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OF GAS-SIDE FOULING IN FOSSIL FUEL EXHAUST
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Workshop on an Assessment of Gas-Side Fouling in Fossil Fuel Exhaust Environments

Editors
W.J. Merner
R.L. Webb



July 1982

Prepared for
U.S. Department of Energy
Idaho Operations Office
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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ABSTRACT

A Workshop sponsored by the Department of Energy, Office of Energy Systems Research, Energy Conversion and Utilization Technology (ECUT) Program, has been carried out to assess the state-of-the-art of gas-side fouling in fossil fuel exhaust environments. Special emphasis was placed on heat recovery applications. The major objectives of the Workshop were to: (1) Promote an interchange of ideas among workers interested in gas-side fouling, (2) Define the state-of-the-art for fouling in fossil fuel exhaust environments, (3) Identify and attempt to quantify the deleterious effects of gas-side fouling including increased energy consumption, increased material losses, and loss of production, and (4) Recommend a well-defined R&D program in gas-side fouling with both short-term and long-term objectives. The Workshop was held on October 8-9, 1981 at the University of Colorado, Boulder, Colorado. Forty-one participants from industry, academia, government, and national laboratories participated in the Workshop. The industrial participants included representatives from the cement, glass, nuclear, solar, petrochemical, power, and steel industries. For purposes of discussion, the Workshop was organized into four different groups as follows: Group A: Characterization of Fossil Fuel Exhaust Gases, Group B: Gas-Side Fouling Characteristics and Mechanisms, Group C: Design of Heat-Transfer Equipment for Gas-Side Fouling Service, and Group D: Operation and Cleaning of Heat-Transfer Equipment in Dirty Gas Environments. This Workshop Report includes edited transcripts of the most important presentations at the Workshop, including brief state-of-the-art assessments and a list of specific R&D projects by each of the four groups listed above. The following seven projects were identified by the participants as being of the highest priority:

- o Characterization of Fossil Fuel Exhaust Gases
- o Development of a Gas-Side Fouling Measuring Device
- o A Study of Attachment and Removal Mechanisms and Predictive Methods for Gas-Side Fouling
- o Collection of Empirical Gas-Side Fouling Data for Specific Geometries
- o Effectiveness of Cleaning Devices for Gas-Side Fouling Service
- o The Mechanism of Wet Wall Fouling in Fossil Fuel Exhaust Gases
- o Alternative Types of Heat Exchange Equipment to Enhance Heat Transfer and to Mitigate the Effects of Gas-Side Fouling

A short economic analysis shows that the cost of gas-side fouling on equipment alone to recover 2 quadrillion Btu/year in the United States would be \$3 billion, with an additional penalty of \$1 billion/year for maintenance costs. An extensive bibliography includes about 175 references related to gas-side fouling in heat recovery applications.

ACKNOWLEDGEMENTS

In an undertaking such as this, the contributions of many people are required to make the effort a success. The editors would particularly like to single out several individuals for special recognition. First, the participants in the Panel Discussion, "What We Know and Don't Know about Gas-Side Fouling" were Richard E. Thompson, Thomas E. Duffy, R. C. Weierman, and George Borushko. Their contributions were very important and helped to set the stage for later discussions in the Workshop. In addition, R. C. Weierman graciously agreed to write a short section quantifying the deleterious effects of gas-side fouling after the completion of the Workshop. The Banquet Talk by David O. Watts stimulated a great deal of interest and helped to give the participants a better appreciation of the equipment used in heat recovery applications and some of the associated gas-side fouling problems. The four group leaders were Anil Kulkarni, Jerry W. Suito, Vernon L. Eriksen, and James M. Chenoweth, and they deserve special plaudits. In addition to leading their respective discussions throughout the four Workshop Group Sessions, they were required to present a state-of-the-art assessment and a list of detailed R&D projects based on their respective group discussions. Special thanks are extended to all of the Workshop participants, each of whom individually made unique contributions and collectively made the Workshop possible. The Workshop-related arrangements at the College Inn Conference Center went very smoothly, and for that Debbie Cook of the University of Colorado deserves a great deal of thanks. Finally, Sue Myers of the Jet Propulsion Laboratory skillfully typed the entire manuscript.

This work was performed by the Applied Mechanics Technology Section, Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the U.S. Department of Energy, Office of Energy Systems Research, Energy Conversion and Utilization Technology Program, under Interagency Agreement DE-AI07-80ID12138, Amendment A001 through NASA Task Order RD 152, Amendment 300. Technical Monitor for the project was W. H. Thielbahr, Chief, Energy Conservation Branch, DOE/Idaho, without whose initiative, support, and keen interest in gas-side fouling, this Workshop would not have been possible.

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SECTION 1

INTRODUCTION

Heat recovery from medium and high temperature exhaust gas streams is essential for the efficient operation of most industrial energy conversion systems. However, in many instances such gases are dirty, contain corrosive components, and are laden with particulates which can result in severe gas-side fouling problems in heat recovery systems. In the present context, fouling may be defined as the buildup of a deposit on a heat exchanger surface which retards the transfer of heat, and includes the associated problems of corrosion and erosion. Although gas-side fouling has been identified as a major consideration in heat-recovery systems, inadequate research has been done in this area and many technical problems remain.

In order to assess the state of the art of gas-side fouling in fossil fuel exhaust environments, the U.S. Department of Energy (DOE), Office of Energy Systems Research, retained the Jet Propulsion Laboratory, California Institute of Technology (JPL), to carry out a workshop in this area. This Workshop was funded as a part of the Energy, Conversion and Utilization Technology (ECUT) Program. The Workshop was planned and conducted by W. J. Marnier of JPL and R. L. Webb of The Pennsylvania State University who served as a consultant to JPL. Technical Monitor for the project was W. H. Thielbahr, Chief, Energy Conservation Branch, DOE/Idaho.

OBJECTIVES

The major objectives of the Workshop were to:

1. Promote an interchange of ideas among workers interested in gas-side fouling.
2. Define the state-of-the-art for fouling in fossil fuel exhaust environments.
3. Identify and attempt to quantify the deleterious effects of gas-side fouling including increased energy consumption, increased material losses, and loss of production.
4. Recommend a well-defined R&D program in gas-side fouling with both short-term and long-term objectives.

SCOPE

The Workshop focused on gas-side fouling in fossil fuel exhaust environments with special emphasis on heat recovery applications. In particular, equipment of primary interest included: boilers, prime movers (gas turbines and internal combustion engines, e.g., Diesel engines), and fired heaters and furnaces. Fuels considered included: natural gas, light oils, heavy oils, incinerator exhausts, coal and coal slurries, and synthetic fuels. All aspects of gas-side fouling in exhausts from these fuels--with the exception of the formation and removal of coal slag--were potential topics of discussion at the Workshop. Finally, although a wide variety of industries was represented at the Workshop, the emphasis was placed on generic gas-side fouling problems.

SECTION 2

WORKSHOP ORGANIZATION

In order to achieve the objectives stated in Section 1, about 40 carefully selected participants from industry, national laboratories, government, and academia were invited to attend the Workshop. The two-day workshop was held on October 8-9, 1981 at the College Inn Conference Center, University of Colorado, Boulder, Colorado. Participants from the cement, glass, nuclear, solar, petrochemical, power, and steel industries were in attendance, and the heat-exchanger-related consulting, engineering, and manufacturing firms were also well represented. The technical backgrounds of the participants covered a broad spectrum, ranging from plant operations to basic research. A list of the workshop participants is given in Table 2-1 and the workshop agenda is given in Table 2-2.

DOE/ECUT PROGRAM

Following a short introduction period, W. H. Thielbahr of DOE/Idaho opened the two-day workshop by presenting a "Description of the Physical Processes Project in the DOE/ECUT Program." This talk provided an overview of the ECUT program with a special focus on the importance of the Workshop. An edited version of this presentation is given in Section 3.

WORKSHOP GROUPS

For purposes of discussion, the Workshop was organized into four different groups as follows:

- Group A: Characterization of Fossil Fuel Exhaust Gases
- Group B: Gas-Side Fouling Characteristics and Mechanisms
- Group C: Design of Heat-Transfer Equipment for Gas-Side Fouling Service
- Group D: Operation and Cleaning of Heat-Transfer Equipment in Dirty Gas Environments

A fairly detailed description of the topics considered by each of these groups is given in Table 2-3.

PANEL DISCUSSION

Following the presentation on the DOE/ECUT Program, a panel discussion was held on the topic: "What We Know and Don't Know About Gas-Side Fouling." Four panelists, one from each of the four groups as indicated in Table 2-3, participated in the discussions. The purpose of this session was to stimulate some preliminary thinking relative to gas-side fouling, prior to breaking up into four Workshop Groups. The edited presentations of the panelists are given in Section 4.

ORGANIZATION OF WORKSHOP GROUPS

Following the panel discussion, the participants were divided into four groups by the workshop organizers, as indicated in Table 2-3. The assignment of individuals to specific groups was made on the basis of background, experience, and interest. The organization of the four groups is shown in Table 2-4. The workshop organizers W. J. Marner and R. L. Webb, and the sponsor W. H. Thielbahr, circulated among the four groups, and W. Greenlee spent about half-time in Group C and half-time in Group D. All other participants spent the entire time in their assigned groups in order to preserve a sense of continuity throughout the Workshop Group Session discussions.

The Workshop group leaders were selected on the basis of their ability to: lead a group, keep the discussions focused on the workshop objectives, and enlist the participation of all the members of the group. The group leaders were not necessarily expected to be the "resident experts" on the particular topics their groups were considering.

WORKSHOP GROUP SESSIONS I AND II

A total of four Workshop Group Sessions were held as indicated in Table 2-2. During these four sessions, each group was asked to prepare the following items:

1. A brief state-of-the-art assessment of the assigned group discussion area.

2. A limited number of specific R&D projects (a set of blank forms was provided for this purpose).
3. A prioritized listing of the projects in Item 2.

At the end of the first day of the workshop, after the completion of Workshop Group Session II, a plenary session was held. At this session each of the four group leaders made a short presentation of about 10 minutes in length indicating how the discussions had gone in his group up to that time. The purpose of this short plenary session was to effect a preliminary interchange of ideas among all the groups and to ensure that none of the groups had become bogged down.

BANQUET AND BANQUET TALK

Following the workshop banquet on Thursday evening, D. O. Watts of the John Zink Company gave an illustrated talk on "Heat Recovery Equipment in Gas-Side Fouling Service." This very interesting presentation stimulated a great deal of discussion, and there were many questions and comments, both during and after the talk. An outline of this presentation is given in Section 5.

WORKSHOP GROUP SESSIONS III AND IV, FINAL PLENARY SESSION

After Workshop Group Sessions III and IV were completed on Friday morning, the four group leaders presented their Summary Reports at the third and final plenary session. Following these reports there was a period of general discussion. During this final discussion period the participants reached a consensus on the R&D projects with highest priority from the original list which had been submitted. The edited version of the final summary reports is given in Section 6, a compilation of all the recommended projects is given in Section 7, and a listing of the highest priority R&D projects, along with a summary of the major items of discussion, is given in Section 8.

QUESTIONNAIRES

After the Workshop, each participant was sent three questionnaires relating to:

1. Short-Term (0-3 Years) and Long-Term (3-10 Years) Ranking of the Importance of Various Fuels Used in Gas-Side Fouling Heat Recovery Service.
2. Evaluation of the Importance of Gas-Side Fouling on Internal Heat Exchanger Surfaces Versus External Heat Exchanger Surfaces.
3. Workshop Evaluation Form.

The first two questionnaires, along with a summary of the results obtained, are given in Section 8. The questionnaire dealing with the evaluation of the Workshop is given in Section 10, and the results are self explanatory.

THE DELETERIOUS EFFECTS OF GAS-SIDE FOULING

After the completion of the Workshop, one of the participants -- R. C. Weierman of Escoa Fintube Corporation -- graciously agreed to write a short section quantifying the deleterious effects of gas-side fouling. In particular, he placed special emphasis on the impact of gas-side fouling as it relates to energy utilization in industrial applications. This discussion is given in Section 9.

BIBLIOGRAPHY ON GAS-SIDE FOULING

Finally, as part of the task of assessing the state-of-the-art of gas-side fouling in fossil fuel exhaust environments, a bibliography on gas-side fouling was compiled and is listed in Section 12 at the end of the report. This list was compiled from: (1) references in the files of the organizers, (2) references provided by the workshop participants, and (3) references obtained in several computer-based literature searches.

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Table 2-2. Workshop Agenda

Thursday, October 8

7:00 - 8:00 am	Breakfast (College Inn Dining Room)	
8:00 - 8:30 am	Registration (College Inn Lobby)	
8:30 - 8:45 am	Introduction	W. J. Marner, JPL
8:45 - 9:15 am	Description of Physical Processes Project in DOE Energy Conversion and Utilization Technology Program	W. H. Thielbahr, DOE
9:15 - 10:00 am	Panel Discussion: "What We Know and Don't Know about Gas-Side Fouling	W. J. Marner and Panelists
10:00 - 10:20 am	Break	
10:20 - 11:30 am	Continuation of Panel Discussion	
11:30 - 12:00 pm	Organization of Workshop Groups and Instructions to Participants	R. L. Webb, Penn State
12:00 - 1:00 pm	Lunch (College Inn Dining Room)	
1:00 - 3:00 pm	Workshop Group Session I	
3:00 - 3:20 pm	Break	
3:20 - 4:30 pm	Workshop Group Session II	
4:30 - 5:00 pm	Plenary Session (Progress Report)	W. J. Marner and Workshop Group Leaders
5:00 - 6:30 pm	Recess	
6:30 - 7:30 pm	Social Hour	
7:30 - 8:30 pm	Banquet (College Inn Dining Room)	
8:30 - 9:15 pm	Banquet Speaker: "Heat Recovery Equipment in Gas-Side Fouling Service"	David Watts John Zink Company

Friday, October 9

7:00 - 8:00 am	Breakfast (College Inn Dining Room)	
8:30 - 10:00 am	Workshop Group Session III	
10:00 - 10:20 am	Break	
10:20 - 12:00 pm	Workshop Group Session IV	
12:00 - 1:00 pm	Lunch (College Inn Dining Room)	
1:00 - 3:10 pm	Presentation of Workshop Group Summary Reports and Recommendations, Followed by General Discussion	R. L. Webb and Workshop Group Leaders
3:10 - 3:15 pm	Resume	W. J. Marner
3:15 pm	Adjourn	

Table 2-3. Workshop Groups

Group A: Characterization of Fossil Fuel Exhaust Gases

Panelist: Richard E. Thompson, KVB, Inc.

Group Leader: Anil Kulkarni, Pennsylvania State University

Topics for discussion will include: types of fuel; components of exhaust gases; particulates; properties of exhaust gases; effects of premixing fuel and oxidizer; burner design effects; simulation of dirty gases; additives to avoid gas-side fouling; dew-point temperature of contaminants; soot formation; plus additional items as appropriate.

Group B: Gas-Side Fouling Characteristics and Mechanisms

Panelist: Thomas E. Duffy, Solar Turbines Incorporated

Group Leader: Jerry W. Sutor, Occidental Research Corporation

Topics for discussion will include: effects of parameters such as velocity, temperature, characterization of gases, geometry, pressure, and surface roughness; particulate fouling deposition and removal mechanisms; deposit characterization; corrosion fouling and related materials effects; erosion and the interaction of fouling with erosion; measurement of gas-side fouling; deposition of condensables; effect of coatings; plus additional items as appropriate.

Group C: Design of Heat-Transfer Equipment for Gas-Side Fouling Service

Panelist: R. C. Weierman, Escoa Fintube Corporation

Group Leader: Vernon L. Eriksen, Deltak Corporation

Topics for discussion will include: heat exchanger selection criteria (types of exchangers, internal versus external gas flow, vertical versus horizontal orientation, etc.); augmentation of heat transfer; tube and layout geometry; tube materials including metals, alloys, coatings, and ceramics; fouling factors; cost of gas-side fouling, especially that due to additional surface area; flow distribution problems when erosion is a potential problem; effect of off-design start-up conditions; plus additional items as appropriate.

Group D: Operation and Cleaning of Heat-Transfer Equipment in Dirty Gas Environments

Panelist: George Borushko, Exxon Research and Engineering Company

Group Leader: James M. Chenoweth, Heat Transfer Research, Inc.

Topics for discussion will include: cleaning techniques such as sootblowers (using steam, water, or air), sonic horns, chemical and mechanical cleaning, vibration, and alternative methods of cleaning; deposition of condensables; experience with additives to retard fouling; effect of electrostatic charge on particulates; start-up problems; problems unique to specific applications; identification of specific problem areas based on field experience; cost of fouling including cleaning, down-time, and energy penalties; effect of fouling on pressure drop as well as heat transfer; plus additional items as appropriate.

Table 2-4. Organization of Workshop Groups

GROUP A

A. Kulkarni, Group Leader
D. Anson
G. Blizard
F. Dibella
H. Henneken
R. Thompson
G. Wieland

GROUP B

J. Suitor, Group Leader
S. Beal
C. Butler
L. Casper
T. Duffy
W. Ebert
D. Eissenberg
G. Godfrey
F. Kreith
R. Rhodes
R. Wenglarz

GROUP C

V. Eriksen, Group Leader
R. Baron
A. Doucet
B. Ghofranian
W. Greenlee
A. Hall
D. Hawkins
G. Theoclitus
D. Watts
C. Weierman
D. Werner

GROUP D

J. Chenoweth, Group Leader
G. Borushko
R. Castellani
J. Locke
D. Maxwell
J. Moore
J. Streich
L. Thomas

SECTION 3

DESCRIPTION OF THE PHYSICAL PROCESSES
PROJECT IN THE DOE/ECUT PROGRAM

W. H. Thielbahr

Description of the Physical Processes Project in the DOE/ECUT Program

W. H. Thielbahr

Introduction

I anticipated that one of the first questions asked of me would be: "What is the status of affairs with DOE?" I tried desperately to get some hard data and I am not sure I was all that successful. But, here is the situation as I know it, as of today. I cannot discuss DOE policy matters but I can tell you what the President has said regarding the disestablishment or dismantling of DOE. This has been approved by the White House, and I think this is of interest because it helps to dispel some of the misinformation which exists today. The President's words are "dismantling of DOE"; he uses "abolishment" for the Department of Education. The Administration will submit to Congress the latter part of this calendar year, or in January 1982, plans for dismantling DOE.

The fiscal 1982 year began 1 October, a week or so ago. The thrust of President Reagan's DOE program is much different than President Carter's. This new course is a radical change to those of us who have been involved in both administrations. In Carter's administration the emphasis was near-term, demonstration, commercialization: get conservation going and give as much government assistance to the private sector as possible to achieve rapid results. The principal idea was to reduce fuel consumption quickly. Now you can argue whether or not that was prudent, but that certainly was the major thrust of Carter's administration. With the new administration, DOE will not assist the private sector in commercializing conservation technologies. The private sector is solely responsible for carrying on all commercialization efforts; they will support and conduct the demonstration testing of novel devices, novel systems, advanced energy conversion schemes, and the like. The federal government's role is to support high-risk, long-range, generic R&D. Government supported projects will not displace private sector investment. In terms of these new guidelines, we in the government have to be extremely careful in justifying government supported R&D. The private sector must convince us that financial support is necessary and that the technology is important. Government supported R&D is aimed at lowering the technical risk

to an acceptable level where the private sector then can step in and make a proper assessment of the merits for them to continue or not.

In this viewgraph I show a portion of the official White House position on the dismantlement of DOE. The most important item on this viewgraph is the last tick. You may have heard that conservation is gone, solar energy is gone, fossil energy is gone, and what is left behind will be nuclear energy R&D. But, in fact, the President has left himself considerable flexibility in what the Administration will choose to support. As you can read, "Basic Scientific and Engineering Research on a Broad Range of New Energy Technologies" will continue. If ECUT supports heat exchanger fouling R&D it will fall under that category and apply over a broad range of energy conservation technologies. Other DOE activities will include "Carefully Targeted Conservation Programs, Strategic Petroleum Reserve, Defense Programs, and Nuclear R&D." This is the President's position today, and I see no sign that it will change.

Eissenberg: May I ask a question? The Department of Interior will pick up some functions. Is there, in any of the President's statements, anything to the effect that the Interior Department will pick up the fossil programs?

