Executive Summary

R&D Opportunities in Gas-Side Fouling

February 1984

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ABSTRACT

This report provides an overview of five research reports that were generated for the Fouling and Corrosion Program. In addition, a listing of research and development opportunities in gas-side fouling is provided. R&D opportunities are designated as technology transfer, basic research, or applied research opportunities.

1.0 INTRODUCTION

The objectives of this report are to summarize the findings of the Fouling and Corrosion Program and to provide a listing and discussion of research and development (R&D) opportunities in gas-side fouling. The R&D opportunities are discussed in Section 2.0. Section 3.0 presents the major conclusions from the five research reports prepared for this program.

The purpose of the Fouling and Corrosion Program was to develop background information for the U.S. Department of Energy (DOE), Office of Industrial Programs (OIP) to assist them in planning a long-term, generic research and development program on fouling of industrial heat exchangers at low temperatures. Corrosion was to be addressed only to the extent that it causes, occurs as a result of, or occurs synergistically with fouling.

This effort was divided into five major tasks:

- The characterization of industrial fouling,
- An economic assessment of fouling,
- Review of prevention and mitigation techniques,
- The compilation of a data base, and
- Identification of R&D opportunities.

In addition to the Pacific Northwest Laboratory (PNL), the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech), and ten nationally-recognized consultants contributed to these tasks. Four research reports in addition to this one were generated for this effort. Two were written by PNL, one by JPL and one by Caltech.

The four research reports are:

- Industrial Fouling: Problem Characterization, Economic Assessment, and Review of Prevention, Mitigation, and Accommodation Techniques (PNL-4883).
- Proceedings of the PNL Fouling and Corrosion Workshop (PNL-SA-12014)
- Particulate Fouling of Heat Transfer Surfaces (JPL D-1055 - Caltech)
- A Survey of Gas-Side Fouling in Industrial Heat-Transfer Equipment (JPL D-1054)

Each of these reports addresses a segment of our objectives. The matrix shown in Figure 1.1 identifies which tasks are addressed by each of the reports. The characterization of fouling, costs and mitigation techniques is primarily addressed by PNL-4883, with supplementary information provided by the other reports. For example, JPL D-1055 provides an in-depth look at particulate fouling, which is the dominant type of fouling on the gas side. A final report, documenting the structure of the data base and how it can be used, will be prepared at a later date. The R&D recommendations are addressed in detail in this report and supplementary information is provided in PNL-4883, PNL-12014, JPL D-1055 and JPL D-1054. Each of the reports is described in more detail in section 3.0 along with a discussion of the status of data base development.

		TOPICS				
REPORT NUMBER		CHARACTERIZATION OF FOULING	ECONOMIC ASSESSMENT	REVIEW OF PREVENTION AND MITIGATION TECHNIQUES	FOULING DATA BASE	IDENTIFICATION OF R&D OPPORTUNITIES
	PNL-4883	•	•	•		•
	PNL-SA-12014	•		•	•	•
	JPL D-1055	•				•
	JPL D-1054		•	•		•

FIGURE 1.1. Matrix of Project Tasks and Reports

2.0 RESEARCH OPPORTUNITIES IN GAS-SIDE FOULING

Research conducted over the past twenty years has contributed to the understanding of the types and mechanisms of fouling. However, for the most part, it has not resulted in significant and reliable means of predicting and mitigating fouling.

Most of the fouling research conducted to date has been directed toward liquid-side fouling problems, with much less attention given to gas-side fouling. Reported research primarily deals with the electric utility industry, with relatively little published data addressing problems in the manufacturing industries. Escalating fuel prices and decreasing availability of some fuels have resulted in increased interest in waste heat recovery from exhaust gases and in fuel switching to less costly, lower-quality fuels. Both of these trends have increased the importance of understanding the basic mechanisms of gas-side fouling and also the practical approaches that can be used to mitigate gas-side fouling.

PNL estimated that fouling costs the U.S. industrial sector between \$3.8 and \$7 billion annually⁽¹⁾. Of this total, between one and four billion dollars per year are estimated to be due to gas-side fouling⁽⁷⁾. With about 25% attributable to energy losses, including the additional heat that must be supplied to overcome increased resistance to heat transfer, the additional pumping or fan power required due to restricted flow areas, and the opportunity cost of not recovering waste heat due to potential fouling problems. The energy penalty associated with fouling is significant in the aggregate; however, many types of fouling research will never be undertaken by industry because of the relatively high costs with respect to the individual benefits. Industry typically concentrates its research efforts on process-side problems rather than gas-side or water-side problems. Solution of the process-side problems yields concentrated benefits to a particular industry. Many fouling problems associated with the gases and liquids on the nonprocess sides of heat exchangers are common to broad segments of industry. Solution of these problems could yield widespread benefits in terms of more efficient energy utilization by the industrial sector.

Since the high associated risks (technical and economic) involved in fouling research are perceived to be too great for any one company to undertake, a government role in fouling research is warranted.

PNL identified potential research and development (R&D) opportunities by assessing information from previous fouling workshops, conferences, and meetings, by contacting cognizant personnel in industry and academia, and by holding a workshop to clarify industrial fouling problems, mitigation strategies, and research needs. For the purposes of this discussion, research opportunities are classified as technology transfer, applied research or basic research opportunities. Technology transfer opportunities applicable to gas-side fouling are discussed first. Next, the research opportunities (both basic and applied) in gas-side fouling are discussed separately. Although the literature contains information on process-side research needs, these will not be discussed here since they are most appropriately dealt with by the private sector.

