reviewed the literature concerning the effects of fouling on frictional resistance. Chlorine generally is used for controlling microbial fouling in such systems. However, both economic considerations and increasingly stringent environmental regulations require a systematic understanding of microbial fouling, its effects, and methods of control. This paper describes research directed toward the following objectives:

1. Development of a suitable apparatus for experimental determination of frictional resistance as a function of film thickness.
2. Determination of the dependence of frictional resistance on film thickness and flow rate.
3. Determination of the effect of varying chlorine application rates on film thickness and frictional resistance.
4. Development of mathematical models describing both film growth and film destruction by chlorine.

MATERIALS AND METHODS

System description. A tubular reactor was used for reasons of dynamic similarity to full-scale systems. Figure 1 is a schematic diagram of the experimental apparatus. Two loops permitted simultaneous experiments at different flow rates. Each loop contained a rotameter and separate sections for film thickness, film density, and pressure drop measurements. The entire system, including test sections (Fig. 2), was acrylic tubing (1.27 cm I.D.) roughened to promote microbial attachment. The tubular reactors were operated on a once-through basis during chlorine addition.