Thielbahr: That is a very good question and one that I did not address. Rephrased, this question is "What will the DOE look like when dismantling is complete? Will it be an equivalent to ERDA or will there only be nuclear left behind? And, what of conservation, solar, fossil, geothermal, wind and other alternative energy areas -- will they be dispersed to existing government organizations?" There has been no direct guidance from the Administration to people like myself. However, I have heard of two possible scenarios. One, DOE collapses to an ERDA where essentially all the alternative energy as well as nuclear stay together. The other scenario is that all the alternative energy programs are broken off and put into various existing government organizations. Fossil energy, for example, may go to the Department of Interior. Conservation and solar energy may be transferred to the National Science Foundation (NSF).

But all these matters will be sorted out in time; as yet there is no official word on any definite plans. The administration has not taken an official public position yet. So I do not know what DOE will look like after the dismantlement.

DOE Idaho Operations Office, Energy Conservation Branch

Now, I will tell you a little bit about myself and where I come from. This is an organization chart of the Idaho Operations Office which is headquartered in Idaho Falls, Idaho. It is an Operations Office of the DOE -- it is one of eight in the country. Its primary function is to manage the Idaho National Engineering Laboratory (INEL) which is a large nuclear R&D facility. There is one division in the Idaho Operations Office which handles alternative energy projects: the Energy and Technology Division. This Division houses the Energy Conservation Branch; I head this Branch and manage programs for two groups in DOE-Washington, D.C. These groups are: The Office of Industrial Programs, and the Office of Energy Systems Research (which is the group sponsoring the ECUT program and this workshop). My Branch is responsible for project management or program management -- depending on the subject matter -- for these two groups. EG&G Idaho, Inc. is the largest contractor at INEL; it is to INEL as Union Carbide is to Oak Ridge National Laboratory. EG&G Idaho has about 4,000 employees and Dr. Casper is here as a representative. EG&G Idaho provides my Branch with technical and management support.

I think it is important to give you an idea of the type of projects I am involved in because they all relate to heat transfer, heat exchangers, and energy conversion. Waste heat utilization is the biggest project area. My branch is involved in high temperature recuperators, high temperature burners, bottoming systems that generate power from industrial waste heat, and fluidized bed waste heat recovery systems. There are also a number of projects relating to the production of iron, steel, aluminum, and pulp/paper.

In the alternative materials utilization area I have, for example, a program to advance the technology to efficiently incinerate waste tires. I also have a project some of you may know about involving a novel process to make MTBE from low concentration isobutylene streams. In the category of

agriculture and food processing, I have projects involving hyperfiltration in liquid food products, improved technology in the canning of fruits and vegetables, and eight projects that are part of the Energy Integrated Farm System Program. So, as you can see, the Energy Conservation Branch is responsible for a wide variety of high technology projects.

ECUT Program

A large portion of my time is spent on the ECUT Program. ECUT is an acronym for Energy Conversion and Utilization Technology. This series of viewgraphs will describe the ECUT Program. The Assistant Secretary for Conservation and Renewable Energy is Joe Tribble. Within Conservation and Renewable Energy there are a number of Offices; as I said before, two Offices that assign projects to the Energy Conservation Branch at Idaho are the Office of Energy Systems Research, and the Office of Industrial Programs. The ECUT Program is in the Office of Energy Systems Research. In this Office, which is headed by John Brogan, there are four divisions, one of them being the ECUT Division. The ECUT Division Head is Dr. Karl Bastress. His Division is organized very simply; there are only two branches. One branch is labeled "Conversion", and the other is called "Utilization". The Physical Processes Project is under the "Utilization" Branch, and the Heat Transfer Element is part of this Project.

The words "Energy Conversion and Utilization Technology" were chosen very carefully. This R&D relates to decentralized, relatively small energy conversion and utilization systems. ECUT does not support basic research and stops short of development and demonstration of full scale hardware and systems. ECUT funding is for applied research. The goals of the ECUT Program are: (1) evaluate new or innovative concepts for improved efficiency or alternative fuel use in energy conversion and utilization equipment, and (2) expand the technology base necessary for development of improved energy conversion and utilization equipment by the private sector. ECUT supported research is intended to lower technical risk and confirm technical feasibility. Because of the high risk nature, ECUT research does not have to be as success oriented as do large demonstration and commercialization programs.

The ECUT Program contains six projects, each possessing a certain number of elements. The ECUT projects are Internal Combustion Engine Technology, Closed Cycle Power Systems, Direct Heating and Conversion, Physical Processes, Chemical Processes, and Materials.

Since its beginning in mid-1980, the ECUT Division of DOE has never had many people. Dr. Bastress, Director of the ECUT Division, strongly supports decentralization of project management to various field organizations. Physical Processes has been decentralized to the Idaho Operations Office of DOE, Chemical Processes is at JPL, Materials is at Oak Ridge National Laboratory, Direct Heating and Conversion is also at JPL, Closed Cycle Power Systems is at Argonne National Laboratory, and Engine Combustion is at Sandia-Livermore.

The particular elements of the Physical Processes project are: Heat Transfer, Feedstock Preparation, Industrial and Municipal Waste, Sensors and Control Systems, and Separation Technology. DOE budget cutting has reduced these five elements to two: Heat Transfer and Sensors and Control Systems. Each ECUT project is managed by objectives. Specific technical or management milestones are established and high priority is given to accomplishing them. These milestones are taken very seriously and each field manager is held accountable for meeting them.

ECUT must relate to technology that is associated with a real system, preferably a variety of systems. This Fouling Workshop is an important part of the Heat Transfer Element of the Physical Processes Project for it deals with a generic problem common to many energy conversion systems. The results of the Workshop will provide me with guidance in this particular technology area; specifically, what should ECUT be doing, if anything, to resolve major fouling problems? If it so happens that participants of this workshop feel that fouling problems are under control and there is no place for ECUT in this technology, then I have accomplished my objective here.

This viewgraph depicts the organization of the Physical Processes Project. Dr. Jim Eberhardt is the Branch Chief of the Utilization Branch in the ECUT Division. I report to him. I am responsible for field management of the Physical Processes Project. I am the principal decision maker. My recommendations are often accepted by Dr. Eberhardt and his immediate

superiors in DOE-Headquarters. It is naturally important that I have accurate inputs to make credible arguments to ECUT management. Because the ECUT organization is simple, final approval of specific research projects is not a lengthy process.

Heat Transfer Element

I shall now discuss the Heat Transfer Element. All activities in this element must be generic, the results must impact a broad spectrum of energy conversion equipment, and there must be reasonable energy savings if the results are implemented nationally. The chore of trying to estimate energy savings from successful high risk research is difficult and often frustrating. Often times the research is so high risk and advanced that one cannot foresee all applications; this makes energy savings calculations very uncertain. However, estimated energy savings are a necessary input in deciding which activities are funded by ECUT so I must have this information.

As stated before, ECUT-supported activities cannot displace private sector investment. The applied research must be perceived as being at such a high level of risk that the private sector would not invest in this technology at this time. The ECUT research must also be visible and address real problems that the private sector recognizes as being important.

In a study I did a couple of years ago, several generic heat exchanger problems were identified that affected the timely introduction of energy efficient equipment and conversion systems. Heat exchanger technology relies, in general, on a rather old technology base which is often inadequate today because the environmental demands placed on heat exchangers are significantly greater. Different types of fuels are being utilized and we are trying to get as much as we can out of the equipment. The recovery of energy from very high and low temperature sources is impeded by severe technological and economical deficiencies. At low temperatures, for example, we need enormous surface areas using conventional heat exchangers which make low grade heat recovery uneconomical. To account for technical design deficiencies, designers use very large safety and performance margins; when we do this the equipment gets big and the cost gets high. In addition, there is very little interest in advanced energy recovery systems until they are built and operated for a

reasonable period so the buyer and developer know that they are going to work as desired. Subscale systems are fine, but people wanting advanced systems want demonstrated performance at fullscale.

Activities within the Heat Transfer Element address critical heat transfer/heat exchanger problems in energy conversion equipment. ECUT attempts to resolve major problems to accelerate the introduction and implementation of these new systems. ECUT eagerly seeks very novel ideas, those that are particularly high risk and long-range. Under ECUT sponsorship, these novel ideas will be explored and evaluated to a point where the private sector can make a proper assessment of their merit.

Based on identified technological problems, stated ECUT objectives, and specific guidance from the private sector and DOE, the Heat Transfer Element of ECUT is currently focusing on techniques to mitigate heat exchanger fouling problems, flow induced vibration of shell-and-tube exchangers, and exploring novel heat transfer enhancement devices. To more effectively disseminate technology base information to the private sector, ECUT management is also considering the establishment of specific focal points around the country for selected areas of technology; for example, heat exchanger fouling and flow induced vibration of shell-and-tube exchangers.

In FY'81 the Heat Transfer Element of ECUT had budgeted approximately \$500,000. This Fouling Workshop is a portion of this effort. In addition, Webb Marner of JPL is conducting a study of cement plant waste heat recovery and its accompanying fouling problems. ECUT is also studying heat exchanger fouling in glass plants. Supported by ECUT, EG&G Idaho is conducting an experimental program on fouling of finned tube exchangers in Diesel exhaust environments. Argonne National Laboratory is responsible for the Flow Induced Vibrations Project and General Atomic Company is investigating a particular type of low-cost spirally fluted tube. Also with FY'81 funding, ECUT is supporting, at Garrett AiResearch, an experimental study of chemical vapor deposited coatings for high temperature heat exchanger protection. ECUT recently sponsored a Workshop at SERI on Research Needs of Heat Transfer Processes and Equipment.

Plans for FY'82 are not complete and the ECUT budget is not yet finalized. I expect that the Heat Transfer Element will be funded at least as much as in FY'81. ECUT management will assess the results of the two fouling studies and this workshop and decide what specific fouling research will be supported in FY'82. Your input will be very important in this process. ECUT money has been set aside for addressing heat exchanger fouling problems in FY'82. An ECUT budget for FY'83 has been approved by the Office of Management and Budget. Although the total FY'83 ECUT budget is much less than FY'82, I expect there will continue to be interest and support for the Heat Transfer Element.

Question and Answer Session

Manner: Bill, we have five minutes. Would you want to entertain some questions?

Thielbahr: O.K., I will take a few. The question has been asked by someone, "Will copies of my presentation be made available?" Surely, there is nothing in what I have discussed that is at all sensitive.

Eissenberg: My name is David Eissenberg, from Oak Ridge National Laboratory (ORNL). I just wanted to say that you did not mention the coal conversion heat transfer interests at DOE. And I wanted to note that I am here basically to represent the DOE Office of Coal Gasification, or Division of Coal Gasification, and to find out and to contribute to their interests in dirty gas fouling.

Thielbahr: Dave's comment concerns a program under the Assistant Secretary for Fossil Energy. Fossil Energy is also interested in heat exchangers, heat transfer, and coal conversion systems.

I should point out that in planning this Workshop we had a difficult time with the words "fossil fuel exhausts", trying to convey what that means within the purview of Conservation and Renewable Energy. Programs under the Assistant Secretary of

Conservation and Renewable Energy do not involve the development of coal conversion systems; that technology is strictly within the province of Fossil Energy. In Conservation, we seek to advance waste heat recovery technology in the residential, industrial, and commercial sectors. This Workshop includes heat exchanger fouling in environments produced by the combustion of coal-derived fuels because industry is interested in these fuels. We did not know precisely where to draw the line on this subject; it is clear that we do not want to include fouling by coal slagging in big, coal-fired boilers. However, in Conservation we are interested in heat recovery from the combustion of coal-oil mixtures and heat recovery downstream of a primary coal-fired boiler. If that domain of heat exchanger fouling seems poorly bounded, it is meant to be.

Webb: In your budget, how many dollars do you have committed in FY'82? Is your budget for FY'82 the same as FY'81? How many dollars will be available for new program work in FY'82 beyond what is presently committed?

Thielbahr: You are going for the jugular vein, Ralph. There are certain heat transfer FY'81 projects that will be continued in FY'82. Ralph's question concerns which specific projects have an ECUT mortgage in FY'82. It is expected that Art Bergles' heat transfer enhancement project at Iowa State will be continued in FY'82; and there is continuing work at Argonne with flow induced vibration of shell-and-tube exchangers. That is all. An approximate number for the maximum amount of funding for new FY'82 initiatives is \$1M. There have been some ECUT funding cuts and, as I said earlier, the final FY'82 budget is unknown. If the Heat Transfer Element budget is much less than \$1M, the ECUT management will have to make some hard choices between direct contact heat transfer, heat transfer enhancement, and high temperature heat exchangers.

Marner: O.K., Bill, why don't we cut it off there.

SECTION 4

PANEL DISCUSSION

WHAT WE KNOW AND DON'T KNOW ABOUT
GAS-SIDE FOULING

Group A: R. E. Thompson

Group B: T. E. Duffy

Group C: R. C. Weierman

Group D: G. Borushko

Group A: Characterization of Fossil Fuel Exhaust Gases

Richard E. Thompson, Panelist

Introduction

My topic is the "Characterization of Fossil Fuel Exhaust Gases," which has been divided into what is known and what is unknown following Webb Marner's recommendations. The objective is to try to identify some of the major variables in combustion system design and operation that influence gas-side fouling. In some cases the mechanisms that lead to the fouling are known but in other cases there exists only qualitative correlations or observations of fouling occurring under certain operating conditions.

A more detailed characterization of the exhaust gases is an essential step in obtaining the information needed to understand gas-side fouling. Frequently, the measurement methods to characterize an exhaust gas are well established and the primary need is for more test data with different fuels and operating conditions. In other cases, the development of new measurement methods are needed to properly characterize the exhaust gases so that the heat recovery equipment manufacturer can in turn design for the anticipated fouling environment.

It should be emphasized that in this presentation, I am not going to get into a detailed discussion of fouling mechanisms. I will offer a somewhat subjective opinion about what is relatively known and unknown with regard to characterization of fossil fuel exhaust gases, but some of you may not agree. My intention in "putting my head on the chopping block", so to speak, is to serve as a catalyst for questions and a discussion later in the session about what type of R&D is needed to satisfy the "unknowns". I put together some viewgraphs on characterization of exhaust gases from the standpoint of gas-side fouling for different categories of variables that affect the process. The degree and type of exhaust gas characterization performed is often dependent upon:

1. The type of fuel being burned.
2. The type of combustion equipment and operating mode.

3. The burner design.
4. The measurement methods or instrumentation available for the operating environment.
5. The use of fuel additives or waste inorganics that alter normal combustion conditions.

There are other categories of exhaust gas variables that I cannot cover, because of time constraints, but this list should stimulate some discussion of the major concerns.

Types of Fuel

Fuels are one main area of interest with a somewhat natural progression of increased interest or concern about fouling and exhaust gas characterization starting with the light gaseous fuels progressing to the heavy liquid or solid fuels. There is an increased interest in synthetic and alternative fuels that have not been well characterized, as well as the combustion of conventional heavy fuels in low-NO_x operating modes.

The exhaust gas composition of natural gas fuel has been very well characterized in most industrial applications and is of little or no concern from a fouling viewpoint. The combustion of distillate oil is also well characterized with the possible exception of Diesel applications, particularly with low level heat recovery equipment or "bottoming cycles". Heavy oil, particularly high sulfur residue, is not as well characterized, and there is a need for more information on sulfate formation (acid smut), and the dependence of fouling on trace metals, back-pass time-temperature history in boiler convective sections, catalytic effects of surfaces and oxides, etc.

Recently, the increased use of coal has led to the characterization of exhaust gases and emissions from a variety of coal-fired combustion equipment. However, this increased activity has also revealed that the exhaust gas composition is more dependent upon the coal type, equipment design, and sample technique than with other fossil fuels using the same measurement methods. Exhausts from methanol are pretty well characterized and

so are exhausts from gaseous and light fuels in a low-NO_x combustion mode. I included the latter category because of emission control considerations that can influence exhaust gas composition in some cases.

On the unknown side of the fuels category, there is quite a bit of work being done on exhausts from coal-oil and coal-water slurries, but only the gaseous composition could be considered to be well characterized. There needs to be quite a bit of ash effects work done, particularly in terms of particle size and trying to predict the benefits of using a slurry with a beneficiated coal. DOE is about to fund a coal-water slurry program with different degrees of beneficiation and hopefully that will add some information. There are limited full-scale data for SRC-I/II, solvent refined coal. SRC-I is a solid product that is essentially a chemically beneficiated coal. Once it has been through the process and cooled, it is an ash-free coal that is sometimes formed into a briquet. SRC-II is a liquid product, and it is more hydrogenated. One of the major concerns about the SRC fuels is that they are possibly more prone to soot formation. Also, the dependence of exhaust gas composition on combustion equipment is not very well characterized for these fuels.

There is quite a bit of work going on in coal-derived fuels but detailed characterization of combustion products may not occur until the fuel preparation processes are finalized and commercial quantities of fuel are available. One area that I think has some promise but needs more characterization is emulsified fuels. There is a lot of controversy about whether emulsified fuels give you a cleaner exhaust or not -- it seems to be very application dependent. Recent research in emulsified fuels shows that a good distribution of water droplets in the fuel can give you a lot better combustion and a lot less soot formation. The total ash cannot be changed, but at least there may be a way to reduce the carbon formation.

Eisenberg: Would you explain what you mean by an emulsified fuel?

Thompson: Water emulsion in a fuel, very fine droplets evenly distributed.

Eisenberg: With oil or coal?

Thompson: With oil, primarily. I don't know of any work with other fuels.

Medium and low Btu gas is a fuel category with very minimal fouling concerns. I think the main question is the dependence on trace compounds in the gas. And that is an economic problem of the cost of scrubbing them out versus leaving them in and trying to handle the problem. Finally, the one area that is a concern in meeting emission requirements is the use of heavy and alternate fuels in low-NO_x combustion modes. Typically, NO_x emissions are controlled with staged combustion (operating very fuel-rich in one region and then adding air subsequently). The primary concern is burnout in the second stage to minimize soot formation. Some of the new fuels now being tested in combustion research laboratories have a tendency to soot and smoke and have a high aromatic content. Therefore, they do not stage very well. This tendency to soot is dependent upon the fuel preparation process. They are continually adjusting these new fuel compositions from pilot plants to address the problem, but it is still a major concern.

Burner Design Parameters

Another area of interest, besides the fuel, is design of combustion equipment, particularly burners. Since this is where the whole process starts, it is an important factor in the soot formation.

On the known side of the ledger, and again this is a personal opinion, pressure atomization of liquid fuels is a fairly refined art, but it obviously is not a science. For gaseous fuels -- there is some dependence on gas ring and spud design, but it is fairly well characterized. Flame stabilization is an important concern in burner design and involves the fluid mechanics of swirl and often is very configuration dependent. Finally, the interaction between burner designs and combustor flow patterns for maximum carbon utilization in multiple burner units becomes more complex. This is a real problem for people who have done development work in single burner applications and then install them in multiburner applications and find they have quite different exhaust gas compositions.

For many fuels, the dependence of soot formation on the fuel system operating parameters is relatively unknown. Our firm has done a lot of work

with viscosity control and fuel firing temperature, but there is still quite a bit that can be done at extreme turndowns to minimize particulate and soot formation. There is a strong sensitivity to atomizer tip location relative to the diffuser and other burner geometry factors. Research continues but many exhaust gases are still a long way from being well characterized.

With synfuels, the question is one of high aromatic compounds leading to soot formation. Most of the soot formation work is being done at the research labs at the universities. Another unknown is the dependence of cold-end condensation species on combustor design and the interim time-temperature history. SO_3 formation and condensation on particulates and soot is also a function of the initial combustion process, even though it is generally considered a back-end problem. The potential benefits of using emulsified fuels, if any, brings up the question again of the burner design as well as just the better atomization of the fuel droplets. In other words, you do not get all the potential benefits from emulsified fuels just by making them -- it also depends on how you combust the fuel spray.

Measurement Methods in Combustion Systems

Another concern, of course, is the measurement methods for characterizing exhaust gases. An important variable in exhaust gas composition is not only the fuel and the burner equipment, but also the measurement method in some cases.

Techniques are fairly well known for measuring gaseous composition, particulate loading, particulate size, ash composition, and carbon fractions. Acid dew-point probably needs some further study, and sulfate measurements are somewhat technique dependent.