2.1 TECHNOLOGY TRANSFER OPPORTUNITIES

The major technology transfer opportunities for the near-term are:

1. Development of a comprehensive fouling data base,
2. Establishment of a fouling advisory committee,
3. Case studies of deposit cleaning techniques, and
4. Development of a generic fouling model.

2.1.1 Development of a Fouling Data Base

The available data on fouling of industrial heat-transfer equipment is spread among many sources and is in various forms. Access and use of this data is therefore difficult, and this situation is believed to be significantly retarding development of better understanding and solution of industrial fouling and corrosion problems, particularly since it decreases the usefulness of the data to designers. Many designers have neither the time nor the facilities to search the published literature for quantitative data. To remedy this perceived deficiency, PNL is in the process of building a computerized fouling data base for the U.S. Department of Energy. Since PNL is a national laboratory, the data base will be in the public domain.

Numerous workshops on fouling have recognized the need for a centralized storehouse of fouling data^(2,3,4). All of our consultants have emphasized the value of a computerized data base and the appropriateness of government funding such an effort. We have been encouraged to make a long-term commitment to designing, managing, and updating the data base to assure its usefulness to engineers, scientists, and researchers concerned with fouling.

Feedback from industry is of crucial importance in the evaluation of the data base. Key design engineers and heat-exchanger users have been asked to evaluate the data base from the standpoint of its utility in allowing the determination of more accurate fouling resistances.

PNL has developed two major data files to compile the fouling and corrosion data:

- (1) A comprehensive technical data file of quantitative and qualitative data on plant equipment, probe characteristics, heat exchanger geometry, substrate material, deposit-side thermal details, other-side thermal details, overall thermal details, fuel and fluid additives, service history, deposit information, and deposit-side fluid characteristics.
- (2) A bibliography/abstract file of bibliographic information about the documents and authors, keywords, and abstracts summarizing the documents.

The two files will be loaded into three separate data bases:

- (1) The technical data base containing the technical data file expressed in English units.
- (2) The technical data base containing the same technical data file, but expressed in SI units.
- (3) The bibliography/abstract data base containing the bibliographic and abstract file.

The data bases will be documented by a User's Guide defining the structure and content of the data fields in the files and explaining how to access and query the three data bases using the System 2000 Data Base Management System (DBMS). The System 2000 DBMS is a software package sold by INTEL Corporation. It is installed on many large-scale IBM, CDC, Amdahl, and UNIVAC computers. Users will be able to selectively retrieve data in an online or batch mode, based upon single or multiple selection criteria (e.g., type of fouling, deposit-side fluid type, equipment type, etc.) to satisfy their specific needs. This can be accomplished by using simple English-like commands from the System 2000 DBMS.

2.1.2 Fouling Advisory Committee

It has been recommended that an advisory committee be established to assist in the development of a fouling research program^(3,5). The ongoing committee would consist of participants from industry, government, universities and national laboratories. The committee would provide (1) a vehicle for the exchange of ideas between the private sector and the Department of Energy (DOE) on the appropriate direction and scope of a fouling research program, (2) the means of discerning what the private sector perceives are the research priorities in fouling and what research efforts are currently being funded in the private sector, and (3) a means of making the private sector aware of the research undertaken by DOE in this area. The committee would be in a position to help identify possible joint ventures between the government and the private sector.

2.1.3 Case Studies of Deposit Cleaning Techniques

Little information is available on the relative effectiveness of currently available cleaning chemicals and devices in given applications. Plant visits should be undertaken and case histories should be prepared to detail the benefits and costs associated with the application of particular cleaning techniques (both chemical and mechanical). Case studies should include conventional ones such as air and water sootblowing and water washing, as well as sonic sootblowing, electrostatic cleaning, and other selected mechanical and thermal techniques.

Information gathered for the case studies should be presented in a consistent format and should include the following types of information: description of the cleaning technology, discussion of the application, equipment diagrams or photographs, plant modifications required to adopt the technique, capital cost, operating cost, and effectiveness. This information would provide plant managers with a basis for selecting deposit cleaning techniques.

2.1.4 Generic Fouling Model

In some cases, the theoretical understanding of the individual steps within the fouling process (deposition, adhesion, removal) exceeds that reflected in existing fouling models. Development of a generic fouling model(s) which reflects the state of the art of fouling knowledge will help to bridge the gap between theory and current engineering practice. A generic fouling model(s) would provide an important technology transfer vehicle for systematically

making use of the information in the fouling data base.

2.2 APPLIED RESEARCH OPPORTUNITIES

Applied research opportunities can be categorized as follows:

- Data Collection
- Heat Exchanger Design
- Additives and Cleaning Products (chemical and mechanical)

Applied research opportunities in gas-side fouling are summarized in Table 2.1. Most of the applied research in gas-side fouling undertaken to date has centered on central-station utilities burning either coal or oil in high-pressure boilers. This data is not necessarily relevant to gas-side fouling of industrial boilers and furnaces. Thus, research is needed to investigate the characteristics of gas-side fouling as it occurs within the range of industrial operating conditions.

2.2.1 Data Collection

This section discusses opportunities for research and development that are related to the collection of empirical data in industrial settings.

2.2.1.1 Develop Gas-Side Fouling Measurement Device

Before gas-side fouling data is collected in industrial settings, there is strong sentiment that a standardized fouling measurement device (e.g., a probe or test section) should be developed to allow for standardization and comparison of data collected from different gas streams. A survey of gas-side fouling measuring devices has been conducted which reviews about 25 different devices that have been developed and used to date⁽⁸⁾. Results from this survey should facilitate selection or development of a standardized probe.