Relatively unknown are methods for accurate measurement of contaminant formation rate and condensation mechanisms, cloud formation, and other fouling related factors. The interaction of gaseous and particulate species properties at operating temperatures is important but not well understood. This is one of the limitations in laboratory experiments that try to simulate the exhaust gas environments. Another big question is agglomeration. Often you know what size particles you have in a coal-oil slurry or in a pulverized

coal/air mixture. But what does it mean in terms of ash properties as a function of the flame zone time-temperature history? Another need is accurate reproducible real-time particulate characterization as opposed to batch measurements. Finally, an area that is relatively unknown is measurement techniques for examining -- in actual industrial heat transfer equipment -- supercooling condensation mechanisms.

Smoke and Corrosion Suppressant Additives

At first I was not going to say much about additives partly because some other people are going to cover them. Also, I will just talk about them from a flue gas characterization standpoint because they are so controversial.

I guess the only thing that I am comfortable in saying is "relatively known" are the generic additive compositions and possible benefits. Many of us will agree that user satisfaction and technical performance is not well documented.

Unknown, from a gaseous exhaust gas characterization standpoint, are some of the gaseous and solid phase reactions, both for combustion improvers and cold-end corrosion additives. From our point of view, even though you know generic chemical composition, there is still a lot of dependence on the physical preparation method -- in other words the grind size, pore size, and specific surface area. Other variables are the injection method, carrier medium, temperature history, and how much the environment has changed the surface structure of the catalyst. Also unknown are the reasons for the substantial site-to-site performance variations in almost identical applications (e.g., where you have two identical boilers that are sitting right next to each other).

Combustion Equipment Categories and Operating Parameters

The last thing that I would like to cover, while trying to stay within the time allotted, is a topic that we think is perhaps one of the most important in terms of influencing exhaust gas properties. The relationship of fouling properties of exhaust gases to specific combustion equipment categories and the operating parameters is very important.

I think we do know a lot about the relationship between the major gaseous species and the primary combustion control parameters of boilers, furnaces, and these other devices. We also know (or can predict) the approximate ash loadings for a specified fuel. However, there are still more data needed, I think, on SO₃ formation for some combustion devices. Another factor that is understood in a qualitative sense -- by physical observation, not by any quantitative measurement -- is the importance of "off-design" operating conditions that could aggravate gas-side fouling. Many fouling problems appear to originate during light-off of direct fired units, during high turn down, or combustion upsets. These "off-design" combustion conditions deteriorate with wear and corrosion of equipment and maintenance-related problems. We have seen a lot of cases where the data suggest that these operating conditions may have been the precursors, so to speak, that started the fouling problem, made it worse, or aggravated a situation that could have been handled under normal circumstances.

Relatively unknown is the particulate size dependence on specific combustion equipment design categories and operating parameters. There is still a great deal of characterization needed there. Everybody talks about total particulates (or ash) loadings but the actual breakdown of the particulates into the carbonaceous fractions, inert material fractions, sulfates, and other "pseudo-particulates" or detailed size characterization is lacking. This often leads to the question of, "What is particulate?" What is considered particulate at one temperature may not be particulate at another temperature. The fouling problems you experience may be very much dependent on condensible "particulates" that are not really there as solid particulate at higher temperature upstream locations where measurements were made due to limitations of physical access within the heat exchanger.

The dependence of fouling on increased component wear is, in my opinion, a very important factor in exhaust gas composition variations -- (e.g., Diesel injectors, blowby, burner orifice erosion). I have seen many utility boilers where their problems were directly related to the wear of equipment at the burner front.

Another unknown is the nuances of soot formation, the dependence on fuel injection pattern, injection schedule, fuel viscosity control, premixing,

etc. An area that has been studied quite heavily recently is acid smut formation mechanisms and their dependence on component specific design. There is also a trace element fuel dependence involved in some cases -- sodium content. Finally, an area in which we are doing quite a bit of work for EPRI is potential fouling due to emission control techniques. With NO_x control systems using ammonia injection, there is a concern about sulfate formation in the air preheater or other heat recovery equipment leading to fouling and increased backpressure.

The last thing that I wanted to mention, that is not on the charts, is that many of the fouling concerns relate to the use of conventional heat recovery equipment. There is another whole category of direct contact flue gas condensation heat recovery equipment which should be considered to avoid the traditional concerns of fouling due to operation near the acid dew-point. With direct contact flue gas condensation heat recovery, you remove a certain level of high temperature heat, and then go immediately into a complete condensing mode. This condensation process traps many of the fouling species in a manner similar to that of an exhaust gas wet scrubber. Also, the transfer of heat at a slightly lower temperature frequently reduces the equipment corrosion problem. Materials that would be severely affected at higher temperatures have longer lifetimes at lower temperatures. Considerable research and development in direct contact heat exchange is needed to optimize the handling of exhaust gases with high fouling potential.

Group B: Gas-Side Fouling Characteristics and Mechanisms

Thomas E. Duffy, Panelist

Introduction

What I will try to do is stimulate some ideas. The parameters such as velocity, temperature, characterization of gases, and geometry are all associated with fouling of a compact heat exchanger. Solar's interest in this area goes back several years. Solar Turbines Incorporated has hundreds of gas turbine units out in the field with waste heat boilers in the exhaust. Most of these are relatively standard types of boilers that are available from industry. Several years ago Solar Turbines looked at the increasing price of fuel that was becoming an apparent trend and also the availability of fuels. We decided it was necessary to go into heat recovery with the development of a very compact waste heat steam generator.

Naturally, with the development of a compact unit like this, our interests turned toward potential problems associated with gas-side fouling. In order to investigate these, we approached it with experimental rigs. The first was essentially a 4,000 hp engine with a waste heat steam generator soot evaluation module. We also did a number of bench scale tests, as well as tests with this large module. The module produces the most realistic type of soot fouling data that we have been able to obtain. It, however, is fairly expensive to operate; therefore, we have also used various subscale models and bench tests to complement this work.

Engine Soot Evaluation Module

Starting with the module, it is a full-size gas-flow path version of the waste heat boiler. All the geometries of interest are incorporated, as well as the temperature profiles and velocity profiles. Instrumentation was extensive, to determine the actual tube temperatures, fin temperatures, and the gas temperatures. The exhaust gases come from beneath the unit and flow up through the unit. This has a surface area of 24,000 ft², and its dimensions are roughly 8 ft by 7 ft by 8 ft.

We were reducing exhaust gas temperatures to 230 F. Again, this was designed for perhaps -- at the time we went through it -- to the ultimate in terms of reducing the stack temperatures. And there are zones in which we get into sulfuric acid dew-point issues. I will go to some overall results that we obtained from this particular test program using a full-size boiler module, and then I will go back into specific parameters such as velocity, temperature, and the geometry. We performed a 100-hr test, to get into equilibrium fouling conditions.

The loss of boiler performance dropped off because of soot fouling. We were running No. 2 Diesel fuel. The engine opacity was running somewhere in the order of 14 percent. There is a limit in Southern California of 20 percent. However, there is a practical limit, where people complain, somewhere around 14 percent. So, we were running at the 14 percent limit. Essentially, with the engine was at full power, the boiler was starting at 100 percent steam generation and there was a rapid reduction of the performance of the steam generation capability of the unit. This particular unit produced superheated steam, with water entering at 90 F in the test module.

Results showed that fouling stabilized in about 65 hours with a loss of approximately 7 percent of the steam generation capabilities and then it stayed at that level or possibly improved for the remaining 40 hours. There is always some data scatter in tests like this. It is difficult to repeat each of the calibrations because conditions change. We were looking at pretty small changes in boiler performance, but there was a stabilization in about 65 hours with a possible trend of slight improvement after 100 hours.

The effects of fouling on the pressure drop across the steam generator was also investigated. The down performance was about seven percent of steam generating capability. Again, it tends to support the concept that there is a stabilization or possible improvement after this period of time which introduces another factor. I am not sure it is on the list here, but time is an extremely important parameter -- on the fouling rate.

Both operating time and shutdown time are important. These particular tests were run with 92 F water inlet temperature with a once-through boiler. There was some condensation in the first 2½ rows. We were able to correlate

well with expected SO_3 conversion rates and the location of the dew-point as a function of the fin temperature. It seemed to be repeatable enough that we could see the difference in the leading edge of the fins to the trailing edge, in terms of dew-point. I might mention that this dew-point occurred with the Diesel fuel running with 0.14 percent sulfur. So, it was relatively low sulfur No. 2 Diesel Fuel.

But there was one thing that was extremely apparent and that is that temperature is an extremely dominant feature. This unit had about 400 thermocouples, so we obtained a good temperature history of it. We could go back and measure soot thickness and relate it quite accurately to temperature. And, at the superheater end there was no soot. As we went through the unit, we could find a very clear correlation between surface temperature and the thickness of the soot. This is just a general characterization of the type of soot. We found in general there were several types of soot somewhat related to the temperature level and the fuel type. Fuel type does have an important influence on the characterization of the deposited soot. This research included measuring corrosion penetration, particularly where there was dew-point involvement on mild steel fins over a period of time. Chemical characterization of the composition of the soot was made. Of course, carbon content was very high and there was some iron from corrosion products. Generally, the soot had a very high percentage of carbon (70 percent) and a very high percentage of sulfur also. And that is from fuels that were in the 0.1 percent sulfur regime. Soot was found to contain approximately 25 percent sulfur, which is quite a concentration of the sulfur in the soot.

The acid dew-point correlations were good in terms of measuring the actual SO_3 , and relating them to published ASTM techniques for making these calculations. We also were able to correlate well with the actual dew-point locations along the tubes. We also looked at corrosion pit penetration, or affected areas, as a function of sulfur.

One observation was made that the soot seems to catalyze the corrosion, particularly adsorbing, absorbing, or otherwise concentrating the sulfur attack on the fin materials. Another observation was the percentage of fin area affected by sulfuric acid corrosion versus the location within the

boiler. When we go from Row 1 through Row 45, we are going from the cold end where water enters at 90 F, passing through the dew-point and, as expected, a very sharp drop-off was observed in soot formation where the unit was not operating within the dew-point. However, there was still an affected zone throughout the unit. There are several explanations for that, and I think I should mention that these effects were significant. Penetrations in 100 hours were quite high. We were able to hold test conditions for approximately 100 hours and compare tubewall temperature versus the sulfuric acid dew-point temperature with actual tube wetting. We were quite interested in locating that wet zone cutoff to save as much energy as possible, and yet not have the heat exchanger turn to ashes or rust. We found that the fouling could be correlated directly with the dew-point location.

Relative fouling was a function of temperature in the low pressure superheater where the wall temperatures were 800 F. The tests showed how the relative fouling factor varied as we went through different temperature zones of the boiler. Of course, we could have broken it down into smaller zones, but we correlated various sections of the heat exchanger such as: preheaters, vaporizers, and superheater. There are two boilers in this particular unit -- it is a dual pressure unit -- and we could see a very distinct correlation with temperature. This is almost another way of measuring the temperature of the tubes in the unit. In this particular series of experiments, the wall temperature seemed to be the dominant parameter correlating with fouling factors.

There were a number of other experiments run on that particular unit where we used bare air-cooled tubes in the exhaust. We examined the velocity effects and found that there were no velocity effects on the initial soot deposition of any consequence within a range of velocities of 25 to 200 ft/sec. Soot would deposit uniformly regardless of the velocity or direction of flow, except for the shedding phenomena. Shedding is a velocity-dependent phenomena where you have large chunks of soot that have already been deposited that moved from one row to another. In these experiments, shedding moved upwards in our flow regime, but the shedding phenomena was a very important velocity effect. The initial deposition of soot, from the testing that we ran, showed that it was uniformly deposited, almost like a vapor-deposited process, extremely uniform. And, in some cases it did not matter whether the

velocity was zero or up to hundreds of feet per second. The deposition still occurred at the same rate.

Test Cell Module

We, in parallel with these tests, worked on a much lower cost test. It was a test cell version to try to use a small liquid-fuel-burning combustor with a high flexibility on primary air, secondary air, and a small heat exchanger module with various types of finned tubing and temperature regimes. Its purpose was to develop correlations between the full-scale engine tests and a more economical bench scale system. This particular unit is much more cost effective. We found that measuring the smoke index gave us the best test correlations. We were able to compare a combustor rig with an actual engine. To do this we would use the same fuel and adjust the combustor to have the same soot loading. In this case we were using opacity as a parameter. We would measure the soot buildup and its characteristics as a function of that soot loading and compare the time and operation with the actual engine tests. What we found is a relatively good correlation with soot opacity measurements. There was a problem with the rig in correlating the soot removal. Deposited soot from the rig that looked the same and had a similar composition as that of the engine soot did not remove itself as it did with the engine. I should mention that our interests are the "so called" selfcleaning method of soot removal. We turned the water off and removed the soot by increasing the temperature of the entire unit to over 800 F.

With our present module we can vary several parameters: soot loading, fuels, geometry, velocity, and temperatures. Different finned tube spacings are easily accommodated in the module. We found, in general, that geometry had no effect on deposition rates. Of course, it would have an effect on heat exchanger performance. Deposition rate and the characteristics of the soot, were also the same with both inline and staggered tube bundles. We used various coatings in one series of tests and found that they had no effect on soot deposition. However, the coatings did have a big effect on the soot removal, and it was a noticeable effect. Soot removal by the dry cleaning technique was greatly enhanced with coatings. We also had a field probe developed for soot fouling. Some of the experience we got on the field probe enabled us to correlate bench module and engine module data. The field module

was used in the exhaust of an LM 2500 engine in the Philadelphia Navy Yard. We also correlated it with tests on our engines at Solar Turbines and the soot combustion module. The results of these tests are documented in the referenced reports in some detail. But I think I might initiate questions by indicating that velocity had virtually no effect -- temperature was the dominant effect on this field test probe as in the rigs. Composition of the fuel does seem to have a significant effect on the deposition and also the cleaning ability.

Conclusion

In summary, there are quite a few unknowns in fouling even when working with Diesel fuels. However, we found that a very good correlation can be obtained, at least in deposition rates between various combustion rigs and an actual boiler, on an engine and a field test probe arrangement.

Group C: Design of Heat Transfer Equipment for Gas-Side Fouling Service

R. C. Weierman, Panelist

Introduction

Good morning, gentlemen. My assignment is to discuss with you some of the basic heat exchanger types used for heat recovery in gas-side fouling services.

Types of Heat Exchangers Used in Gas-Side Fouling Services

Figure 1 shows several aspects of one of the oldest types of equipment, the rotary gas-to-air regenerator which is used quite extensively in power generation boilers and petrochemical heaters. With this type of system, a set of rotating metal plates picks up heat from a hot gas stream flowing through them. The plates rotate into the cold air stream and release the heat. The rotors are made up of individual baskets filled with the plates which can be replaced as they become corroded or otherwise unserviceable. With this system it is particularly important that the plates be kept clean due to the possibility of spontaneous combustion when fouling is present. Cleaning is usually accomplished with air or steam sootblowers or with online water washing. Figure 2 shows examples of gas-to-air plate fin recuperators. Essentially, what you have is two channels, one or both of which may contain fins, with a membrane wall between them. This type is commonly used in heating combustion air for gas turbines. In this particular application the high pressure air flows in the narrow channel and the low pressure exhaust gas flows in the larger channel exposed to the fins. Figure 3 shows a cast iron finned element. I believe this type is more common in Europe, but it is now being manufactured in the U.S. This type has fins cast on both the gas-side and the air-side. The two halves are bolted together to make a single tube and then several tubes are bolted together to form the heat exchanger.

Eissenberg: What are the methods used for cleaning the cast iron units in dirty gases?

Weierman: I am not sure what they are using for cleaning these units. It would be possible to clean them with sootblowers in some areas. But I do not know how effective a sootblower would be on some of the long gas passages.

Borushko: You can use water wash and steam lance. You could also put dragging chains and so on on the outside.

The tubular-type heat exchanger is shown in Figure 4. This type of unit is also used in gas-to-gas service. Essentially you just have bare tubes exposed to the gas flow. As shown, it can be either a single pass or a multipass arrangement. A relatively new device being used in gas-to-gas heat transfer is the heat pipe. Its operation is illustrated in Figure 5. Essentially, you have a sealed pipe with some type of fluid inside the pipe. The fluid is vaporized at one end, flows down the tube and condenses at the other end. These tubes are put together either in plate fin units or as individual finned tubes in a bank. The tubes are also being used in boilers. In that case, one end of the tube will be finned for exposure to a hot gas and the other bare end will be put into a steam drum.

Eissenberg: Who are the manufacturers of this type of unit?

Weierman: I am familiar with Q-Dot Corporation in Dallas and Howden Thermal in Newton, New Jersey.

Getting into gas-to-liquid heat recovery equipment, probably one of the oldest types here is an adaptation of the firetube boiler. Instead of putting a burner on it, the hot gas stream is put through the inside of the tubes and water or another fluid outside the tubes is heated. This type of unit can easily be supplementary fired also. If the hot gas stream is intermittent, a burner can be added to give a constant steam output or a constant flow of heated fluid.

Where the fluid to be heated is more easily handled inside the tubes, a bare tube or finned tube bundle is commonly used. Typical applications for this type of equipment include convection sections on petrochemical heaters used to heat various process streams, boiler economizers for heating feed water, and steam generators used to produce process steam or drive steam turbines for power generation.

A new option which has developed recently utilizes ceramic tubes which look much like steel finned tubes except that they are made of a ceramic

material capable of sustaining very high temperatures and resisting certain corrosion problems. Another recent study used finned tubes in a shallow fluidized bed to avoid fouling problems. In this case, it appears that the fluidized particles help clean the finned surface and eliminate the buildup of fouling deposits on the tubes. The fluidized bed also enhances the heat transfer to the finned surface.

Kreith: Are there experimental data verifying this concept that the fluidized bed will inherently clean the fin?

Weierman: I have seen one paper on this concept. They were using copper finned tubes and injecting carbon black particles into the bed to simulate a flue gas exhaust stream. After several hours all the tubes had on them was just a dark discoloration, and no buildup or fouling to speak of. I think this essentially establishes the concept in general, but a lot of work remains to be done to see how far this concept can be carried.

Kreith: Were there quantitative measurements or just visual observations?

Weierman: The report also includes the heat transfer data. [Cole, W. E., "Investigation of Waste Heat Recovery Utilizing Fluidized Bed Heat Exchangers," Report No. DOE/ET/11348-T2, United Technologies Research Center, East Hartford, Connecticut, November 1978.]

Types of Extended Surface

At this point I would like to examine some of the various types of extended surfaces available. One of the oldest types is the stud. This type of surface has been in use in boilers and petrochemical heaters for over 40 years. Typical designs use half inch diameter studs up to two inches long. The new API Standard 560 limits stud height to 1 inch under fouling conditions. Since the standard is voluntary, this restriction will probably

be ignored whenever it is impractical. Back in the 1940's, a lighter weight stud was examined for marine economizer applications and this led to the development of the elliptical or lens shaped stud. It gives lower pressure drop and lighter weight, but is seldom used today because of cost considerations.

The most common type of extended surface in use today is the helically wound fin. These are produced in both plain and segmented types as shown in Figure 6. There is considerable controversy over the relative cleanability of the two types as the following two statements will attest:

"Segmented and plain fins are most frequently used as extended surface. We prefer the segmented ones not only for its slightly lower weight and slightly higher heat absorption (in most practical cases) with the same fin-configuration, but also because it is easier to keep clean. This is because the sharp edges of the segments cut larger solid particles in pieces and also because the steam jets emerging from the sootblower orifices can penetrate between the cuts to the root of the fins while in the case of plain fins the shaded area behind the plain fins are hard to reach. There is proof that with narrower fin segments cleaning is still easier." [Csathy, D., "Heat Recovery from Dirty Gas," Presented at the Sixth National Conference on Energy and the Environment, Pittsburgh, Pennsylvania, May 1979.]

"Both solid (or smooth) and serrated (or segmented) continuously welded finned tubes are available. Serrated-type finned tubes should be used only in a clean gas stream. Although the serrated fin does offer somewhat better heat transfer than the solid fin, soot can quickly accumulate in its serrations with cleaning becoming a real problem. As a result, only solid-type fins are recommended in dirty gas streams where oil coal, wood, or other high-fouling fuels are burned." ["Maximizing Heat Recovery," Tranter, Inc., Lansing, Michigan, 1981.]

This is obviously an area that needs more research. The smaller tubes shown in Figure 6 are 2 in. O.D. and are typical of those used in boiler economizers and gas turbine waste heat boilers. The larger finned tubes are made from 4 in. and 5 in. diameter pipe and are typical of tubes used in petrochemical heaters.

Design Considerations

Now this is where it gets dirty. To design a unit where fouling is expected some rational guidelines need to be followed. I went through the literature to see what had been recommended and a summary of those recommendations is shown in Table 1. Equipment designers have simplified the characterization of flue gases into three categories: clean gas, average gas, and dirty gas. Design parameters are given as recommended fouling factors, minimum spacing between fins or plates, and maximum gas velocity over the fins. Clean flue gas is usually produced when burning natural gas, propane, and butane. Burning No. 2 fuel oil usually produces an average flue gas but the recommended fouling factors vary depending on how it is burned. I found one author that said if you are burning No. 2 fuel oil in a gas turbine you have a fouling factor of $0.015 \text{ hr-ft}^2\text{-F/Btu}$, but if you are burning it in a diesel engine the fouling factor is double. So it appears that the type of fuel, along with how it is burned, is important and can affect the design of your equipment. As the fuels or flue gases get dirtier this would probably imply that some type of particulate loading and cleaning devices are absolutely necessary. In this category, we would envision coal as probably the worst case where the fin spacing has to be opened up the most. You will also note that recommended velocities are reduced as the flue gas gets dirtier to avoid problems of erosion of the surface.

Webb: Are those velocities correct -- 100 ft/sec is 6000 ft/min -- is that correct?

Weierman: That is right.

Eissenberg: How do you define the surface area and the fouling factor on an extended surface? Is that on the extended surface?

Weierman: The fouling factor here is based on the total outside surface area.

Samples of Fouled Tubes

Figure 7 shows a finned tube with a severe fouling problem -- it is plugged solid except for a section which has been cleaned out to show the

fins. The extended surface is not very effective when this happens. This piece was taken from an economizer on an oil fired boiler. The unit was designed for No. 2 fuel oil so no sootblowers were installed and a fairly close fin spacing was used. It was put into the field and as sometimes happens, they never burned No. 2 fuel oil, they only burned No. 6 fuel oil. The unit ran for almost three years before they gave up on it. Something about the heat loads -- they could not get anything out of it. This case is a very good example of what happens when you violate some of the basic design parameters.

Figure 8 shows an economizer tube which was designed following good practice, but even at that there were still severe fouling problems involved. The yellow color of the fouling indicated a relatively high sulfur No. 6 fuel oil and the scaling fins are typical of sulfuric acid corrosion. The problem here is probably a combination of low fin metal temperature causing condensation and an ineffective cleaning system.

Theilbahr: Chris, could you point out what a fouling factor of 0.02 hr-ft²-F/Btu looks like. A 0.02 fouling factor does not look like anything clogged. It looks relatively clean, right?

Weierman: The tube shown in Figure 9 is probably close to a 0.02 fouling factor. That is the kind of fouling that you are probably designing for -- not really too thick. You can still see what the fins look like. This one was taken out of an economizer on a coal fired boiler. This particular tube illustrates another problem just the opposite of what we have been discussing. This tube was right in front of a sootblower and as you can see, the fins have actually been cut off the side facing the sootblower.

The suspected problem here was condensate in the steam which made it much more erosive. Overall design on this unit was probably pretty good, but the problems were caused by operation.

Watts: What was the top clearance from the head of the lance of the blower to the tube?

Weierman: I think it was about nine inches.

Theilbahr: Chris, would you say that a fouling factor of 0.005 would dominate the thermal resistance of the system or would it be like 50 percent, 30 percent or less?

Weierman: This gets into the economic impact of fouling on design so let me go into that a little here.

As you look at most, say gas-to-liquid heat transfer situations, your overall heat transfer coefficients are in the range of, let us say 5 to 10 Btu/hr-ft²-F. In terms of thermal resistance this would be 0.2 to 0.1. In this case then, a fouling factor of 0.005 or even 0.01, is not too significant. You may end up increasing your surface area by maybe five percent. A ten percent increase would be a bad fouling case. So the extra surface area requirements due to gas-side fouling do not usually represent a great cost increase on a unit. I think the major costs are involved in the cleaning provisions.

Cleaning Techniques

In his paper Csathy discusses an extremely dirty case and the thing that drove up the cost was the cleaning provisions -- replaceable bundles, special cleanouts, and additional sootblowers. Sootblowers are pretty expensive. Another way to design for fouling is to make no provisions for cleaning, but adjust tube and fin spacing and total surface area for the highest fouling factor possible under those conditions. Can we design for that situation? In some cases you can, and in some cases you cannot. For the two cases I showed you earlier where the fins were plugged solid, obviously you would not design it to just let it run. You have to design clean. However, in another case we looked at recently, no cleaning was allowed because the dirty gas was actually a carefully controlled process stream. In this case, the unit was designed with a fouling factor of about 0.1 which remained fairly constant during operation. A fouling factor of this magnitude nearly doubles the amount of surface area required and the effect on the cost is proportionate.

Since some of you may not be familiar with some of the different options in cleaning, let me address them briefly here. Most of you are probably familiar with the steam sootblowers where high pressure steam is directed through a nozzle at the surface. You can also go to an air sootblower which does essentially the same thing except with high pressure air. Allowing tubes to run dry in gas turbine waste heat boilers was mentioned earlier as a viable cleaning technique. This causes the tubes to heat up to 700-800F and essentially burns off the soot. This can be augmented, it appears, with certain types of ceramic coatings which tests indicated seemed to enhance the burn off.

Medium and low frequency sonic horns are being introduced in the U.S. for cleaning purposes. The horns operate at 20 to 250 Hz and 100-145 db. The idea is to knock the deposits loose from the surface and let the gas stream carry them out.

Another method which is being used is mechanical vibration of the tubes to free deposits. I mentioned earlier the apparent cleaning effects of fluidized beds. Other possibilities include: (1) letting steel or ceramic shot fall through the exchanger, and (2) hanging chains in the bundle which are moved around to knock off deposits. There are very few data on most of these ideas so it is difficult to evaluate their effectiveness.

Eissenberg: Why are there so few data? Is that because each user has to invent his own thing or is it that people do not like to talk about it or what?

Borushko: It is proprietary and it is embarrassing.

Conclusion

Let me conclude my remarks with a few comments on the costs of fouling. Generally, fouling results in increased pressure drop which lowers efficiency of boilers and gas turbines. Fouling lowers the heat transfer rate which is compensated for by higher temperatures and higher fuel costs. Fouling increases maintenance costs involved in cleaning the tubes and replacing units made unusable by fouling. One of the biggest costs of fouling comes when a

plant or process must be shut down because of a fouled heat exchanger. Fouling has also been the cause of an untold number of fires which are generally catastrophic in terms of lost production and repair costs. Although we have come a long way in designing for fouling, we are still a long way from understanding many aspects of the problem.

TABLE 1.
DESIGN PARAMETERS FOR EXTENDED SURFACES IN FOSSIL FUEL FLUE GASES

TYPE OF FLUE GAS	FOULING FACTOR hr-ft ² -F/Btu	SURFACE SPACING in.	GAS VELOCITY ft/sec
CLEAN GAS (Cleaning devices not required)			
Natural Gas	.0005 - .003	.050 - .118	100 - 120
Propane	.001 - .003	.070	
Butane	.001 - .003	.070	
Gas Turbine	.001		
AVERAGE GAS (Provisions for future installation of cleaning device)			
No. 2 Oil	.002 - .004	.120 - .151	85 - 100
Gas Turbine	.0015		
Diesel Engine	.003		
DIRTY GAS (Cleaning device required)			
No. 6 Oil	.003 - .007	.180 - .228	60 - 80
Crude Oil	.004 - .015	.200	
Residual Oil	.005 - .02	.200	
Coal	.005 - .05	.231 - .340	50 - 70

References: Boyen, J. L., Practical Heat Recovery, John Wiley, New York, 1975.

Csathy, D., "Heat Recovery from Dirty Gas," Presented at Sixth National Conference on Energy and the Environment," Pittsburgh, Pennsylvania, May 1979.

Watts, D., "Economy Begins to Favor Heat Recovery," ASHRAE Journal, Vol. 12, No. 2, 1970, pp. 54-62.

"Escoa Engineering Manual," Escoa Fintube Corporation, Pryor, Oklahoma, 1979.

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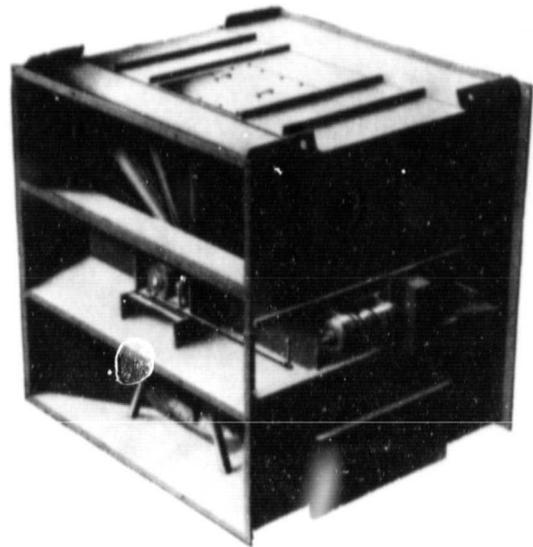
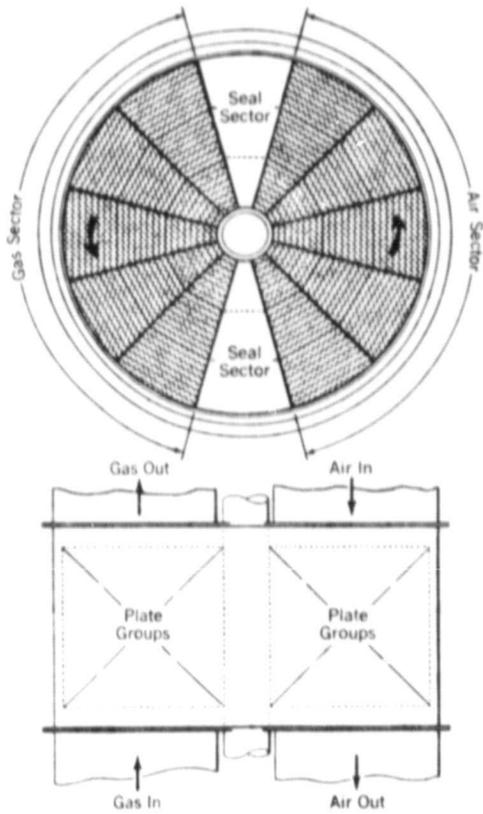


Figure 1. Rotary Regenerator

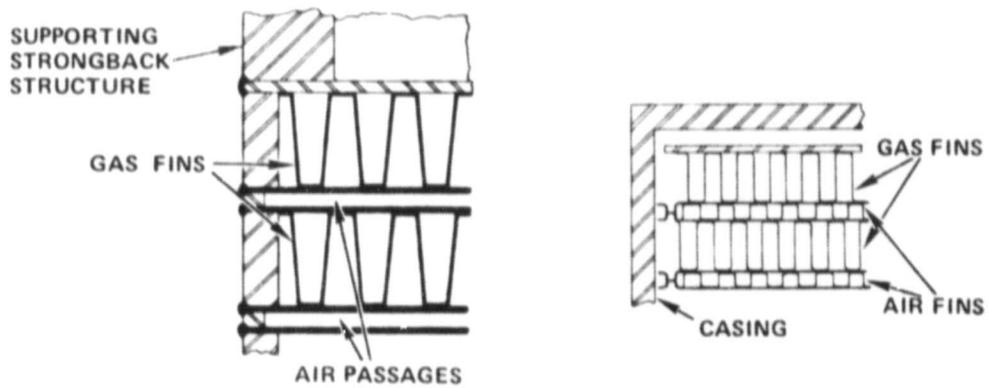


Figure 2. Plate Fin Recuperators

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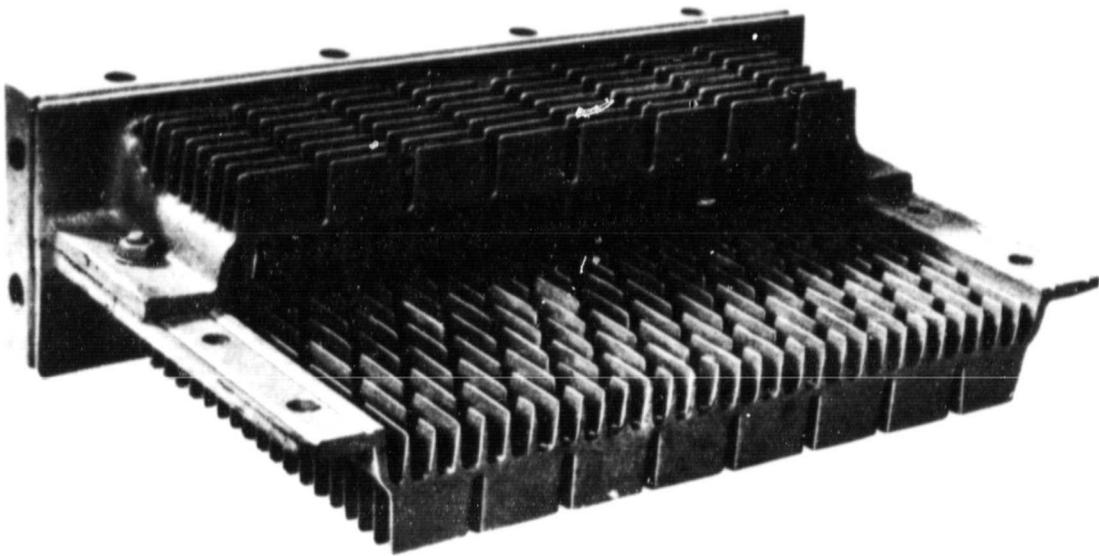


Figure 3. Cast Iron Finned Element

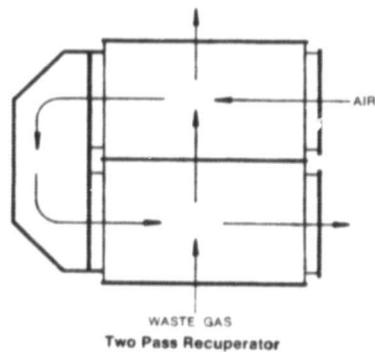
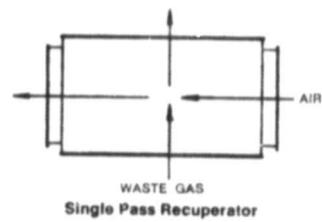
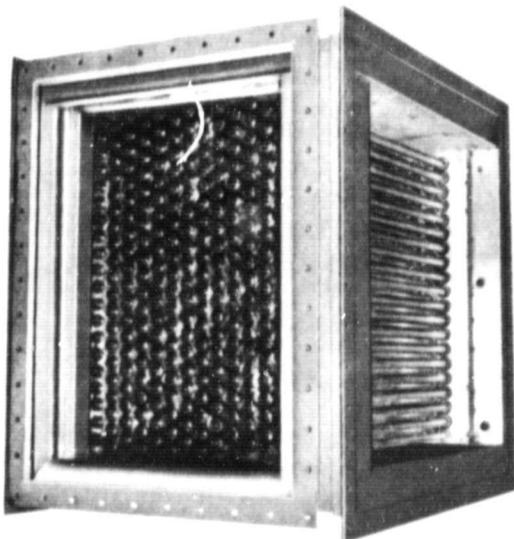


Figure 4. Tubular Recuperator

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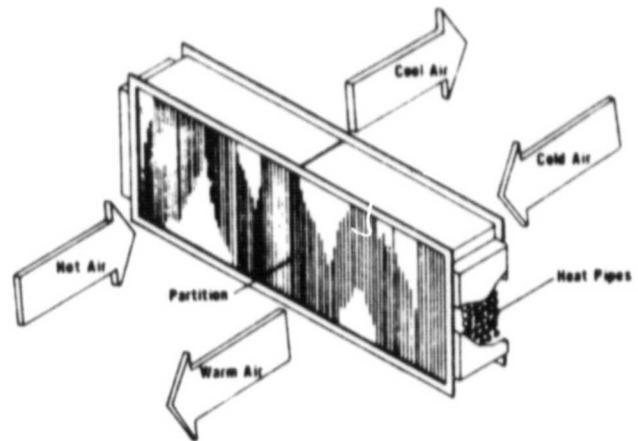
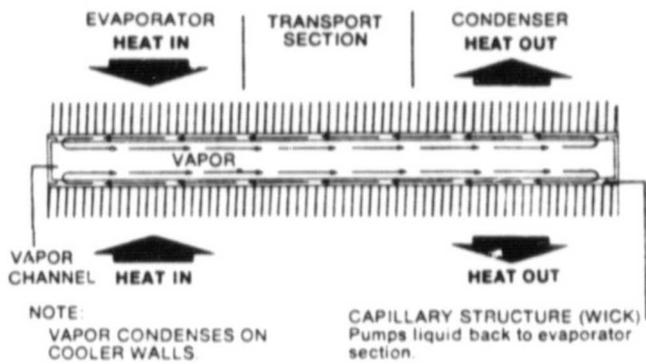


Figure 5. Heat Pipes

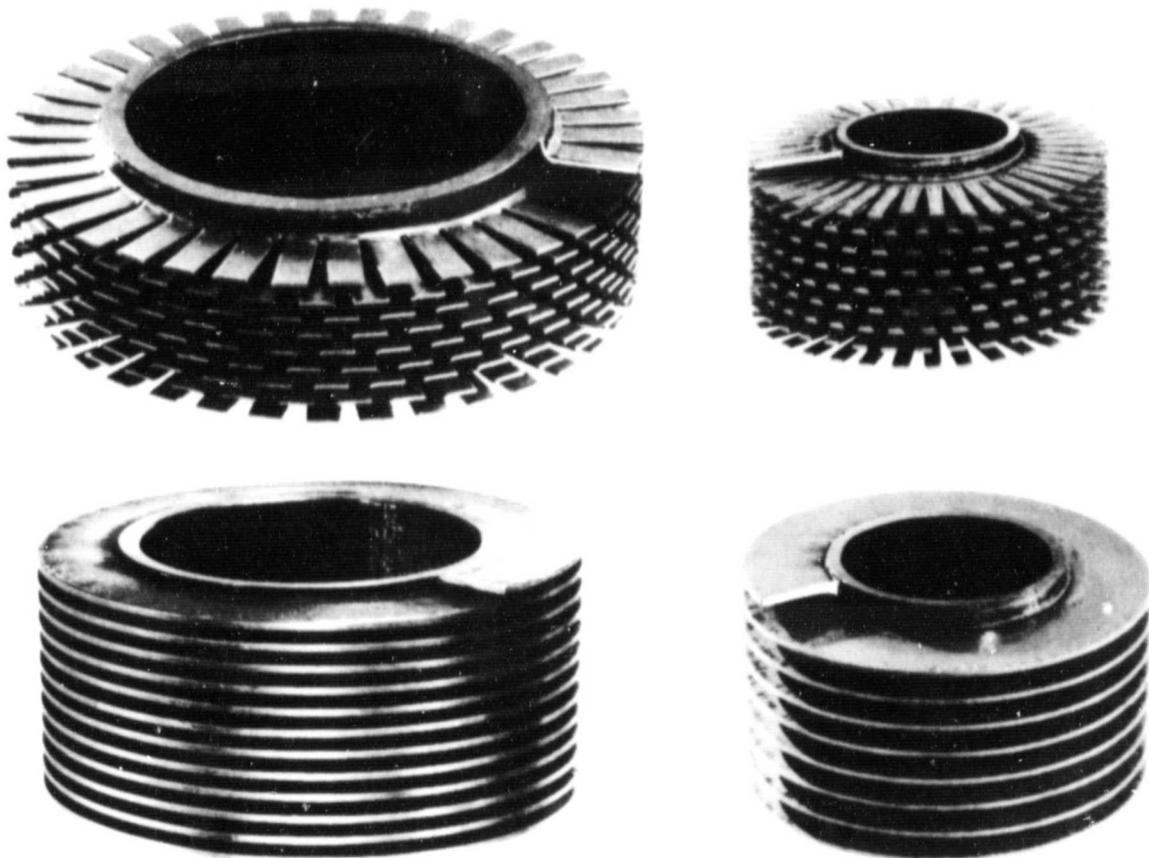


Figure 6. Plain and Segmented Helical Finned Tubes

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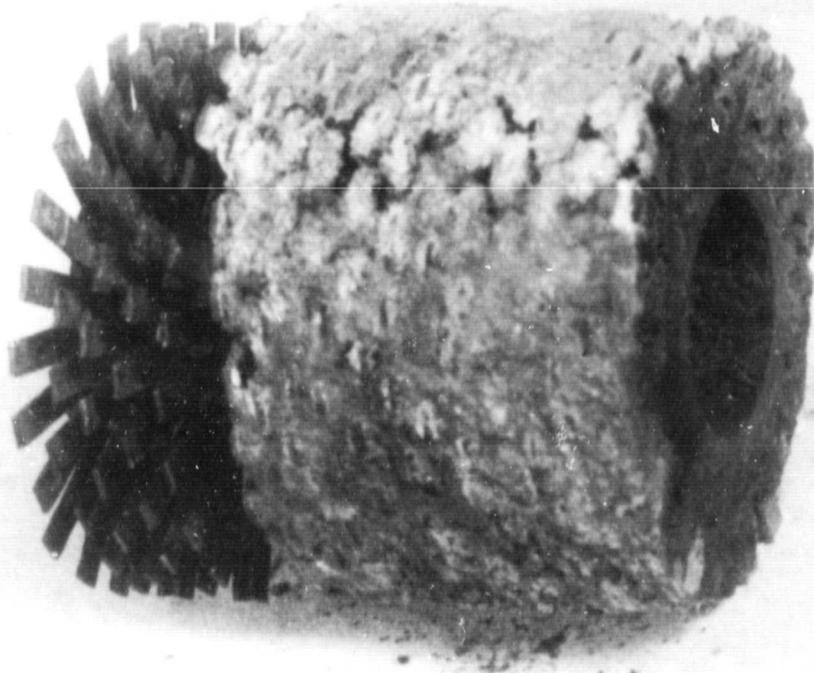