Suggested conceptual design criteria for a gas-side fouling probe include: (1) the probe should be cylindrical, (2) it should be simple, robust, lightweight, and inexpensive, (3) it should be capable of monitoring online gas-side fouling resistances, (4) it should be capable of testing several different materials simultaneously for corrosion effects, and (5) it should have a reliable temperature control system⁽⁷⁾. In addition, a standardized method of collecting, analyzing and reporting the data should be formulated. We recommend a standardized format similar to the current format of the PNL fouling data base.

TABLE 2.1. Opportunities for Applied Research in Gas-Side Fouling

DATA COLLECTION:

1. Develop gas-side fouling measurement device.
2. Collect empirical data in industrial settings^(5,7,8).
3. Develop gas-side fouling factors^(2,7).
4. Survey instrumentation practices^(1,3).

HEAT EXCHANGER DESIGN:

1. Quantify effects of typical and advanced heat exchanger configurations on gas-side fouling^(1,4,5).
2. Develop alternative heat exchanger configurations with enhanced heat transfer and low fouling potential⁽⁵⁾.
3. Investigate alternative surface materials and coatings for the following^(4,5,7):
 - low-temperature waste heat recovery
 - corrosive streams at intermediate temperatures
 - high-temperature applications
4. Investigate the impact of current fabrication techniques on subsequent fouling⁽¹⁾.

ADDITIVES AND CLEANING PRODUCTS:

1. Test alternative cleaning chemicals, additives, and equipment^(4,7).
2. Test combinations of control approaches for acid dew-point corrosion⁽⁷⁾.

2.2.1.2 Collect Empirical Data in Industry

Empirical data need to be collected in industrial settings which reflect startup, shutdown, and alternative operating conditions as well as normal, steady-state operating conditions. Basic data are needed for typical heat exchanger geometries, burner designs and operating conditions that are encountered in industry today in order to provide a baseline for comparing alternative, improved designs or operating practices.

2.2.1.3 Develop Gas-Side Fouling Factors

Gas-side fouling factors for design purposes are virtually non-existent. Except for gas turbine and diesel engine exhausts, most of the fouling factors used today were developed by trial and error rather than with actual data. In cases where gas-side fouling factors are available, there are notable differences in data from different sources. There are many applications, for example, in the cement, aluminum and pulp and paper industries, where gas-side fouling factors simply do not exist. Studies should be carried out using specific geometries in typical industrial gas streams to obtain experimental, transient gas-side fouling factors. These data should be obtained as a function of gas composition, gas temperature, surface temperature, and gas velocity.

2.2.1.4 Survey Instrumentation Practices

Instrumenting heat-transfer equipment can provide a reliable means of determining the extent of fouling in operating exchangers. This would facilitate the collection of time-dependent data in industrial settings and would provide information needed to optimize cleaning cycles. Such data would also facilitate comparison with data from a standard measuring device. Such a comparison is essential to the development of practical predictive methods. Online control of fouling problems should be pursued through investigation of feedback control systems for automated deposit removal. For example, automated sootblowers might be developed to be able to sense the onset of significant deposit accumulation and act to keep surfaces clean enough to promote particle bounce⁽⁹⁾. Currently, it is not a widespread practice in industry to fully monitor heat exchangers. A survey of instrumentation practices currently used with heat exchangers should be conducted. Alternative instrumentation practices used in other applications should be investigated for their applicability to heat exchanger monitoring.

2.2.2 Heat Exchanger Design

This section discusses opportunities for applied research related to heat exchanger design and fabrication.

2.2.2.1 Quantify Effects of Heat Exchanger Configuration

A number of research opportunities have been reported in the area of heat exchanger design. One of these is to investigate the effect of currently used and conceptual heat exchanger geometries on fouling.

2.2.2.2 Develop Alternative Heat Exchangers

Once the baseline has been established, alternative heat exchanger configurations with both enhanced heat-transfer capability and reduced fouling potential need to be developed and tested. These may include:

- Advanced waste heat boiler designs
- Low-finned tube designs
- Fluidized beds
- Heat pipes
- Jet impingement devices⁽⁵⁾.

2.2.2.3 Alternative Surface Materials and Coatings

The effectiveness of alternative surface materials and coatings in mitigating fouling both at low temperature and high temperature needs to be investigated. One of the major problems in low-temperature heat recovery is that of gas-side fouling and corrosion associated with acid dew-point condensation. Suitable materials and coatings are needed to prevent these corrosion problems. Waste heat is available in many high-temperature, abrasive gas streams that would require special materials considerations for practical waste heat recovery. Investigation of advanced materials and coatings such as ceramics, teflon, glass, plastics and corrosion-resistant alloys in industrial environments is needed. In addition, there is a need for continued development of stainless steels and superalloys for use in intermediate-temperature environments where corrosion is a problem⁽⁷⁾.

2.2.2.4 Investigate Fabrication Practices

The fabrication practices of heat exchanger manufacturers should be surveyed to determine if this is an area where alternative techniques could be used to decrease the propensity of exchangers to foul. This may include techniques to:

- test welds to assure absence of leakage,
- avoid scratches on polished tubes that may initiate fouling and corrosion,
- roll tubes securely to avoid premature crevice corrosion, or
- to protect heat exchanger surfaces from contact with corrosive materials during storage, shipment and installation.

2.2.3 Additives and Cleaning Products (Chemical and Mechanical)

Applied research opportunities related to fuel or exhaust additives and mechanical cleaning devices are discussed below.