Figure 7. Economizer Segmented Finned Tube Fouled in
No. 6 Fuel Oil Exhaust

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Figure 8. Economizer Solid Finned Tube Fouled in a High-Sulfur No. 6 Fuel Oil Exhaust

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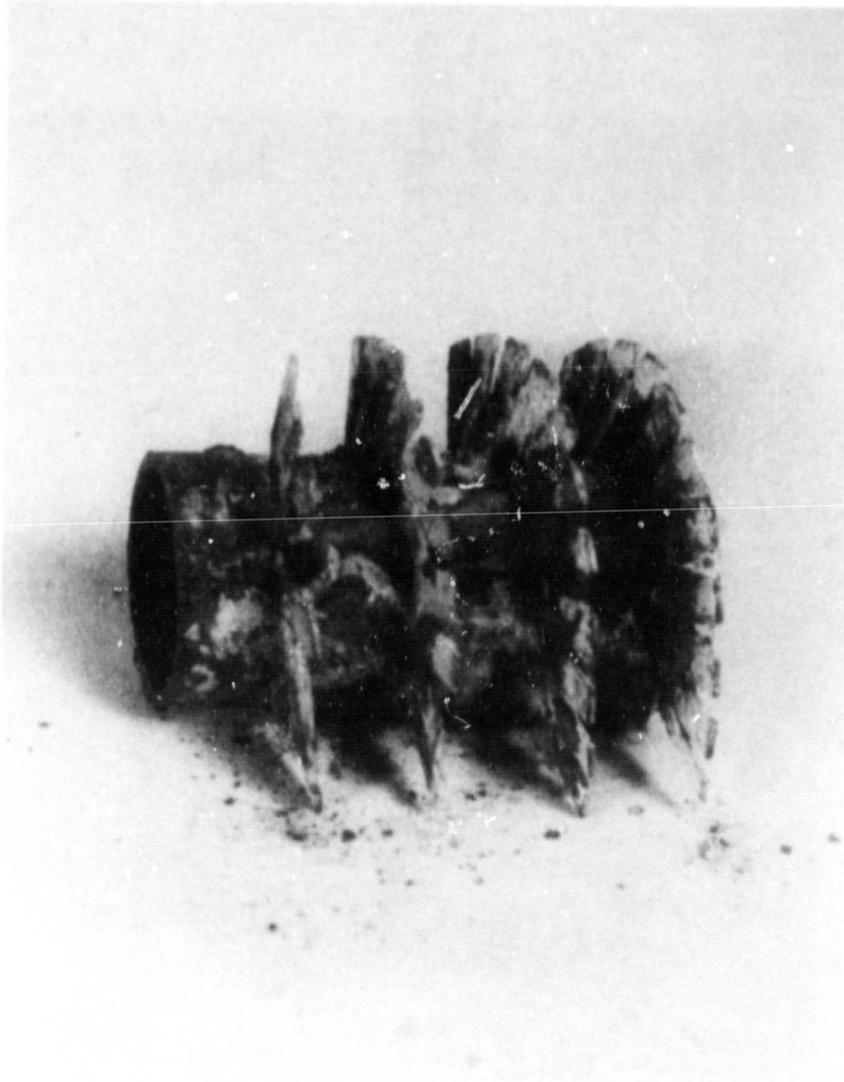


Figure 9. Finned Tube Fouled in a Coal-Fired Boiler Economizer
with a Portion of the Fin Cut Off by Sootblowers

Group D: Operating and Cleaning of Heat-Transfer

Equipment in Dirty Gas Environments

George Borushko, Panelist

Introduction

I am going to talk about part of the assigned topic, "What We Don't Know About Gas-Side Fouling." This is based on experience in our company installations. This tells me that the highest incidence of gas-side fouling problems is in the heat recovery steam generators in fluid catalytic cracking units.

Gas-Side Fouling in Fluid Catalytic Cracking Units

In the first applications, the total dilute phase of the regenerator--this is the device that burns the carbon off the catalyst--passed through a fixed tubesheet tubular boiler to keep the unit in heat balance. In those days, they were still working on methods to control the movement of heat between the regenerator and the reactor. There was no problem with fouling in these heavily solid loaded units because you had a massive content of catalyst in the flue gases which acted to scrub the tubes clean. Actually, the catalyst destroyed the waste heat boilers due to rapid erosion of the tubes. If you had a waste heat boiler lasting more than two months you were pretty happy. You had a very short run time so the waste heat boiler service factor was not very critical. With time, better catalysts and improved reactor design gave better utilization of heat between the generator and the reactor and there was no need for an external heat sink. The regenerator flue gases simply passed through cyclones and then were dumped to the atmosphere. However, this was an 1125 F gas stream, so there was incentive to recover this heat; we did this in waste heat boilers.

My first exposure to the problem was in a 1948 design in which I got involved. Based on some plant experience in a modified cat unit, we designed a firetube steam generator like the one shown in Slide 1. In a firetube unit of this type, gas comes in the top and goes out the bottom. The steam drum is on the side with the circulating water stream entering the boiler at the

bottom and the steam-water mixture returning to the steam drum from the top. Some of the data we got in the field showed that the operating coefficient of this exchanger was about 7 Btu/hr-ft²-F. The calculated clean coefficient of this unit---operating with about 120 ft/sec gas at 10 psig---was about 14 Btu/hr-ft²-F. So we see that the fouling factor in this case was something like 0.07 hr-ft²-F/Btu.

At the time we were working on this, the fouling was attributed by some to electrostatic forces acting on the catalyst fines. These catalyst fines were predominantly submicron particles of alumina/silica. Other people blamed this fouling on a phenomena called thermophoresis. In this process, a particle moves to a colder surface because the bombardment of gas molecules on one side, the hot side, is greater than that on the cold side. The resultant force drives the particle to the cold surface where it then gets into the laminar film and stays.

Based on some company R&D done in the 1950's, several operating units were equipped with spiral-wire turbulence promoters inserted in the tubes. This is simply a wire spiral that went down the tube and was held against the inside diameter by its spring action. The tubes were 2 or 2½ in. OD, with roughly a 0.25 in. wall thickness. The wire was 1/8 in. diameter with a pitch of about 1½ in., more or less.

These units worked quite well, we found out. In one particular cat plant, the coefficient was somewhere around 6 or 7 Btu/hr-ft²-F. When they inserted the turbulence promoters, they got back not only their clean coefficients, but an increase of some 30 to 40 percent. So the steam rate went from 75,000 lb_m/hr without turbulence promoters to over 150,000 lb_m/hr with them. What was very interesting was that the steam rate stayed at 150,000 lb_m/hr until we shut down. And we did not lose any coefficient due to fouling.

Recent improvements in catalytic cracking catalysts and modifications in regeneration procedures have changed our flue gas conditions, so instead of being available at 1100-1125 F, the temperature is now about 1325 F. Also, pressures have been raised to about 20 to 30 psig. At the same time, due to increased demands for energy conservation, people thought this would be a good

place to recover energy. One way to do this is by running these hot regenerator effluent gases directly through energy recovery turbines. To avoid problems due to erosion, highly efficient cyclones are used to remove as much catalyst as possible. The remaining cat fines now are much smaller diameter and, of course, the loadings are lighter. Since these turbines are located at grade, the economics favor putting the waste heat boilers at grade in a horizontal position. These are still one pass firetube units with the steam drum located above them. There are several units of this type in service now. Some of these horizontal units have also been equipped with the spiral turbulence promoters.

There are two catalytic cracking units operating with essentially identical regenerator outlet gas streams flowing through two steam generators in series, a 300 to 400 psig high pressure unit followed by a 150 psig low pressure unit. Unfortunately, these units do not operate as designed. Unit A has a clean high-pressure generator operating with an overall coefficient of about 40 Btu/hr-ft²-F and a low-pressure unit barely managing to get 10 Btu/hr-ft²-F. There is no doubt that the low pressure unit is highly fouled. Unit B, on the other hand, leveled out with 10-12 Btu/hr-ft²-F in the high-pressure generator and 40 Btu/hr-ft²-F in the low-pressure unit. Since the flue gas temperature exiting the steam generator with the high coefficient in both cat plants is for all purposes about the same as the steam temperature, I think this casts considerable doubt on the thermophoresis theory. The different reaction to the same gas/fines combination in the series pairs also weakens the electrostatic force theory. There was the thought that a difference in the carbon content of the catalyst might have changed the ability of the material to remove the electrical charges, but again we have no information there. So we are even more in a quandry now than when we started out.

Eissenberg: Are A and B streams parallel on the same catalytic cracking unit?

Borushko: No. Unit A is at one location and Unit B is at another location.

Eissenberg: What about things like minor differences in particle size? You are talking about micron-size particles. At that point van der Waals forces are becoming important and, if it is half a micron, it might act differently than one micron.

Borushko: Well, we start out with catalyst particles around 40-100 microns in size. The catalysts are identical catalysts, manufactured by the same catalyst manufacturer. They are heated through the same temperature cycle. The regenerator flue gases, although they may have different chemical composition, are essentially the same. The velocities in the regenerators are the same, and the operating pressures are the same. Thus, the velocities in the tubes are the same, since the tubes are the same diameter. The tubes are the same material, too.

Eissenberg: But did you measure the particle size?

Borushko: No, but the particle size should have the same range that it has had for the last 40 years.

Eissenberg: But you didn't measure it?

Borushko: No, we didn't measure it.

Question: What about the sulfur content in the gases?

Borushko: The sulfur content is relatively low because the feed is treated to remove the sulfur. If you don't take it out of the feed, then you have got to take it out of the products. It is easier to treat one stream than to treat several smaller streams.

Duffy: One thing that is happening with jet engine combustors is that there is a great deal more smoke because the feedstocks have a lot more aromatics. I do not know if that is typical of all feedstocks. The aromatics in the crudes are going way up.

Borushko: The feedstocks are cracked by the catalysts in the reactor. This catalyst, fouled by coke, flows to the regenerator carrying some entrained product vapors. By the time you get through the regenerator, you have burned all the carbon, or essentially all the carbon, off the catalyst. The slight amount of residual carbon on the catalyst has gone through a 1350 F burn, so I think you have got mighty little volatiles in it.

Eriksen: Are your cyclones identical?

Borushko: Made by the same company.

Other refineries faced with this same fouling problem have adopted other solutions. Slide 2 shows a water tube boiler, as opposed to a firetube boiler, designed for 1350 F, 7.5 psig gas. The flue gases come in the bottom, pass across the tubing, and then go out the top. Fouling on the 2-in. OD carbon steel tubes with four $\frac{1}{2}$ -in. high circular fins per inch is controlled by four retractable steam soot blowers. And I understand, in talking to the owner of this unit, that it is doing about what they expected. The weak point in this system is the poor reliability of the seals on the soot blower.

The unit shown in Slide 3 was supplied for another cat cracking regenerator heat recovery boiler. This unit is equipped with 2-in. OD tubes, with $\frac{1}{2}$ -in. high longitudinal fins, arranged on a square tube pattern. The gas flows parallel to the tubes. With this arrangement you cannot put soot blowers in the tube bundle. And so the ingenious designer put in a sonic horn. Slide 4 shows another view of the same exchanger with the front end of the superheater mounted on top of the boiler. A sonic horn is shown at the near end and there is another one down at the far end. The idea, as somebody mentioned here, was to move the resonating particles off the wall and blow them away. Unfortunately, the sonic horn barely squeaked during initial operation and the unit became heavily fouled.

Question: What was the frequency of the horn?

Borushko: This was, I believe, about 200 Hz.

Testing of the unit revealed that the sonic horn operation was extremely sensitive to installation characteristics. There was a gate valve installed in the attachment piece to allow work on the horn for replacing the diaphragm. Also, I believe there was a projecting gasket that contributed to the loss in effectiveness. This acoustic sootblower installation has been modified based on the tests and has just gone back into operation.

My interest in gas-side fouling mitigation has been heightened by recent activity in coal gasification. Here, temperatures can go as high as 2,600 F at pressures of hundreds of psi. With spiral turbulence promoters of questionable value, with no steam sootblower experience at these pressures, and with acoustic sootblowers still at the experimental stage of development, we are faced with exorbitant costs if we have to accommodate the expected higher fouling rates.

Discussion

Marnar: Let's entertain questions for 9 or 10 minutes. I know we are not going to get them all, but we will take what we can.

Question: The gentleman seemed to be making reference to a sonic horn earlier as if something did not work the way you wanted it to. But how did they work? How did the last one work that you showed on Slide 4?

Borushko: Well, the sonic horn did not work because the installation was not as good as it should have been. We do not know.

Eriksen: They were our horns at that installation. We bought the horns and installed them. We tested them in the shop and they worked very well. What happened is that we took the horn and mounted it on a flange. The flange is on the gas-side of the unit, with a valve between the horn and flange so that the horn can be removed for maintenance. There was also a gasket at the flange. I believe the flange was about 1-½ in. diameter with about a 4 in. diameter ID on the gasket. What we had was a horn mounted to the valve and flange with a step about 1/8 in.

wide by about 1- $\frac{1}{4}$ in. high all the way around the inside of this tube. That gap soaked up a lot of energy. When you blew the horn, it changed the frequency and everything. Where we tested it in the shop, there was no gasket. The horn blew with a good strong pitch. We put it in the field and operated it at that pressure and it just squeaked---it had a very high pitch. So the gasket was changed, the valves were reamed out some, and now the horns are working properly. We also should have used a ball valve to have a nice straight bore for the sound. The gasket was part of the problem also but both were fixed. I called back to the office this morning after I talked to George last night. The horns are blowing properly, but the unit is fouling. It was cleaned after we got the horns working properly since the unit was really heavily fouled at that time. The cleaning was done by scouring it with walnut shells. The unit came back to the performance level where it should have been after the scouring but the horns don't seem to be doing the job. There are three horns in the unit.

Thielbahr: Are there guarantees from the sonic sootblower community on the performance, or is it do it at your own risk?

Borushko: I am sure that these were all developmental people getting together trying to work their way out of a problem.

Thompson: I am not directly affiliated with the horn work that KVB, Inc. is doing, but I should comment that there have been quite a few applications where the horns have worked very well. They are used extensively in Europe and there are about 30 applications in the U.S. The practice has generally been that there is an appreciation that horns are very installation-dependent and dependent upon the type of deposit that you are trying to remove. And for that reason, it is very difficult to know exactly what the efficiency of the horns is going to be in a given application. So, what has been done in quite a few instances is to provide horns on a trial basis, with the understanding that if they are not successful, they will be removed. And that is probably about as good a guarantee as you can get, I think.

Borushko: Well, I think the same guarantee goes there as you get for a rotary filter. I mean, the filter cloth holds the filter cake in place and that is all it is supposed to do. Whether it filters or not is something else. In your case, the horn makes noise which is what it is supposed to do.

Eriksen: That was the understanding on that particular job. Everyone understood up front that it was a developmental process and the guarantee was that the horn would make noise at the proper pitch.

Locke: There are two kinds of horns available in the market. There is a high frequency horn and there is a low frequency horn. Diamond Power Specialty Company is marketing a low frequency horn, but it has not been completely field tested in all kinds of applications. And so, yes, we will also work with users of equipment on a trial basis of some type. We have not really decided on our market approach to it, but we have released it for cleaning precipitators. We are experimenting with regenerative air heaters at, I think, Philadelphia Electric.

Marner: Who has another question or comment?

Ghofranian: Is that gas you are talking about that has catalyst particles in it the same gas that you are now burning in CO boilers?

Borushko: Carbon monoxide (CO) boilers were an interim step. We went from simple 1100 F waste heat recovery applications to burning that gas in a CO boiler. The gas had one percent or less carbon monoxide with low temperature regeneration at 1100-1125 F. With the recent development of 1325-1350 F high temperature regeneration, most people go to an oxygen-rich gas---no carbon monoxide whatsoever. So CO boilers are being phased out in those refineries. There is one refiner that I know who still operates with a CO content in the regenerator flue gas, but that is unusual. With the higher CO you get more carbon residual on your catalyst. The higher the carbon on the

catalyst, the more carbon and gas you make in the reactor, and you get a different product mix. People are going for lower gas and more gasoline.

Marner: We have time for one more question, either to George or one of the three other panelists.

Kreith: What is the concept or principle of operation you envision with the low frequency horn?

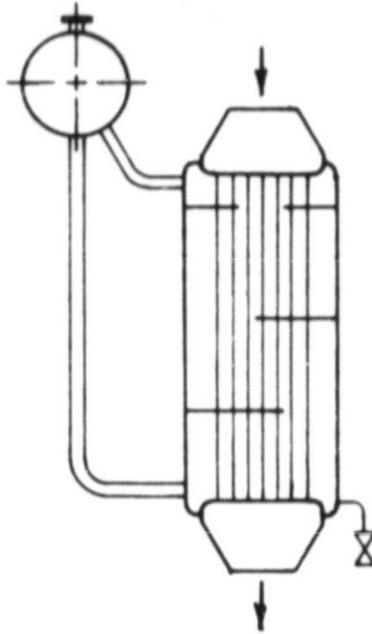
Locke: There are two philosophies of sonic vibration. One is a high frequency Kochens horn from Sweden which KVB is now marketing. And it is a small, high frequency horn. They have been used successfully in Sweden on recovery boiler services--chemical recovery process boilers, if you will. They have also been used on the back end of oil fired boilers. Now, that is a high frequency horn and you can hear it. It sounds like a siren. It is a ship's horn that has been adapted to moving ash -- lightly deposited ash -- and it will do the job.

Diamond's design is a low frequency horn. This is a 20 Hz, low frequency horn. The length of the tube is $\frac{1}{4}$ wavelength. And it is much larger than that, of course. It is going to have application difficulties. We have looked at sonic cleaning of boilers, power boilers, for years. Now this low frequency horn, I am pretty sure -- if I read the literature right and saw what I did when I went to Europe -- is set inside the containment vessel. Now, either horn works but in certain applications, I feel one might work better than the other one. The high frequency horn has been tested a lot and this low frequency horn is now being tested quite a bit by Diamond. I think it is a good way to move light deposit, fairly dry deposit ash. We tried ours on a recovery boiler, as the high frequency horns have been used on recovery boilers as well. We were able to supplement sootblower cleaning, and I believe the high frequency horn will also supplement sootblower cleaning.

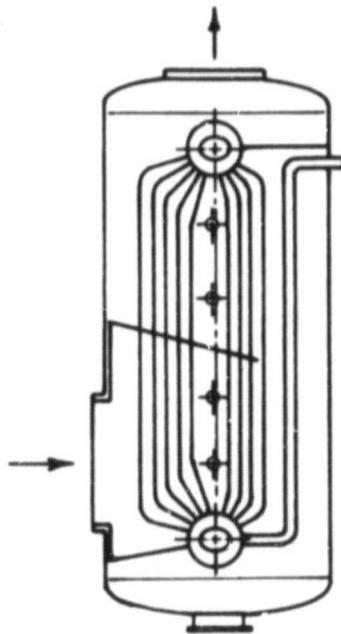
Marner:

Alright, on that happy note why don't we finish. I would like to thank each of the panelists for their informative comments. I apologize for the fact that we did not have more time for questions, but I think you were stimulated and that is what we were trying to accomplish here. So, now we will send you off into the working groups where you will have additional opportunities to ask questions, comment, or whatever. The next important phase of the Workshop is to break up into four working groups, and Ralph Webb has a plan to do that.