2.2.3.1 Test Alternative Additives and Cleaning Products

Systematic studies should be carried out to determine how well currently available cleaning devices remove typical deposits from commonly used heat-transfer surfaces. Cleaning techniques tested should include conventional ones such as air and water sootblowing and water washing, as well as sonic sootblowing, electrostatic cleaning and selected mechanical and thermal techniques. This information will provide a baseline against which alternative cleaning chemicals, additives, and devices can be compared.

2.2.3.2 Test Acid Dew-Point Control Measures

A variety of alternative methods for control of acid dew-point condensation is available including burner redesign, use of additives, use of low-sulfur oil and increased exhaust gas temperatures. A systems analysis of the simultaneous use of combinations of these control approaches might result in a procedure for optimizing the control of acid condensation problems⁽⁷⁾.

2.3 BASIC RESEARCH OPPORTUNITIES

From PNL's Fouling and Corrosion Workshop, it was concluded that basic research is needed in process analysis⁽³⁾. Process analysis was defined as the study of the sequential steps in fouling to determine the rate-limiting step. Once the rate-limiting step (i.e., the "weak-link") has been determined, methods to slow down or stop the fouling process can be developed.

The sequential events that occur in the fouling process should be analyzed for each of the various types of fouling in order to characterize basic fouling mechanisms. With respect to gas-side fouling, the types of fouling that are most likely to occur are particulate fouling, corrosion fouling, and chemical reaction fouling.

The basic research opportunities in gas-side fouling (Table 2.2) can be classified into three general areas: (1) Initiation, (2) Transport, Attachment and Removal, and (3) Aging. Taken together, these three types of research can lead to the development of predictive fouling models, effective prevention, mitigation and removal techniques or equipment, and the definition of design and operating parameters that will prevent or reduce fouling deposits.

2.3.1 Initiation

Initiation refers to conditions which promote subsequent fouling. Under this classification, basic studies are needed to characterize the properties of fluids and of surfaces that lead to or prevent fouling.

2.3.1.1 Characterize Fossil Fuel Exhausts

Fuels and fossil fuel exhausts need to be characterized to determine the physical and chemical properties that lead to fouling. In the case of gas-side fouling, this characterization would involve defining factors such as fuel composition, combustion conditions, particulate characteristics, dew points of various combustibles, presence of trace materials, and interactions between soot particles and other species in the exhausts. Research should be conducted to accurately characterize the size distribution, concentration, density, and chemical composition of particulate suspensions encountered in typical industrial gas streams where fouling problems are encountered. In addition, dew-points of various acids, salts and vapors present in fossil fuel exhausts should be measured. This information is needed to solve dew-point corrosion problems. Those data are necessary before any designer could hope to apply theoretically-based transport models in order to arrive at fouling deposit accumulation rate estimates⁽⁹⁾.

Although exhausts from diesel engines, and to some extent those from gas turbines, have been reasonably well characterized, this is not the case for most industrial exhaust gases. Characterization is needed of the following fuels, and their exhausts, at both low and high temperatures:

- heavy oils, particularly with high sulfur content
- ash effects of coal, coal-oil, and coal-water slurries
- emulsified fuels and synfuels
- heavy and alternative fuels in low-NO_x combustion mode⁽²⁾

2.3.1.2 Study Surface Parameters

A large gap exists in the fouling literature regarding which surface parameters control or influence fouling. The state of the art in applied surface studies has advanced to the point where it can be applied to the problem of fouling. Both laboratory studies (including scanning electron microscopic analysis) and "online" data acquisition can be undertaken to extend the understanding of the mechanisms of fouling initiation. A knowledge of the mechanisms will help in predicting behavior of systems and in designing mitigation techniques.

2.3.2 Transport, Attachment, and Removal

Specific opportunities in particulate fouling are discussed first, followed by a discussion of opportunities for basic research on transport, attachment and removal mechanisms that are applicable to all types of gas-side fouling.

2.3.2.1 Particulate Fouling

Because particulate fouling is the most common type of fouling on the gas-side, basic studies applicable to particulate fouling are discussed separately in this section. In general, basic studies are needed to characterize the phenomena associated with transport of particles to the interface, the nature of the interface itself, and deposit removal mechanisms. The detailed survey of particulate fouling performed by Caltech produced the following discussion of specific research opportunities in particulate fouling⁽⁹⁾.

- Characterize Velocity Fields Around Typical Heat Exchanger Geometries.

While the principles underlying deposition by inertial impaction are well understood, application of theory to practical problems requires that many individual particle trajectories be computed to determine the fraction of the particles in a flow that will strike a heat exchanger surface. These particle trajectory calculations are dependent on knowing the fluid velocity field within the heat exchanger. Research should be conducted to describe the velocity fields around typical complex heat exchanger geometries. Then models for particle collection efficiency could be constructed by integrating particle trajectories through the flow fields found in common heat exchanger geometries.

- Determine Relative Importance of Transport Processes as a Function of Particle Size. Little work has been done on the competitive effect of several processes acting together within heat exchanger geometries.

Research should be conducted to establish the order of magnitude of competitive transport processes as a function of particle size under conditions found in common heat-transfer systems.