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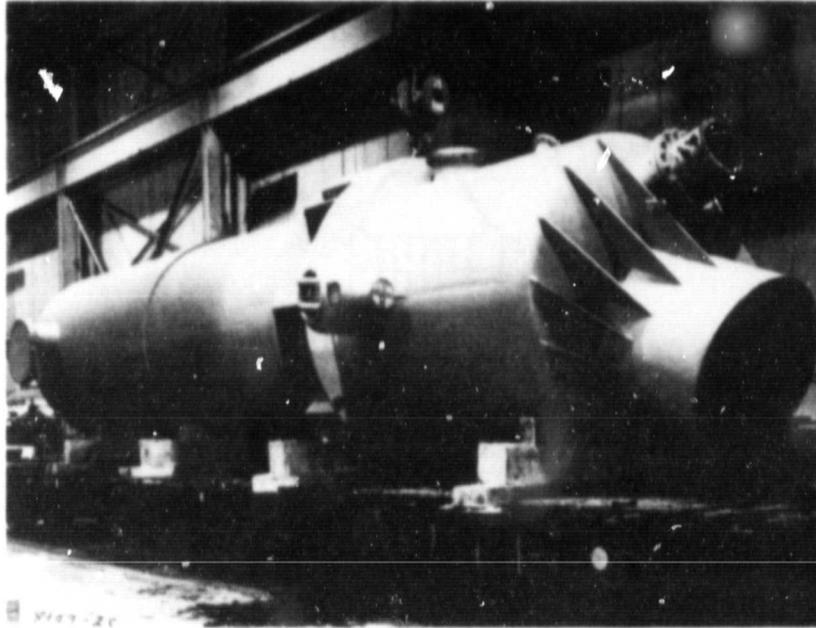


SLIDE 1. VERTICAL FIRETUBE STEAM GENERATOR

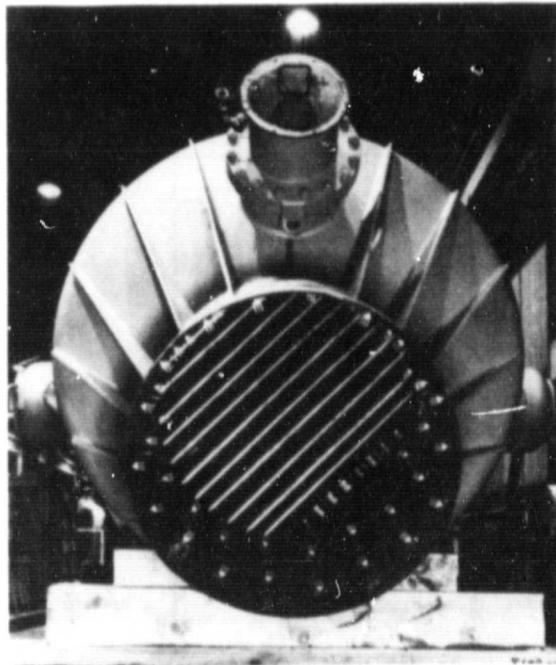


SLIDE 2. VERTICAL FIRETUBE STEAM GENERATOR
FOR MEDIUM PRESSURE GAS

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



SLIDE 3. VERTICAL WATERTUBE STEAM GENERATOR
WITH SONIC HORN SOOTBLOWER



SLIDE 4. SONIC HORN INSTALLATION IN VERTICAL
WATERTUBE STEAM GENERATOR

SECTION 5
BANQUET TALK

HEAT RECOVERY EQUIPMENT IN GAS-SIDE
FOULING SERVICE

David O. WATTS

Banquet Presentation: "Heat Recovery Equipment in Gas-Side Fouling Service"

David O. Watts

OUTLINE

I. Systems in Service Involving Heavy Gas-Side Fouling

- A. Watertube Boiler System with Gas Containing Oxides of Heavy Metals**
- B. Once through Steam Generator with Products of Combustion of H_2S**
- C. Forced Circulation Generator Coil in Steam Methane Reformer Effluent Gas Stream Showing Fouling Due to Silicia Migration**
- D. John Zink Down-Fired Salt Waste Disposal System with Watertube Steam Generator**
- E. Fouled Tubes Used in Heat Recovery from Combustion of Various Wastes:**
 - 1. Atactic Polypropylene**
 - 2. Sodium Centrate**
 - 3. Sodium Sulphate**
- F. Fluidized Bed Steam Generator System**

II. Watertube Heat Recovery Boilers

- A. Drum Drilling**
- B. Setting, Refractory**
- C. Waste Fuel Fired Type**
- D. Two Drum Convective Type**

E. Types of Extended Surfaces

1. Helical Solid Fins
2. Helical Cut Fins
3. Round Studded Tubes
4. Lens Shaped Cast Fins

F. Recommended Fouling Factors for Various Types of Fouling Service

III. Various Heat Recovery Units

- A. Stack Gas Steam Superheater
- B. High Pressure (ASME Section VIII) Gas Steam Superheater
- C. Gas/Air Exchanger
- D. Economiser

IV. Firetube Heat Recovery Boilers

- A. Vinyl Chloride Monomer Waste Fired Boiler
- B. Two Drum Firetube Boiler
- C. Integral Drum Firetube Boiler
- D. Design Concepts for Cl_2 and HCl Gas Service

SECTION 6
SUMMARY REPORTS

Group A: A. Kulkarni

Group B: J. W. Suitor

Group C: V. L. Eriksen

Group D: J. M. Chenoweth

Group A: Characterization of Fossil Fuel Exhaust Gases

Anil Kulkarni, Group Leader

Introduction

In our working Group A, after two days of very interesting discussions, this is what we have decided, or we have concluded. First of all, the state-of-the-art will be considered.

State-of-the-Art-Assessment

There are several points which I will try to go through quickly.

(1) We divided the fuels into various types and that is what we discussed in the beginning. We decided natural gas exhausts do not present fouling problems, and so they need not be studied further, at least from the fouling point of view, right now.

(2) The composition and particulate size and particle loading measurements for the rest of the fuel exhausts, at high temperatures, are possibly only in the laboratory and not out in the field. At high temperatures -- I mean relatively high temperatures -- about 1300 F, you get into problems. However, at low temperatures, for steady state cases and when you allow the exhaust gases to quench, the composition and particulate loading are known very well for most of the fuels.

(3) The third point is that the hydrocarbons in exhaust gases have a deleterious effect on downstream heat exchangers, even though the hydrocarbons may be present only in trace amounts. They can present very severe fouling problems in the sense that they form a sticky layer on heat exchanger surfaces which may be only a few molecules thick, but which catches the solid particles and is hard to remove.

(4) Exhaust characteristics of distillate oil, natural gas, and methane -- which are high quality fuels -- are reasonably well documented. The exhaust characteristics are also documented, to a lesser degree, for coal and heavy fuel oils. As far as ash effects of coal, coal-oil, and coal-water

slurry exhausts are concerned, a lot more has to be done. Also, characterization of exhaust gases of emulsified fuels and synfuels has not been studied in detail.

(5) Techniques for achieving complete combustion from the point of view of burner design are relatively well known. However, flow mixing characteristics and geometry effects of the combustor shell are in the developing stage, and more work needs to be done in this area.

(6) Acid dew-points are generally known from a chemistry point of view. However, dew-points of hydrocarbons, salts, and other condensables for complex systems---such as in exhaust gases---should be studied further.

(7) Characterization of deposits on surfaces, that is foulants, has been done for isolated conditions. There are scattered studies and most of these studies are for long term fouling where the surface, for example, is put into service for several hundred hours.

(8) Experimental methods for sorting out the dew-points of condensables are generally known. Now, I am talking about experimental methods themselves; however, they should be refined further for finding the best and most suitable ways from the exhaust gas fouling point of view.

(9) In terms of soot formation, a great deal of work has been done from the combustion point of view where the soot is formed. But the interactions between soot particles, hydrocarbons, and other species that are present in the exhaust are not very well known. And they should be studied further because that is one of the major problems, for example, in Diesel engine exhausts.

(10) There are some fuel additives known for reducing fouling and corrosion in the downstream. However, this approach is used only as a last resort in some cases, and the consensus was that it should be left to industry for further development.

(11) As far as post-combustion additives are concerned, the Electric Power Research Institute (EPRI) is actively involved in this work. There are

some additives currently in use, such as the MgO, which are used for removal of SO₃; and more can be invented. There are promising methods.

Recommended Projects

Based on this assessment, we have formulated about 12 tasks. Out of these, we have five top priority ones. I am going to present only the top priority tasks.

This task will be divided into three parts, and I will ask Dick Thompson to read the details of the first task.

Thompson: This is a project that was a combination of three sub-areas. I guess the general title would be Characterization of Exhaust Gases as Related to Gas-Side Fouling because that covers the world. The first subtask objective would be developing new experimental techniques for high temperature exhaust gas characterization, i.e., measurement of species, particulate loading, and size distribution. And the idea there was that in these high temperature regions there is a need for technique development which must precede the actual characterization. Then the second objective or subtask was to actually devise a methodology for characterization of fossil fuel exhausts. One approach to devising this methodology would be to use one or two fuels as a baseline characterization to illustrate to people how this methodology would be used. From that point on, it would be a discussion item as to whether industry would then take over and do it, or whether -- depending on funding -- DOE would continue to do it. To illustrate this methodology, there was quite a bit of interest in the Diesel exhaust -- particularly, the hydrocarbon characterization of the diesel exhaust. However, one additional conventional fossil fuel would probably also be required to illustrate the methodology. Then the third category, or subtask, would be the characterization of exhaust gases of synfuels or alternative fuels for future use. And the idea there was to address the objective of doing some characterization and more advanced

R&D in the 3-to-5 year time period. Whether that work is done or not would be a function of funding and priority and whether industry, particularly the fuel supplier, would provide this type of information and make it available to the heat exchanger people. If not, then who should do that kind of work? I have some more details, but that covers the basic ideas.

Our second task will be read by Gordon Blizard.

Blizard: The second task that we gave high priority to was the Physical and Chemical Characteristics of Deposits. And the objective here would be to study the fouling characteristics of deposits by means of the physical and chemical properties. In conjunction with this, the outline would follow somewhat this form. First, the selection of combustion conditions would be made under which this task is to be examined. What type of fuel or what kind of generation of the effluents should be examined? Second, the physical and chemical properties that are to be examined must be specified. For example, parameters related to characterization include surface roughness, orientation, and temperature. Also included are material properties such as the chemical identification of the composite, density, and the other characteristics that would be germane to the fouling conditions. Finally, the time interval over which these measurements are to be taken should be included.

Third, a subportion of this task would be to find appropriate measurement techniques to determine the above: (a) what would the techniques be and are they known and available, or (b) would they require new technology? Fourth, once this has been developed, then a literature survey of some sort would be necessary to define just what portion, or portions of these, would fall under the scope as being germane to the general knowledge of the fouling problem. We really did not discuss the manpower or time requirements to do all this, but I would think -- based on my own personal judgment from having done

similar work -- perhaps two manyears. And as far as financial support of the work is concerned, I will let you address that. However, I would think that under the auspices of DOE it would have a coherence that otherwise industry would not provide it.

Kulkarni: I think this program should be supported jointly by DOE and industry because it is mutually beneficial to them.

The third task will be read by Henry Henneken.

Henneken: The third priority was given to Dew-Point Measurements of Various Condensables that seem to cause deposition of foulants. Generally speaking, you would want to determine under controlled conditions the actions of individual condensables as well as interactions between them, and what conditions such as temperature, pressure, and other physical characteristics would change or alter their propensity for forming binders with either the heat transfer surfaces or with particulates in the mainstream.

Kulkarni: Those were our three top priority tasks, and I will just quickly read through the second and third priority tasks.

Second and Third Priority Projects

The second priority tasks are: "Determine the Effects of Coal and Oil Combustion Parameters on Exhaust Gas Particulate Contributions" and "Determine the Corrosion Potential of Foulants." Third priority tasks are: "Investigate the Effects of Additives Such as MgO and Others on Fouling Potential of Gases and Exploration of New Additives", "Emulsified Fuels Studies for Reduction of Fouling Problems," and "Soot Deposition and Agglomeration Fouling."

Those are our recommended tasks, and with that I will let the second group take over.

Group B: Gas-Side Fouling Characteristics and Mechanisms

J. W. Suitor, Group Leader

Introduction

I would like to make some basic comments before talking about the results from our group. First of all, the study of fouling mechanisms represents basic research. It is very hard to be specific about equipment or gases. Often the gas you are using as the fuel impacts only as a parameter upon the basic fouling mechanisms that you are looking at. We also determined that there is an underlying cost motivation that exists for all of the work on basic mechanisms. And that is, if we could understand the process better, we could ultimately reduce the size, and therefore the cost, of the exchanger and that would lead to a reduction in oil consumption or energy consumption from outside sources. The need for decisions based on sound engineering, rather than general experience, is another motivating force. For example, based on some information we discussed, an exchanger that would be used in a natural gas-fired process would probably have to be two times larger if it were used on a No. 2 fuel oil. This is just one particular comment. I am sure that other people would probably use different factors. Choice of equipment is another motivation. You might use a particular type of exchanger, such as a plate fin, in a service with natural gas but you would not use it in, say No. 6 fuel oil service unless you wanted to filter the flow. These basic comments support what we were out to do. As I said yesterday, we identified some important mechanisms; that is, particulate transport to the wall, particle attachment, deposit transformation, and deposit removal. And by deposit removal I don't mean the type of removal such as that with sonic horns or sootblowers. I am talking about the natural type of removal that would occur due to the fluid action on the surface. Also, and I don't really mean to degrade this -- measurement of the foulant, the fouling resistance, and the composition -- all of these types of measurements are critically important in trying to understand the fouling process.

State-of-the-Art Assessment

With regard to these five areas, the four having to do with mechanisms plus the measurement, here are a few state-of-the-art comments. Particle

transport to the wall is reasonably well-known for the most part in gas turbine technology. The folks that deal with gas turbines, and the dirtiness in gas turbines, feel that they can accurately predict particle transport to the wall. As a consequence, while there is some translation required to more complex geometries, as you find in heat exchangers, the research task is somewhat minor compared to some of the others. There is reasonably little known currently on particle attachment. We know that there are some circumstances in which particles will attach more readily than in other situations. For example, in the presence of liquids or molten materials you may get more particle attachment. Deposit transformation means the change in the deposit structure as it lays on the surface. The transformation is sometimes due to temperature increases, sometimes due to aging, and sometimes due to the presence of other materials in the gas stream. Here again, there really is not that much known on a basic mechanism like this. On deposit removal the basic things that we know currently, as far as state-of-the-art is concerned, is that certain deposits can be removed by sootblowers and certain deposits can be removed by sonic horns. This indicates that certain deposits are subject to mechanical removal by fluid dynamic forces created by the sootblower and certain deposits are subject to mechanical degradation by vibration. As for measurement state-of-the-art, there are a number of fouling measuring devices that currently exist in various forms. There are techniques available that have been used in other areas and we are sure that with proper application of this available information, we could develop a device, or a series of devices, that would be capable of measuring fouling and the constituents of foulants in this type of service. In developing our recommended projects, we recognized that gas-side fouling results in a decrease in heat transfer, an increase in pressure drop, a loss in mechanical integrity due to corrosion, and an increased safety hazard. We also recognized that fuel characterization such as particle size distribution, chemical composition, physical properties, and the effects of additives impacts the fouling mechanisms. So, what we wound up doing is dealing with these five particular areas.

Recommended Projects

These projects are listed in order of priority except that we felt they are all of fairly equal priority. We had a very difficult time selecting one above the other.

There was a strong feeling that a Fouling Measuring Device is needed. The objective of this research program would be to develop a standard measuring device to study gas-side fouling for a relative comparison of different streams. This might be a device that would be put into an existing heat exchanger or it might be a device that would be used in a model simulation.

The second recommended project does not really fall under the area of basic mechanisms -- it falls under the area of basic common sense. And that is, based on our experiences here, we feel that a Gas-Side Fouling Standards/Advisory Committee ought to be formed. The objective of this project would be to establish an ongoing committee that would be composed of all technical sectors; that is, industry, government, the universities and national laboratories, to assist in any program development. It would be very similar to an ASTM-type committee. I know there has been some discussion this past year at the National Heat Transfer Conference in the ASME K-10 Committee about establishing some sort of a group to talk about fouling and to deal with the problems of fouling.

A third project is Particle Transport to Heat Exchanger Surfaces. Now, this is the one in which the gas turbine technology exists and probably it just needs to be translated into useful relationships that we can use in complex geometries. In addition to that, we would like to also recommend looking at the importance of electrostatic and thermophoretic mechanisms as to whether they are valid or not and whether they are useful. Possibly in looking at electrostatic types of processes we might find that there is a way to do some upstream cleaning to remove the foulant material before it actually gets to the heat exchanger surface. Now, that may be a little far out, but you do not know until you look at it.

The last two projects are Particle Attachment and Natural Foulant Removal Mechanisms. Although they seem to go together, there are some rather complex things that separate them into two different projects. However, in both we would be determining and quantifying the dominant parameters that would affect both attachment and removal. In these particular instances, the standardized fouling measuring device would be very important. It would also be very important to have some sort of advisory committee that would monitor some of

the work that was done to make sure people did not get off on the wrong path. We felt that these two particular projects ought to be funded, at least initially, by the DOE because of the relatively high risk and low return in the industrial sector. But later on that could be passed on to the industrial sector.

Group C: Design of Heat-Transfer Equipment for Gas-Side Fouling Service

V. L. Eriksen, Group Leader

State-of-the-Art Assessment

We were Group C, the heat exchanger designers. And as far as the state-of-the-art goes we are designing and operating equipment with those fossil fuel sources that Bill Thielbahr listed on day one, although we do not really understand the fouling very well. We do not like it, but that is the way it is. That is just a fact. We are quite comfortable with natural gas -- it does not bother us. We are using No. 2 fuel oil quite a bit, and only when it is in Diesel exhausts are we uncomfortable. We do not understand No. 6 fuel oil exhausts very well at all. In designing the equipment we are over-surfacing, we are doing things to try to clear it better, but we do not understand the mechanisms and that is one of the problems that we have. If we could better understand fouling, and better understand some of the mechanisms, we could do some important things.

One is, we might be able to alter our designs and reduce our costs. This would, in turn, permit us to sell into other places where the heat recovery equipment might be marginal from an economic standpoint right now, so that would stimulate increased heat recovery and energy conservation in the country.

Now, the other thing, if we understood fouling a bit better, is that we could operate in temperature ranges other than we do now. And what we are really referring to there is dew-point fouling and dew-point corrosion that we talked about earlier. Everyone is pretty well staying away from that point right now. And that is in effect putting a limit on the stack temperature. We do not go below a certain limit. If we understood that better, people would operate closer. There would be a lot more interest in some of these real low temperature bottoming cycles and things like that. There is a tremendous amount of energy conservation that could be achieved if we understood the fouling in these ranges better.

If we understood fouling better in these fuels, there is a better chance we could extrapolate some of these results and understand some of the other fuels for which there is so much interest in now.

So, those are reasons why we should better understand fouling. Even though we are designing equipment for these fuels now, there are good reasons to try and understand fouling better. That can stimulate a great deal of additional heat recovery. In addition to this, better understanding of fouling can help in the operation of existing equipment we have out in the field right now. It can minimize the costs. If you understood fouling better you might be able to clean surfaces more effectively and reduce pressure drops or fan power consumption; or, sootblow less often, so you would not use as much steam in sootblowing -- things like that. The equipment could be kept cleaner, more reliable, and last longer. Equipment could be operated much safer. Greg Theoclitus, in particular told us stories about fires in equipment that had fouled and how the fouled surfaces could ignite easier and set the exchanger on fire. Safety is another good reason why you do not want fouled equipment around.

Now, as we went through all of these things we kept coming back, as designers, to the conclusion that what we really need is some good empirical data. There just is not much around in terms of data with which to design equipment. Everyone has a few guidelines and there is a lot of guesswork so that many of the recommendations we came up with are requests for empirical data -- studies to develop empirical data.