- Microscopic Study of Transport Phenomena. A microscopic examination of the mechanistic steps that occur between the gas phase and the deposit in the vapor diffusion/condensation process should be undertaken. If particulate material condenses in the gas above the heat-transfer surface, then its size distribution will strongly influence the further probability of transport to the heat-transfer surface. The size distribution of condensing particulate material might be manipulated by varying the size distribution and concentration of pre-existing particles in the system. Nucleation and condensation processes that form new particulate matter should be examined mechanistically within heat exchanger system environments, including interactions between condensation and transport phenomena.
- Particle/Surface Interactions. There has been a considerable amount of work devoted to understanding the individual forces that act to bind particles to surfaces. Much less progress has been made at putting that theoretical understanding to work in making practical calculations of the probability that a particle that collides with a surface will, in fact, stick. Investigation of the competition between different microscopic-scale interactions between particles and collection surfaces should be pursued.
- Sticking Probabilities. A pragmatic approach to the adhesion question suggests that systematic experimental determination of sticking probabilities for real and model heat transfer systems should be pursued. A range of collection surface geometries should be considered, as well as a range of particle and surface physical properties (hard particle-hard surface collisions, hard particle-soft surface collisions, etc.). These sticking probability data can be put to immediate use in fouling models.
- Removal Probabilities. Opportunities for research into deposit removal processes at the microscale level should be pursued to acquire experimental or theoretical values for removal probabilities analogous to sticking probabilities that can be integrated with theoretically-based transport models to determine mechanisms of removal and validate current theories of removal (i.e., shear stress or turbulent burst). A second research

objective should be to further study simultaneously-occurring deposition and removal processes at the microscale level.

2.3.2.2 General

The basic opportunities for research that are discussed in this section apply to all types of fouling that may occur on the gas-side, either singly or in combination.

- Fuel/Exhaust Additive Mechanisms. With respect to deposit removal, some empirical evidence is available that suggests that certain removal techniques are more effective with certain types of deposits. However, the underlying mechanisms that cause these phenomena are not well understood. In particular, the use of magnesium-based additives has been widely employed in connection with oil-fired systems, but the mechanisms by which such additives are successful in mitigating the effects of gas-side fouling are not completely understood. Therefore, fundamental studies are needed to obtain a better understanding of why additives are successful in mitigating gas-side fouling in some cases and not in others.
- Fundamental Studies of Adhesion, Growth and Detachment. Basic studies of the adhesion, growth and detachment processes are needed for all types of gas-side fouling as well as for various types of fouling that occur in combination. These basic studies will allow the development or refinement of quantitative, mechanistic models of fouling. These models will help to clarify the weak-link in the overall fouling process.

2.3.3 Aging

Basic research opportunities related to deposit aging are aimed at studying the physical and chemical nature of deposits from fossil fuel exhausts and how they change with time. This information is needed for a variety of fuels, operating conditions, and surface configurations. This information provides the basis for developing effective deposit removal equipment or techniques and for determining which operating and design conditions are least likely to lead to fouling, as well as providing a basis for the development of mechanistic models.

TABLE 2.2. Opportunities for Basic Research in Gas-Side Fouling

INITIATION

- Characterize fossil fuel exhausts^(5,7).
- Study surface parameters that influence fouling.

TRANSPORT, ATTACHMENT AND REMOVAL

1. Particulate Fouling:

- Characterize velocity fields around typical heat exchanger geometries.
- Determine relative importance of transport processes as a function of particle size.
- Microscopic study of transport phenomena.
- Particle/surface interactions.
- Sticking probabilities.
- Removal probabilities.

2. General:

- Study mechanisms associated with fuel and exhaust additives⁽⁷⁾.
- Fundamental study of adhesion, growth and detachment of deposits⁽³⁾.

AGING

- Examine factors that affect the structure, composition and strength of fouling deposits⁽³⁾.

3.0 SIGNIFICANT CONCLUSIONS

This section summarizes the significant conclusions from each of the five reports.

3.1 INDUSTRIAL FOULING: PROBLEM CHARACTERIZATION, ECONOMIC ASSESSMENT, AND REVIEW OF PREVENTION, MITIGATION AND ACCOMMODATION TECHNIQUES (PNL-4883)

This report provides a comprehensive overview of heat exchanger fouling problems as they occur in the industrial manufacturing sector. Specifically, this overview addresses:

- the types of fouling and conditions that influence fouling,
- the characteristics of generic industrial heat exchanger fouling problems,
- the mitigation and accommodation techniques currently used by industry,
- the types and magnitude of costs associated with industrial fouling, and
- the characteristics, costs and mitigation techniques associated with fouling problems in the Food, Textiles, Pulp and Paper, Chemicals, Petroleum, Cement and Glass, and Primary Metals industries.

This analysis focuses on gas-side fouling problems that are generic in industry. Less emphasis is given to process-specific problems. Both high-temperature and low-temperature fouling problems are addressed, since fouling that occurs upstream at high temperatures often promotes fouling downstream at lower temperatures.

The annual cost of fouling to the U.S. industrial sector is estimated to be between \$3 and \$10 billion. Of this, it is expected that one to four billion dollars per year can be attributed to gas-side fouling⁽⁷⁾. The general lack of detailed information on fouling costs makes a precise estimate extremely difficult. Therefore, two approaches were used in this study to estimate these costs. The first approach is based on the methodology developed for the United Kingdom⁽¹²⁾, and assumes that fouling problems are similar to those experienced in the U.S. This approach yields an order-of-magnitude estimate of \$8 to \$10 billion per year.

The second approach uses a similar logic to that applied to the U.K. experience and incorporates the limited amount of data available for the U.S.

With this approach, all estimates tend to be somewhat conservative due to the assumptions made, and the lack of detailed information. This approach yields an order-of-magnitude estimate of about \$3.8 to \$7 billion per year (Table 3.1).