In regard to the state-of-the-art, I would also like to say that we are seeing a lot of interest in fuels other than those you have mentioned, Bill. And we think that is very important and there is going to be increased interest there. We think that fouling in those areas is very important. Beyond the cement and the glass that you have mentioned, coal gasification, refuse, other fuels, other waste sources, and in general, fouling is a real problem as we get into some of these other sources. So that is our feeling of where the state-of-the-art stands.

Recommended Projects

Based on that, we came up with several specific requests, or projects, that I will run through quickly.

The first was, Empirical Fouling Data at Metal Temperatures Above the Dew-Point, really just to find some good empirical data; fouling data at metal temperatures above the dew-point. The idea here was to get some good accurate data on typical geometries that everyone is using these days. Finned tubes (serrated and plain), bare tubes, and things like that. Let's truly try and measure the thickness of the deposits and the fouling factors.

Webb: Could you tell us who ought to sponsor that work?

Eriksen: O.K., in general I was going to talk about sponsorship at the end, but...

Webb: O.K., good.

They all are similar things that would be very useful to industry. And you can say at first glance, industry should really sponsor that because that is data they need. However, our feeling was that if someone in industry does it, he is going to keep it for himself and it will never be distributed. It will be considered proprietary data. It also might not be done in as open-minded a fashion or unbiased fashion if it was done by a specific manufacturer. So we were really thinking in terms of an independent study by the government. There could be a lot of cost-sharing involved, and I would think it would not be too difficult to get some equipment donated also. I think manufacturers would be willing to participate in submitting some materials and maybe finding some test and some gas sources to help you.

Thielbahr: Are you talking about your first project now?

Eriksen: In general all of them on the cost. A couple of them at the end we said should really be government sponsored. They are high risk types of things and the government would really be the one that would be more appropriate.

Thielbahr: Would you just tick off 4 or 5 what you mean by data?

Alright, the first one. We said: Obtain accurate, empirical data to use in the design of heat exchangers, and these are with the gas sources that we are talking about. Determine the thickness of the fouling layer and the fouling factor for several heat exchanger geometries in use today as a function of:

1. Gas Source (this would be the fuel, and the way it is burned)
2. Gas Temperature
3. Surface Temperature
4. Gas Velocity
5. Time

It is very basic stuff, and it is not around very well. We said that cost sharing would be a good idea on that one.

The second one that we put up is Effectiveness of Cleaning Devices. And it kind of ties into the first one. A lot of people are using sootblowers, you know horns are starting to be used more, and there are other ways that people have of cleaning things, but there are not very good data on what is really working well. In other words, they are put into service somewhere, and it seems to be doing O.K. The stack temperature is not getting too far out of hand. No one has really taken these things and put them on a heat exchanger core and sootblown it and said, "O.K., now let's go back and measure what the thickness of the layer is. Did it take it all off or not?" So we said a program, again, to determine how well these conventional cleaning devices such as sootblowers, sonic devices, or water washing really clean fouled layers from heat exchanger surfaces. This would again be a test program to determine how the different surfaces can be cleaned of different types of deposits. Those are the two main variables we saw.

Thielbahr: Do you think that if the government were to support some of that, you could get cooperation from various people that have cleaning devices, knowing that they are going to be compared with their competitors?

Eriksen: Yes.

Comment: We do it all the time.

Eriksen: Yes.

Comment: I know some don't, but...

Thielbahr: So you're willing to take your lumps, then?

Comment: You don't have to identify the participants, but you can identify them as A, B, and C.

Locke: Oh yes, we would ask that when you put the report out that you not identify the companies by name. But we would consider donating.

O.K., Project Three, Dew-Point Type Fouling. And it is a study very similar to Project 1 except we said this is such an important topic we don't want it to get lost in Number 1. That is to conduct a very similar study to Number 1, only down where the tube is wet. If you have got a wet tube we feel that the fouling mechanism is quite a bit different. This is the low temperature end where there is a lot of heat recovery interest and people are afraid of the fouling. It is very difficult to unlink corrosion and fouling in this area. It is very important. And so that is what we had for a third one, and then in this area cleaning is also important. In the dew-point range, how do you clean these deposits off the surface. We are looking at typical heat exchanger geometries being used today, again.

The fourth one we said is Alternate Fuel Fouling. Even though the Workshop is supposed to be looking at just the fossil fuels listed, we felt it was important to consider some of the alternate fuels because that is where there is an awful lot of interest these days. And we said, again, somewhat similar to Project 1, determine fouling rates for typical heat exchanger geometries with some of the alternate fuel sources such as: coal gasification, incineration of chemical wastes, refuse (there are many kinds of refuse in addition to municipal refuse -- you can consider burning wood or a

wide variety of other things). And again, cleaning of some of these deposits is very important because some of them foul quite miserably.

The next one we had was Fouling and Cleaning of Non-Conventional Materials. And here is where we are looking at coatings and things like: ceramic tubes, teflon coatings on the tube, some of these things. Does the material on the tube change the fouling characteristics? That is the real question. And, again, this can be done with some empirical testing, I think, as much as anything. And the objective, as we defined it there, was to determine the fouling and cleaning characteristics of alternate surface materials and finishes. The typical materials might be teflon and other coatings, glass, ceramics, or plastics. Again you are measuring fouling rates and material thicknesses as a function of gas source, temperature of the gas and the surface, velocity, and time. And that is a riskier one that we would see the government doing primarily.

Duffy: Do you want to include also the cleaning of non-conventional materials?

Eriksen: That's right. Cleaning should be included there.

Thielbahr: I am just wondering. Does anybody have any information that would lead them to believe that surface roughness or going to a very smooth surface would really have a pronounced effect on fouling rate. Solar Turbines Incorporated says no.

Comment: I don't think so. Initially it might affect it for a very short time, but after you put a layer of something on it, I don't think it would affect it much.

Thielbahr: Is there anybody that feels otherwise? I am talking about fouling rate, not cleaning per se, but fouling rate.

Marnier: I am not going to attack anybody, but we were going to let the four Group Leaders make their presentations, and then we were going to get them all up here and let you have a crack at all of them.

Thielbahr: O.K.

Alright, the last one was one of these things that was hard to categorize, but we said Flue Gas Treatment to Reduce Fouling, or to make the deposits easier to remove from the surface. This is looking at things like treatment of the gas, the flue gas itself, with some sort of treatment, or fuel treatments. Another possibility is, perhaps if you are downstream of a precipitator, that the particles that come through might already be charged. Perhaps if you put an opposite charge on your exchanger, will it repel the particles and not foul? Again, we threw that in the high-risk category because it was a bit far out.

Those were our six recommendations. In terms of priorities, they are pretty well in order there. The top three or four we said we considered as one group, and the bottom two as a lower priority group.

Ghofranian: I think we discussed in our group, while we were preparing these six items, that one important factor was also to study these things under upset conditions, startup and shutdown.

Eriksen: Yes, that is a very good point, Bob; in particular, the dew-point one. It is not the fact that you want to operate the equipment down there continuously to recover more energy, but this is a condition you get during startups and shutdowns, or some transients. It affects the way existing equipment fouls right now and it includes the operation and the safety of that equipment.

Group D: Operation and Cleaning of Heat-Transfer

Equipment in Dirty Gas Environments

James M. Chenoweth, Group Leader

Introduction

Thank you, Ralph. I was very much impressed by the last presentation by Vern Eriksen because practically every item he had on his list was somehow related to cleaning. Our working group was asked to look at the operation and cleaning of exchangers in a dirty gas exhaust service. It is amazing the way we came up with the same type of problems that exist from the standpoint of cleaning. We really did not have the accordion door between our two groups open as you might suspect from my presentation.

Well, I have taken a somewhat different approach to this presentation. First, I would like to discuss a premise that came out of our discussions. We decided that we were dealing with a dirty gas environment that could have resulted from operation upstream of the heat exchanger. We got kind of sandbagged yesterday in our interim report due to our decision not to dwell on operation, but rather to concentrate on cleaning. Once again we discussed our position and concluded that the many problems associated with operation were often uniquely application and site dependent. They result from such things as off-design conditions and erratic operation. We have talked about the fact that you cannot just look at the operation of an exchanger at its design conditions. You have got to worry about the start-ups, upsets, and alternate operating conditions. From an operation standpoint there is always the possibility of treating the dirty gas ahead of the exchanger by the application of some additives or the inclusion of a scrubber. Now there is one thing which we do know; and that is that if you have not done a good job upstream, you are sure as heck going to clean up the dirty gas in the exchanger. And what is left behind is going to foul and corrode the exchanger. You have a loss in the thermal performance and an increase in the pressure drop. Local high temperatures can adversely affect the process stability and mechanical integrity of the exchanger. Our conclusion was that at the current state-of-the-art, it is probable that you are going to require cleaning to control the buildup of fouling. And so, we have centered our discussion and recommendations from our working group on the area of cleaning.

State-of-the-Art Assessment

Although fouling from dirty gases occurs both on the inside and the outside of tubes, the external fouling problem was considered the most critical. As a result, the discussion of the state-of-the-art will emphasize that condition. We identified cleaning techniques in two different ways: those that can be operated on-line without shutting down the operations, and those that must be operated off-line. Certainly, if you can clean the exchanger while the units is on stream, you will choose to do so.

Of the on-line techniques, sootblowing is one of the most common. We discussed the limitations as to where sootblowing should be applied, and the problems that currently result when it is considered for high pressure services. Another on-line technique is the use of sonic horns to remove fouling. Although some success has been reported, the state-of-the-art is very crude at this time. Both high frequency and low frequency horns are available, but the limitations of each are not well understood. The removal effectiveness has been demonstrated with a dry buildup, but it is suspected that there will be problems with some liquid, slurry, or baked-on buildups. Momentum transfer removal techniques are another of the on-line methods for removing fouling. As an example, consider the addition of water that vaporizes to greatly increase the velocity of the stream to accelerate the removal of fouling deposits. It should be pointed out that this approach may lead to a temporary upset in the operation of the system. Another example is the mass scrubbing with walnut shells, steel pellets, sand, etc. that are inserted into the incoming flow only to be removed, cleaned, and either dumped or recirculated. Recirculation has had many problems and has not been too successful. Finally, mechanical vibration has been tried as an on-line technique for removing fouling buildup. Problems exist with large heat exchangers where the mass of equipment vibrated requires a large input of energy and concern for the mechanical integrity of the unit.

The second series of techniques are those that you can use once the exchanger is taken out of service. Some of the most common out-of-service techniques are baking and hydroblast. Another is to flood the exchanger with a solvent, dissolve the fouling deposit, and wash it away. Differential

thermal expansion can be used to break the bond of the fouling layer to the tube surface. Finally, the fouling layer can be burned from the surface if this material is combustible.

All of the cleaning techniques discussed were felt to have problems. Our overall conclusion was that the cleaning of heat exchangers is more an art than a science. It is best understood where a particular technique has a long history of being successfully used. However, the group felt that there probably must be better ways than those that are currently used.

In that regard, it was felt that one must match the cleaning technique to a particular fouling material and attachment mechanism. Is the fouling a slurry, is it a buildup of solid particles, or is it the products of polymerization? What is it? And what should the technique for cleaning it be? Most probably there will be a number of different ones that will be effective for a particular type of fouling. But you must identify the application limits, determine the cleaning parameters, and demonstrate the effectiveness. Unless you do, people are not going to consider any new technique for cleaning their exchangers.

Well, it would be great if you could prevent or retard the development of fouling. This is a neat way to solve the cleaning problem -- you just eliminate it. Along these lines, there are several techniques that have been suggested. Additives to the fuel or to the exhaust products have been used with varying success. Coatings have been applied to the heat transfer surfaces. Possibly the effectiveness of the coatings may involve a delay in the initiation and/or the ease of deposit removal. However, the most important factor is the proper design of a heat exchanger to lessen the possibility of fouling. Start with any given exchanger specification. You are interested in the heat transfer and pressure drop performance. But do not forget that you must provide for cleaning when the exchanger becomes fouled. For cleaning purposes, nice wide tube pitches, few fins per inch, or better yet bare tubes, are all attractive, but they may be detrimental to thermal performance. Since fouling is known to be velocity and surface temperature dependent, the various tradeoffs must be weighed. And these should dictate the way the exchanger is finally designed.

Another consideration that is always present is the economic impact. The first cost of the exchanger, the operating costs, and the cost of cleaning need to be considered. Depending upon the technique, the cost of cleaning must include any decrease in product value due to being "off spec", or the loss of valuable product during a cleaning shutdown.

Recommended Projects

Well, this has been a rather rambling presentation of discussions that have led us to our particular recommendations. You will see our list looks very much like Vernon's. So help me, we did not discuss our lists with each other. If you look down the list, you will see seven different projects that we feel need to be considered.

Particulate Fouling Mitigation. For our group one of the most important would be one that would lead to an understanding of particulate fouling mitigation. In particular, we need to understand why particles actually move to a surface to be deposited there and what is the characterization of the deposited material. This is a very fundamental type of activity. We see it as being initially a DOE-type activity, followed by industry participation with contributions of equipment, services, and funds. The situation that brought this need to our attention was what happens in firetube boilers with "fines" being deposited at relatively high temperatures somewhere between the dew-point and the solidification point for the particles.

Wet Wall Problem. We are concerned about the wet wall problem where corrosion results. This problem was discussed earlier so I will not say more other than we feel this is again an activity where probably a combined activity between the DOE and industry is warranted.

Electrostatic Cleaning. We feel that this is a high-risk area with little assurance that it is going to work. We are not sure that electrostatics can repel particles from surfaces or whether they can be precipitated out of the exhaust ahead of the heat exchanger. We feel that this is an activity that DOE should become uniquely involved with, certainly initially. Later on, a cooperative venture between industry and DOE would be necessary. Ultimately, if and when electrostatic cleaning has been demonstrated as attractive, industry should and would take over.

Sonic Cleaning. We are aware that research activities are being conducted by industry for the development of sonic cleaning devices. However, it is the concern of the group that these are proprietary studies that will not answer some of the fundamental questions about the application of this cleaning technique. So far there is little understanding of the placement of horns, the limitations of the effectiveness of these devices, and the characteristics of the cleaning mechanisms. We recognize that this on-line type device is attractive and shows promise, but we do not believe that industry will provide the answers. Therefore, we recommend that DOE become involved.

Thielbahr: Jim, are you talking about more of an empirical approach to sonic cleaning, as opposed to a more fundamental understanding of where and how the sound waves interact and how they affect the fouling layer?

Chenoweth: I think it is a little of both, Bill. Initially we have got to understand what the mechanism is that causes sonic waves to move particles off the surface. Why do they move? How do they get reentrained in the gas stream? What is involved? The manufacturers are going to be more interested in building hardware and installing it. When it works, that's great. If it does not work, the approach has been to add another horn without fully understanding why. At least, that was the feeling of the group.

High Pressure Seals for Sootblowers. The group pointed out a specific problem that exists for the application of sootblowers where there is a high pressure service. It is my understanding that currently sootblowers operate with only a few psi pressure differential between the wall surfaces and the outside environment. Seals that permit rotation and translation of the lances work well for this service. The upcoming service calls for a pressure differential of 50 to 100 psi for which no adequate seals now exist. There was a strong feeling in the group that industry will probably undertake this project and meet the challenge. But we wanted to indicate it as a project area that we recognized as important.

Low-Fin Tube Configuration. We feel that fin tube geometry is a potentially interesting research area, particularly with regard to fouling characteristics and cleanability. The particular fin geometries that have been suggested are those with very low fins. There is some evidence that they can be particularly attractive in certain types of fouling service. Some of the questions to be answered include what are the types of service and how should fin tube banks be designed? The group felt that both DOE and industry should be involved. Why do we say DOE should be involved? We feel that DOE could provide an independent investigation, rather than one by an organization that has a vested interest. DOE is needed to prevent the results of the study from being proprietary and to provide rapid and widespread dissemination of the results.

Alternative Types of Heat Exchanger Designs. The last of our seven suggested projects involves searching for alternative heat exchanger designs where the potential fouling problem is minimized or eliminated. Several heat exchanger types illustrate the general concept. One is a jet impingement type device where there is no surface to foul. Another is the use of fluidized beds. Possibly heat pipes should be included, as well. There must be a way to transfer heat for extremely dirty services that circumvents the fouling problem. We feel that this is an area of high risk and one that DOE should probably support.

So these are the results of a very intense, hard, and sometimes agonizing one-and-a-half day's work trying to investigate the problems associated with the operation and cleaning of heat exchangers.

Thielbahr: Are those projects prioritized? Are they in order?

Chenoweth: Yes, Bill, the areas of research are in our order of priority.

SECTION 7

COMPILATION OF RECOMMENDED PROJECTS

RECOMMENDED PROJECT A-1

TITLE: Characterization of Exhaust Gases as Related to Gas-Side Fouling

OBJECTIVE:

1. Develop new experimental techniques for high temperature exhaust gas characterization with emphasis on particulate and hydrocarbon measurements.
2. Devise a methodology for characterization of fossil fuel exhausts using Diesel exhaust and conventional fossil fuels to illustrate methodology.
3. Characterize exhaust gases of synfuels or alternate fuels for future use (3-5 years).

TASK OUTLINE:

1. Literature search.
2. Examine previous methods, temperature limitations and new techniques.
3. Technical approach will be defined by contractor.
4. Characterize base fuel(s): Diesel fuel for particulate characteristics, hydrocarbons, etc. and heavy oil for particulate characteristics, hydrocarbons, etc.
5. Assess industry needs for exhaust characterization of synfuels and other alternate fuels. Define needs of heat exchanger industry and time frame.
6. Characterize synfuels/alternative fuels.
7. Publish final report and methodology guideline manual for industry.

MANPOWER AND TIME REQUIRED:

4 manyears labor; 1½-2 calendar years

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

Objective 1: DOE
Objective 2: DOE
Objective 3: Dependent on outcome of task

RECOMMENDED PROJECT A-2

TITLE: Physical and Chemical Characteristics of Deposits

OBJECTIVE:

1. To study the fouling characteristics of deposits by means of the physical and chemical properties.

TASK OUTLINE:

1. Selection of combustion conditions under which task is to be examined.
2. Define physical and chemical parameters to be examined:
 - a. surface character, i.e., roughness, orientation, temperature
 - b. gas temperature, types of fuel
 - c. time interval definition
3. Determine measurement techniques to measure above
 - a. available known techniques
 - b. new technology
4. Literature Survey.

MANPOWER AND TIME REQUIRED:

2 manyears labor

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

RECOMMENDED PROJECT A-3

TITLE: Dew-Point Measurements of Various Acids, Salts, and Vapors

OBJECTIVE:

1. To determine the points at which various condensables form liquid deposits for each condition of fuel.

TASK OUTLINE:

1. Set up test, under controlled conditions, with known condensables.
2. Determine dew-point temperatures and individual action as well as interaction when various condensables are combined.
3. Determine propensity for binding on combining with particulates.
4. Determine formation of corrosion components.
5. Determine propensity for forming fouling layers on transfer surfaces.
6. Determine affect of pressure, temperature and velocity on dew-point.

MANPOWER AND TIME REQUIRED:

5 manyears labor

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

Industry (manufacturers of heat transfer equipment) and indirect help from government through tax incentives.

Government through providing laboratory work on guidance via armed forces budget or DOE.

RECOMMENDED PROJECT B-1

TITLE: Fouling Measuring Device

OBJECTIVE:

1. Develop standardized fouling measuring device to study gas-side fouling for relative comparison.

TASK OUTLINE:

1. Review existing devices for applicability to gas-side fouling.
2. Develop and test device(s) as appropriate.
3. Validation testing.

MANPOWER AND TIME REQUIRED:

2 calendar years

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE

RECOMMENDED PROJECT B-2

TITLE: Gas-Side Fouling Standards/Advisory Committee

OBJECTIVE:

1. To establish an on-going standards advisory committee composed of all technical sectors.

TASK OUTLINE:

1. Identify appropriate technical organizations (industrial corporations, ASTM, AIChE, ASME, NACE, etc.) to convene a group to act as a standards and advisory committee. This committee would be composed of all technical sectors; that is, industry, government, academia, and national laboratories to assist in any program development.

MANPOWER AND TIME REQUIRED:

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

RECOMMENDED PROJECT B-3

TITLE: Particle Transport to Heat Exchanger Surfaces

OBJECTIVE:

1. Develop transport relations for complex geometries in useful forms to minimize fouling.
2. Determine importance of electrostatic and thermophoretic mechanisms.