TABLE 3.1. Summary of Fouling Costs for U.S. Industrial Sector

<u>Component</u>	<u>Cost to Industry (\$M)</u>
Special Design Considerations	\$960-\$1280
Energy Losses	\$700-\$3500
Maintenance Costs	\$2000
Lost Production	\$200
Total	<u>\$3860-\$6980</u>

Fouling problems associated with steam generation, heat recovery, air cooling and water cooling are common throughout industry. Fouling from combustion gases is typically associated with fuels that have high ash contents, such as fuel oil and coal. Rising fuel prices have promoted the use of lower quality fuels, such as coal and wastes. They have also renewed interest in waste heat recovery. With both of these practices, the incidence of gas-side fouling can be expected to increase. At low temperatures, acid dew-point corrosion becomes a major concern on the gas side. This is a particularly relevant concern in waste heat recovery from low-temperature exhausts. In heat recovery from direct-fired operations, fouling by product constituents may occur along with fouling by fuel constituents.

PNL assessed the strategies used to mitigate fouling in industry today and concluded the following:

- Many heat exchangers fail prematurely because of fouling and corrosion.
- Oversizing heat exchangers is probably the most frequently used strategy to mitigate fouling.
- Oversizing heat exchangers frequently increases fouling.
- Chemical treatment (on- and off-line) and mechanical cleaning are the most frequent mitigation strategies used other than oversizing.

- Chemical treatment is a large, service-type business with custom treatments designed for each plant.
- Chemical treatment companies closely guard the formulations they use, but rarely use patents to protect these formulations.

Seven major industries are reviewed from the standpoint of their operations, energy consumption, fouling problems and mitigation techniques used. Fouling problems on the process side vary extensively from industry to industry because of the variety of process fluids that are heated or cooled. Conversely, on the heat source/heat sink side, which involves steam generation, heat recovery, and air cooling, fouling problems are common throughout all industries (i.e., generic problems).

3.1.1 Food and Kindred Products

In the food processing industry, gas, oil and solid fuels are used primarily to generate process steam in boilers. A small portion of the gas is used for direct-fired drying. The generic fouling problems associated with the combustion of fossil fuels are generally left to exchanger manufacturers and chemical or mechanical cleaning vendors.

3.1.2 Textile Manufacturing

Generic fouling in the textile industry includes that associated with steam generation in fired boilers (gas, oil, or coal). As more coal is used, these generic fouling problems will increase, particularly if waste heat recovery becomes widely practiced. The presence of lint and finishing chemicals in exhausts from drying equipment can cause the fouling of heat-transfer surfaces, particularly with waste heat recovery equipment. Lint is commonly removed by air washers.

Mitigation strategies proposed for use with waste heat recovery equipment include use of smooth glass tubes in easily-cleaned heat exchangers, and regenerator-type exchangers which are periodically cleaned.

3.1.3 Pulp and Paper

A wide range of fouling problems is encountered in pulp and paper manufacturing. Few fouling problems are encountered in the fiber sources preparation step. The same is true for the papermaking step. However, extensive fouling problems are encountered in the pulping step.

Generic fouling problems are encountered in power/steam generation for pulp and paper mills. Major fuels are wood, coal and oil, from which typical

fouling deposits are solids and condensed corrosive vapors present in the combustion gases. A major fuel used in Kraft furnaces is concentrated black liquor, which contributes significant amounts of corrosive vapor and particulate materials to the combustion gases.

In the papermaking step, fouling of waste-heat-recovery exchangers can occur due to the presence of fibers in exhaust air streams.

Many mitigation techniques are used in the industry. For mitigation of generic fouling problems, the usual techniques such as sonic horns, lances (off-line), soot blowers, and control of process conditions are used.

3.1.4 Chemicals

Nonprocess fouling constitutes the major fouling problem in the chemicals industry. This includes cooling water fouling (i.e., biofouling of cooling towers and condensers), and water-side and fire-side fouling of power/steam and waste-heat boilers. Mitigation techniques include mechanical (off-line) cleaning and chemical (off-line) cleaning.

3.1.5 Petroleum Refining

The main generic fouling problems encountered in the petroleum industry include water-side and fire-side deposits in boilers and biofouling, scaling, and particle deposition on the cooling-water side of heat exchangers and condensers. These problems are handled by the usual on-line and off-line techniques including water treatment, fuel additives, and on-line and off-line mechanical cleaning.

3.1.6 Stone, Clay and Glass Industries

Fouling problems in the cement and glass industries are discussed below.

3.1.6.1 Cement Industry

Direct-contact heat transfer is the primary mode of heating and cooling in the cement industry, with the exception of heat-recovery units. The exhaust gases contain constituents from both the product and the fuel, which deposit on walls and heat-transfer surfaces. Considerable deposition of dust occurs on the walls of suspension preheaters on kilns. Although these deposits do not hinder heat transfer, they do cause blockage and increase resistance to the flow of gases. Exhaust gas coolers experience particulate and sulfuric acid deposition, causing increased flow resistance and corrosion. Particulate deposits also occur in waste-heat boilers.

Mitigation techniques used to prevent build-up in preheaters with varying degrees of success include provision of extra large cross-sections (reduces effectiveness), by-passing, and using low-chloride, low-ash fuels. Waste-heat boiler deposits are removed by soot blowers or other on-line mechanical methods. Other mitigation methods include dust removal, increasing gas velocity and water spray systems.

3.1.6.2 Glass Industry

Foulants in the glass industry include product degradation materials and constituents from the combustion of fuel. Particulates accumulate in regeneration, causing reduction of effectiveness, plugging and destruction of regenerator brick. Mitigation techniques include the use of clean fuels (natural gas), reduction of foulant materials in exhaust gases (through the use of additives and modification of process conditions), and on-line and off-line cleaning.

3.1.7 Primary Metals Industry

Fouling problems in integrated steel mills, gray iron foundries, copper smelting and refining and aluminum reduction plants are discussed below.

3.1.7.1 Integrated Steel Mills

The main fouling problem is cooling water fouling, for which the mitigation technique is the use of additives. Mitigation techniques include the use of fuel oil additives.

3.1.7.2 Gray Iron Foundries

Fuels used for direct heating are the source of foulant materials which cause cupola shell degradation. No other major fouling problems appear to occur.

3.1.7.3 Copper Smelting and Refining

Foulants in copper smelting and refining are from the fuel used in direct heating and from the product. Gases high in particulates and SO_2 lead to erosion, corrosion and deposition problems. This results in degradation of furnace linings and waste-heat boiler corrosion problems. Remedies include equipment repair and/or replacement when necessary.

3.1.7.4 Aluminum Reduction Plants

The use of natural gas as a fuel leads to few fouling problems in the direct heating part of the aluminum reduction process. Generic fouling and

corrosion problems occur in the power plants and are mitigated by the usual on-line and off-line techniques mentioned earlier. The presence of fluorides and sulfur at high temperatures results in cell degradation, which is remedied by repair and/or replacement of equipment.

3.2 PROCEEDINGS OF THE PNL FOULING AND CORROSION WORKSHOP (PNL-SA-12014)

This report documents the proceedings of PNL's Fouling and Corrosion Workshop held in Seattle, Washington on December 21, 1982. The objectives of this workshop were to determine the manufacturing industries (SIC 20-39) in which major fouling and corrosion problems occur, the specific problems that these industries experience, and the severity of each problem in relationship to other fouling and corrosion problems. In addition, we sought inputs from our consultants on the mitigation techniques currently employed by industry. The consultants also reviewed the parameters we had selected for our computerized fouling data base and provided a list of research and development opportunities in fouling.

The following seven industries were identified as being the only ones with significant low-temperature fouling and corrosion problems:

- Food and Kindred Products
- Textiles
- Pulp & Paper
- Chemicals
- Petroleum
- Stone, Clay and Glass
- Primary Metals

The consultants identified the major processes in which fouling and corrosion problems occur in these seven industries. The problem areas in each industry were then ranked according to three criteria: (1) energy loss, (2) cost, and (3) solvability.

The consultants identified mitigation strategies currently used by industry for the previously-identified fouling problems. In addition, the consultants suggested a large number of industrial contacts for further information on fouling problems and mitigation strategies.

Next, the consultants identified 24 opportunities for government R&D in fouling and corrosion. They also prioritized the R&D opportunities according to the following three criteria: (1) problems common to a number of industry

sectors, (2) problems which cannot or will not be attacked by individual industries or organizations, and (3) particular areas where data and understanding are lacking.

We reduced the list of 24 R&D opportunities to ten categories:

- Basic Study
- Fouling Measurement
- Fouling Probe
- Additives
- Cleaning
- Geometry
- Cooling Tower Water
- Particulates
- Process
- National Advisory Group

We then prioritized these ten categories based on the consultants' prioritizations of the 24 R&D opportunities. "Particulates" and "Basic Study" were ranked either first or second according to each of the three criteria listed in the previous paragraph.

The consultants were divided on the importance of basic vs. applied research. Several of them felt that process analysis is of major importance. Others felt that finding cooperative industries to verify laboratory data is more critical. These differences of opinion among some of the country's top experts in fouling lead us to conclude that a multi-thrust R&D effort is needed.

Regarding the specific industrial fouling and corrosion problems identified by the consultants, it appears that generic problems such as fouling from combustion of fuels (for steam production or direct heating) and cooling water fouling are ranked near the top for each industry. Thus government R&D in these generic areas would benefit a number of industries.

The PNL Fouling and Corrosion Workshop provided useful preliminary data and rankings, but it had a few shortcomings. First, some industries were not adequately represented and, thus, their fouling and corrosion problems were not addressed in sufficient detail (especially textiles and primary metals). Second, some important problems were not discussed (e.g., acid and water dew-point condensation).

3.3 PARTICULATE FOULING OF HEAT-TRANSFER SURFACES (JPL-D-1055)

This report reviews the fouling of heat-transfer surfaces due to deposition of particulate matter from contaminated gas streams. Rather than deal with heat exchanger fouling on a purely phenomenological basis, the fundamental physical processes that govern the gas-side particulate fouling problem are described. Major sections of this report concern the mechanisms of particle transport to surfaces, the questions of particle adhesion and particle bounce, theoretical and empirical models that predict the rate of fouling, fouling deposit properties, and acid/water dew point condensation processes. The authors found that the theoretical understanding of individual steps within the chain of events leading to particulate deposition, adhesion and removal exceeds that built into existing fouling models. Opportunities for future research that could help to bridge gaps between theory and current engineering practice are included in the research recommendations of this report.

Most of the information relevant to the heat exchanger fouling problem is of two types: (1) in-depth theoretical studies of a single facet of the particle deposition and removal process, and (2) largely empirical studies of the overall fouling process in the presence of many competing, but undifferentiated processes. Theoretically sound models for particulate deposition in the presence of competing transport or removal processes are presently lacking, but could be constructed to help bridge the gap between theory and empiricism.

3.4 A SURVEY OF GAS-SIDE FOULING IN INDUSTRIAL HEAT-TRANSFER EQUIPMENT (JPL-D-1054)

This report provides supplementary material to PNL-4883. JPL conducted a survey of gas-side fouling in industrial heat-transfer equipment. Information was gathered by personal contacts, visits to selected industries, attendance at several professional meetings and conferences, and publications in the open literature. Topics of major interest in this study include: (1) heat exchanger design procedures for gas-side fouling service, (2) gas-side fouling factors which are presently available, (3) startup and shutdown procedures used to minimize the effects of gas-side fouling, (4) gas-side fouling prevention, mitigation, and accommodation techniques, (5) economic impact of gas-side fouling on capital costs, maintenance costs, loss of production, and energy losses, and (6) miscellaneous considerations related to gas-side fouling. The present state-of-the-art of industrial gas-side fouling is summarized by a list of recommendations for further work in this area.

The major conclusions of this survey are:

- Materials play a key role in the design of heat-transfer equipment for gas-side fouling and corrosion service. The most pressing materials problems occur in: (a) low-temperature heat recovery where acid condensation is a major problem, with plastic, glass, coatings, and alloy steel as potential solutions, and (b) high-temperature applications, where the development of superalloys and especially ceramic materials is essential.
- Fuel and gas cleaning techniques have had limited success in mitigating gas-side fouling.
- There are very limited gas-side fouling factors available in the literature, and most of these are rules of thumb based on practical experience rather than on experimental data.
- In those cases where gas-side fouling factors are available, there are notable differences in data from different sources.
- There are many applications -- for example, in the cement, aluminum, and pulp and paper industries -- where gas-side fouling factors simply do not exist.
- In some cases startup and shutdown operations cause severe gas-side fouling and corrosion problems because the units are not operating under the conditions for which they were designed. A few of the procedures which have been used to overcome such problems are discussed in this report. However, such procedures are limited and some of them are very site-dependent. In particular the installation and initial operation of new systems such as the Sundstrand Organic Rankine Bottoming Cycle system are especially vulnerable to fouling and corrosion startup and shutdown problems. Unfortunately, in many such cases satisfactory operating procedures must be developed on a trial-and-error basis. It is clear that the development of additional startup and shutdown procedures would be most welcome by individuals dealing with gas-side fouling and corrosion problems.
- Sonic sootblowers or horns have received increasing use during the last five years in this country as a non-intrusive type of cleaning, generally on a retrofit basis. Sonic horns are very effective when the deposits are soft and friable, but do not work well when the

deposits are wet and sticky.

- Water washing is another cleaning technique which is widely used, and standard washing procedures have been developed.
- Mechanical cleaning methods such as the use of shot and scouring with nutshells are also effective in many cases.
- Quenching, or the rapid cooling, of hot gases is used in some cases to solidify particulates which would otherwise deposit onto cooled heat-transfer surfaces.
- The control of operating conditions, including parameters such as gas and surface temperature, is a very important consideration in trying to minimize deposits from dirty gases.

3.5 INDUSTRIAL FOULING DATA BASE PROGRESS REPORT

This section documents progress to date on the compilation and evaluation of a computerized fouling data base. Efforts are directed toward two separate goals: (1) to compile useful fouling data for industry and government, and (2) to identify gaps in the data in order to assist DOE in planning a long-term, generic research and development program on fouling in the industrial manufacturing sector. PNL's intent is to assemble a comprehensive fouling data base that will serve the present and future needs of: (a) engineers concerned with the design and operation of heat exchangers subject to fouling and corrosion, (b) researchers involved in the development of prevention and mitigation techniques, and (c) scientists engaged in fundamental studies aimed at understanding the complex fouling processes.

Much of the literature on fouling describes the use of probes. This points out the need for more heat exchanger data and for studies to relate probe data with heat exchanger data.

As of September 30, 1983 there are 57 documents in our technical data file and 112 documents in our bibliography abstract file. The documents in the technical data file can be categorized as follows:

Field Data	: 27
Laboratory Data	: 29
Probe Studies	: 30
Powerplant Studies	: 17 ^(a)
Deposit-Side Fluid Temperature 500°F	: 14 ^(b)
Deposit-Side Fluid Temperature 500°F	: 27 ^(b)

(a) This includes waste incinerators.

(b) At least four of these documents were counted both below and above 500°F since the minimum temperature investigated as below 500°F and the maximum temperature investigated was above 500°F.

The fluid types represented in the technical data file can be categorized as follows:

<u>Fluid Type</u>	<u>Deposit Side</u>	<u>Other Side</u>
Water	12	12
Combustion Gases	34	0
Inorganic Chemicals	3	0
Organic Chemicals	1	0
Foodstuffs	0	0
Air	1	5
Other	0	1

The fouling types represented in the technical and bibliography/abstract files are shown below:

<u>Fouling Type</u>	<u>Technical Data File^(a)</u>	<u>Bibliography/Abstract File^(b)</u>
Precipitation	15	9
Particulate	22	52
Biofouling	3	4
Chemical Reaction	4	4
Liquid Solidification	2	0
All	1	4
None	0	2

(a) This includes counting multiple fouling types discussed in the same document.

(b) This is based on the principal fouling type discussed in the document.

The percentage of data elements in the technical data file with data defined in the documents varies significantly from one document to the next, but the average is about 33 percent. We hope that this percentage will be significantly increased once we receive the reviews of the computerized data by the original authors.

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