TASK OUTLINE:

1. Review available technology (including gas turbine technology and electrostatic precipitators technology).
2. Based on review results, perform scoping experiments to confirm.
3. Develop relations required for design of heat exchangers.

MANPOWER AND TIME REQUIRED:

2 calendar years

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE

RECOMMENDED PROJECT B-4

TITLE: Particle Attachment

OBJECTIVE:

1. Determine and quantify dominant parameters that affect particle attachment, such as: particle size and distribution, physical state (liquid or solid), physical properties (shape, density, viscosity), temperature, velocity, electrostatic, surface free energy, condensation, and chemical reaction.

TASK OUTLINE:

1. Review fields of plasma chemistry, electrostatics, surface chemistry, pollution control, and lubrication.
2. Study stickability of well-defined aerosols as a function of above parameters, and develop correlations.
3. Validate correlations with field data.

MANPOWER AND TIME REQUIRED:

5 calendar years

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE/Industry

RECOMMENDED PROJECT B-5

TITLE: Natural Foulant Removal Mechanisms

OBJECTIVE:

1. Determine and quantify dominant parameters that affect macro deposit removal such as: deposit composition, fluid dynamics, deposit transformation, mechanical deposit properties (adhesion and cohesion), free stream particle characteristics (size, abrasiveness, etc.), cyclic temperatures.

TASK OUTLINE:

1. Develop classification scheme for deposits.
2. Classify deposits with respect to mechanical strength or erosive strength.
3. Develop test scheme for measuring removal.
4. Parametric Testing.
5. Field Validation.

MANPOWER AND TIME REQUIRED:

5 calendar years

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE/Industry

RECOMMENDED PROJECT C-1

TITLE: Empirical Fouling Data at Metal Temperatures Above the Dew-Point

OBJECTIVE:

1. Obtain accurate empirical data to use in the design of heat exchangers.

TASK OUTLINE:

1. Determine the thickness of the fouling layer and the fouling factor for several heat exchanger geometries in use today as a function of:
 - a. gas source (fuel and type of combustion)
 - b. gas temperature
 - c. surface temperature
 - d. gas velocity
 - e. time

MANPOWER AND TIME REQUIRED:

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE/Industry

RECOMMENDED PROJECT C-2

TITLE: Effectiveness of Cleaning Devices

OBJECTIVE:

1. Determine how well conventional cleaning devices -- such as sootblowers, sonic devices, and water wash -- remove fouled layers from typical heat exchanger surfaces.

TASK OUTLINE:

1. Test several cleaning devices to determine how well they clean:
 - a. different surfaces
 - b. different types of deposits

MANPOWER AND TIME REQUIRED:

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE/Industry

RECOMMENDED PROJECT C-3

TITLE: Dew-Point Type Fouling

OBJECTIVE:

1. Obtain accurate empirical data to use in the design of heat exchangers both for normal operation and startup/shutdown conditions.

TASK OUTLINE:

1. Determine the thickness of the fouling layers and the fouling factor for several heat exchanger geometries in use today when operated in the dew-point region as a function of:
 - a. gas source
 - b. gas temperature
 - c. surface temperature
 - d. gas velocity
 - e. time
2. Also, study the ease or difficulty of removing the deposits.

MANPOWER AND TIME REQUIRED:

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE/Industry

RECOMMENDED PROJECT C-4

TITLE: Alternate Fuel Fouling

OBJECTIVE:

1. Determine fouling rates for typical heat exchanger geometries with gas sources from alternate fuels (coal gasification, chemical wastes, refuse, etc.).

TASK OUTLINE:

1. Determine the thickness of the fouling layer and the fouling factor for several heat exchanger geometries as a function of:
 - a. gas source (fuel and type of process)
 - b. gas temperature
 - c. surface temperature
 - d. gas velocity
 - e. time
2. As part of this task, cleaning techniques should be studied also.

MANPOWER AND TIME REQUIRED:

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

RECOMMENDED PROJECT C-5

TITLE: Fouling and Cleaning of Non-Conventional Materials

OBJECTIVE:

1. Determine the fouling and cleaning characteristics of alternate surface materials and finishes. Materials should include teflon and other coatings such as glass, ceramics, and plastics.

TASK OUTLINE:

1. Measure the fouling rates and cleanability of these materials as a function of:
 - a. gas source
 - b. gas temperature
 - c. surface temperature
 - d. gas velocity
 - e. time

MANPOWER AND TIME REQUIRED:

WHO SHOULD FINANCIALLY SUPPORT THIS WORK? (Industry and/or DOE)

DOE

RECOMMENDED PROJECT C-6

TITLE: Flue Gas Treatment to Reduce Fouling

OBJECTIVE:

1. Reduce gas-side fouling by altering the flue gas through the use of gas treatment or fuel treatment.

TASK OUTLINE:

1. Measure the fouling rates and cleanability of heat exchanger surfaces when the flue gas has been altered by:
 - a. fuel additives
 - b. flue gas additives
 - c. electrostatic charging of particles and surfaces

MANPOWER AND TIME REQUIRED:

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE

RECOMMENDED PROJECT D-1

TITLE: Firetube Particulate Fouling Mitigation

OBJECTIVE:

1. Maintain satisfactory online cleanliness in firetube configuration processing high temperature (below the slag point and above the dew-point), high pressure gas containing unspecified loading of undefined, nonadhesive fine ($<1\mu$) particulates.

TASK OUTLINE:

1. Fouling phenomena definition.
2. Particulate characterization.
3. Testing in laboratory:
 - a. cold, atmospheric
 - b. at operating conditions (simulated)
4. Testing in field:
 - a. demonstration unit
 - b. full scale unit

Note: This project should piggyback on other DOE projects, i.e., coal gasification.

MANPOWER AND TIME REQUIRED:

50 manyears labor; 10 calendar years

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE with industrial support of personnel.

RECOMMENDED PROJECT D-2

TITLE: Wet Wall Problems

OBJECTIVE:

1. Determine methods to avoid wet wall problems. These would include additives, heat exchanger material selection, methods of cleaning, and methods of operation including startup, shutdown, and transients. The economics of the method is very important.

TASK OUTLINE:

1. Characterization of wet wall problems:
 - a. fouling due to particulate adhesion to wet walls
 - b. corrosion
 - c. others
2. Design considerations:
 - a. material selection including coatings
 - b. transient considerations
 - c. heat exchanger geometry
 - d. methods of avoidance
 - i. preheating
 - ii. others (remove and replace)
3. Cleaning techniques:
4. Operation:
 - a. startup/shutdown
 - b. transients
 - c. additives

MANPOWER AND TIME REQUIRED:

5 manyears labor; 2 calendar years; \$750,000 total

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE with industry cooperation on identifying economics and transients.

RECOMMENDED PROJECT D-3

TITLE: Electrostatic Cleaning

OBJECTIVE:

1. Develop a cleaning method which will allow cleaning without shutdown of the process and which can be operated by computer.

TASK OUTLINE:

1. Develop desk top particle/tube charger for preliminary evaluation of effects of electrical charges on tubes and particles of various sizes:
 - a. review and evaluate existing precipitator information
 - b. define particulate size and quantity and tube configurations
 - c. carry out tests in desk top particle/tube charger
 - d. summarize and report findings
2. Demonstration and test mock-up:
 - a. identify possible field test
 - b. select test site and application
3. Field Test.

MANPOWER AND TIME REQUIRED:

- Task 1: 1 manyear labor; 2/3 calendar year
Task 2: 6 manyears labor; 1½-2 calendar years
Task 3: 1½ manyears labor; ½ calendar year

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

- Task 1: DOE
Task 2: DOE/Industry
Task 3: Industry

RECOMMENDED PROJECT D-4

TITLE: The Development of Sonic Cleaning Devices and the Integration of These Devices with Particular Heat Exchanger Types and Designs

OBJECTIVE:

1. Analytically evaluate sonic devices and provide the engineering to match these devices to make them compatible with particular heat exchanger types and services. These design selections must be integrated with the proper heat exchanger type and the mechanical design of that heat exchanger.

TASK OUTLINE:

1. Survey the sonic devices presently available and the types of fouling most often experienced in various heat exchangers.
2. Select present devices or implement the design of especially powerful sonic devices.
3. Study the mechanical design of particular heat exchangers which may assist this acoustical cleaning technique.
4. Integrate the design and/or selected sonic device with the specially designed heat exchanger.
5. Test dynamic models of these integrated designs to verify design.

MANPOWER AND TIME REQUIRED:

Tasks 1-4: 1 1/3 manyears labor
Task 5: 4 manyears labor

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

Tasks 1-4: DOE
Task 5: Industry/DOE

RECOMMENDED PROJECT D-5

TITLE: High-Pressure Seals for Sootblower Penetrations into Heat Exchangers

OBJECTIVE:

1. Develop a reliable inexpensive seal for both rotary sootblower elements and rotating-translating sootblower lances when applied to high environment pressure heat exchangers.

TASK OUTLINE:

1. Identify pressure ranges required.
2. Identify gas stream characteristics:
 - a. physical
 - b. chemical
3. Identify physical arrangement of heat exchangers.
4. Survey the literature.
5. Carry out preliminary design.
6. Carry out final design.
7. Field test prototype(s).
8. Release final design to marketing.

MANPOWER AND TIME REQUIRED:

1½ manyears labor; 1 calendar year

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

Industry

RECOMMENDED PROJECT D-6

TITLE: The Low-Fin Tube in Fossil Fuel Exhaust Environments

OBJECTIVE:

1. Determine the effectiveness of the low-fin tube in a variety of dirty gas environments.

TASK OUTLINE:

1. Design and install test modules in at least four different dirty gas-side services. Attention should be given to various corrosion-resistant alloys which are readily available in the low-fin tube.
2. Monitor on a regular schedule for loss of heat transfer performance and increase in pressure drop.
3. Make qualitative observations of the presence of fouling and record pictorially.

MANPOWER AND TIME REQUIRED:

7½ manyears labor; 1½-2 calendar years

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE/Industry

RECOMMENDED PROJECT D-7

TITLE: Conceptual Study and Testing of Advanced Waste Heat Boiler Designs that Enhance Gas-Side Heat Transfer and Mitigate Gas-Side Fouling

OBJECTIVE:

1. Determine alternate methods of enhancing the gas-side heat transfer coefficient without the use of extended surfaces (finned tubes). Typical candidates for study include jet impingement devices and the adaptation of fluidized bed heat exchange for waste heat sources.

TASK OUTLINE:

1. Conceptual designs including analytical calculations and comparisons.
2. Selection of optimum design.
3. Fabrication of laboratory test units of the best three design choices.
4. Extended testing of these designs to evaluate performance and verify predictions.
5. Re-design and modify concepts in order to promote final design and technology.

MANPOWER AND TIME REQUIRED:

Tasks 1-3: 2 manyears labor; 1 calendar year (minimum)
Tasks 4-5: 4 manyears labor; 1 calendar year (minimum)

WHO SHOULD FINANCIALLY SUPPORT THE WORK? (Industry and/or DOE)

DOE

SECTION 8

RECOMMENDED RESEARCH AND DEVELOPMENT PROJECTS

At the Final Plenary Session, the floor was opened for discussion relative to the 21 proposed research projects presented by the Group Leaders and detailed in Section 7. Considerable time, in retrospect too much time, was spent in trying to combine these 21 tasks in a smaller group of R&D projects. However, in the final analysis, a consensus was hammered out resulting in the following six high-priority items listed below (The bracketed designations refer to the projects described in Section 7 and indicate the commonality among the projects under the listed topic):

- o Fouling Measuring Device [B-1]
- o Attachment, Removal, and Predictive Methods [B-3, B-4, B-5]
- o Collection of Empirical Data for Specific Geometries [C-1]
- o Characterization of Fossil Fuel Exhaust Gases [A-1]
- o Effectiveness of Cleaning Devices [C-2, C-5, D-3, D-4]
- o Wet Wall Fouling [A-3, C-3, D-2]

The participants were then asked to confirm this list of six items or modify it as appropriate. The balloting confirmed that these six items were all of high priority, and an additional item, Project D-7 dealing with alternative types of heat exchangers, was added to the list making a total of seven items.

Thus, the final list of high-priority R&D projects for gas-side fouling in fossil fuel exhausts by the Workshop participants is listed in Table 8-1 below. The titles have been expanded slightly to be somewhat more descriptive.

Table 8-1. List of High Priority Gas-Side Fouling R&D Projects Recommended by Workshop Participants

-
- o Characterization of Fossil Fuel Exhaust Gases
 - o Gas-Side Fouling Measuring Device
 - o Attachment and Removal Mechanisms and Predictive Methods for Gas-Side Fouling
 - o Collection of Empirical Gas-Side Fouling Data for Specific Geometries
 - o Effectiveness of Cleaning Devices for Gas-Side Fouling Service
 - o The Mechanism of Wet Wall Fouling in Fossil Fuel Exhaust Gases
 - o Alternative Types of Heat Exchange Equipment to Enhance Heat Transfer and to Mitigate the Effects of Gas-Side Fouling
-

In the summary discussions at the Final Plenary Session, several general conclusions were reached, either explicitly or implicitly. Characterization of fossil fuel exhaust gases is an important item in virtually all seven recommended projects and hence is a prerequisite to most of the remaining projects. The importance of developing a fouling measuring device of universal acceptance was considered very important. This project is an important prerequisite for a detailed study of attachment and removal mechanisms, as well as wet wall fouling, in gas-side fouling. The lack of validated design data for gas-side fouling factors was, of course, one of the major reasons for the considerable interest in the project dealing with the collection of empirical data for specific geometries. From the general and specific discussions at the Workshop, it is quite apparent that there is considerable interest in cleaning devices, especially sonic horns, for use in gas-side fouling service. However, it was the general feeling of the group that this work would be handled adequately by industry. From the discussion given above there is considerable interest in novel or alternative types of heat exchanger equipment to enhance gas-side heat transfer and to mitigate the effects of gas-side fouling. While fluidized bed and direct contact heat exchangers are logical candidates here, this area is ripe for some creative concepts. Finally, the important role of DOE in gas-side fouling research was mentioned throughout the Workshop discussions. Basically, it was the feeling of the participants that government-sponsored work would be: more objective, more thorough, and more widely disseminated than if it were sponsored by industry. Also, there are some projects which industry will not undertake because of the risks involved.

The original intent at the Workshop was to prioritize the list of R&D projects listed in Table 8-1. However, it was felt, based on the discussions at the Final Plenary Session, that this list of seven items -- all of which have a high priority -- is adequate for DOE purposes. Therefore, no further prioritization was carried out.

However, it was requested that some further information be obtained from the participants regarding the relative importance of various fuels used in heat recovery service where gas-side fouling is a potential problem. Also, the participants were asked to indicate the relative importance of gas-side fouling on internal versus external surfaces for those topics where this

distinction is important. This information was obtained by sending Questionnaires to the participants which are included in this section. The results are also given.

The results of these surveys clearly show that external gas-side fouling is of considerably more importance than gas-side fouling on internal surfaces. In the ranking of the various fuels, petroleum fuels and coal rank at the top for the short-term and coal or coal derived fuels and heavy petroleum fuels rank at the top for the long-term. It is clear that there will be a definite trend toward coal and coal-derived fuels in the future.

QUESTIONNAIRE 1

Short-Term (0 - 3 Years) and Long-Term (3 - 10 Years) Ranking of the Importance of Various Fuels Used in Gas-Side Fouling Heat Recovery Service

Note: Please indicate both the relative short-term and long-term importance of the eight fuels listed below by ranking them 1 through 8, with 1 being the most important and 8 being the least important. Comment as you feel appropriate.

Example: If you feel it is most important in the short-term to mitigate the fouling of heat exchangers exposed to the exhaust of incinerator fuels, score 1 under Short-Term for Incinerator Exhausts, etc.

Short-Term	Long-Term	Fuel/Description
_____	_____	<u>Agricultural Wastes</u> (e.g. sawdust, wood chips, rice hulls, nut shells, fruit pits, etc.)
_____	_____	<u>Coal</u> (lignite, sub-bituminous, bituminous, and anthracite)
_____	_____	<u>Coal Derived Fuels</u> (e.g. coal-derived gases, coal-derived liquids, coal-oil mixtures, coal-water mixtures, etc.)
_____	_____	<u>Incinerator Exhausts</u> (e.g. municipal solid wastes, sewage sludge, waste liquids, waste gases including "sour" gas, etc.)
_____	_____	<u>Natural Gas</u>
_____	_____	<u>Petroleum Fuels, Heavy</u> (e.g. No. 5 fuel oil (heavy), No. 6 fuel oil, etc.)
_____	_____	<u>Petroleum Fuels, Light</u> (e.g. gasoline, kerosene, Diesel fuels, No. 1-4 fuel oils, No. 5 fuel oil (light), etc.)
_____	_____	<u>Shale Oil</u>

Comments:

Name _____

Affiliation _____

QUESTIONNAIRE 1

Short-Term (0 - 3 Years) and Long-Term (3 - 10 Years) Ranking of the Importance of Various Fuels Used in Gas-Side Fouling Heat Recovery Service

RESULTS

<u>Short-Term</u> Weighted Avg Rank		<u>Long-Term</u> Weighted Avg Rank		<u>Fuel/Description</u>
5.04	6	5.41	6	<u>Agricultural Wastes</u> (e.g. sawdust, wood chips, rice hulls, nut shells, fruit pits, etc.)
2.70	2	2.26	1	<u>Coal</u> (lignite, sub-bituminous, bituminous, and anthracite)
4.60	5	2.94	2	<u>Coal Derived Fuels</u> (e.g. coal-derived gases, coal-derived liquids, coal-oil mixtures, coal-water mixtures, etc.)
4.21	4	4.52	4	<u>Incinerator Exhausts</u> (e.g. municipal solid wastes, sewage sludge, waste liquids, waste gases including "sour" gas, etc.)
5.21	7	6.40	8	<u>Natural Gas</u>
2.20	1	3.57	3	<u>Petroleum Fuels, Heavy</u> (e.g. No. 5 fuel oil (heavy), No. 6 fuel oil, etc.)
3.83	3	5.45	7	<u>Petroleum Fuels, Light</u> (e.g. gasoline, kerosene, Diesel fuels, No. 1-4 fuel oils, No. 5 fuel oil (light), etc.)
6.04	8	4.77	5	<u>Shale Oil</u>

QUESTIONNAIRE 2

Evaluation of the Importance of Gas-Side Fouling on Internal Heat Exchanger Surfaces Versus External Heat Exchanger Surfaces

Note: For the five projects listed below, please indicate whether fouling is more important on internal heat exchanger surfaces or external heat exchanger surfaces by writing Internal or External in the blank at the left of each project. Please feel free to comment further.

Internal or External	Project
_____	Fouling Measuring Device
_____	Collection of Empirical Data for Specific Geometries
_____	Effectiveness of Cleaning Devices
_____	Wet Wall Fouling
_____	Alternative Types of Heat Exchange Equipment to Mitigate the Effects of Fouling

Comments:

Name _____

Affiliation _____

QUESTIONNAIRE 2

Evaluation of the Importance of Gas-Side Fouling on Internal Heat Exchanger Surfaces Versus External Heat Exchanger Surfaces

RESULTS

<u>Internal</u>	<u>External</u>	<u>Both</u>	<u>Project</u>
<u>Number of</u>	<u>Respondents</u>		
4	24	5	Fouling Measuring Device
2	29	2	Collection of Empirical Data for Specific Geometries
4	26	3	Effectiveness of Cleaning Devices
5	25	2	Wet Wall Fouling
3	27	2	Alternative Types of Heat Exchange Equipment to Mitigate the Effects of Fouling

SECTION 9

IMPACT OF FOSSIL FUEL GAS-SIDE FOULING
ON ENERGY UTILIZATION

R. C. WEIERMAN

Fossil fuels are used to supply over 60 quadrillion Btu annually in the United States. Of this total, nearly 30 percent is consumed directly in industrial heating applications. Fossil fuels supply over 80 percent of the heat used in industrial processes and this dependence is likely to continue for decades (Reference 9-1). However, energy costs are not always a substantial factor in the cost of sales of the largest energy using industries. As a result, industrial energy efficiency is often as low as 10 percent and seldom exceeds 30 percent. Because of this, significant energy savings are considered possible with the application of existing, emerging, and advanced technologies. While better equipment maintenance and operation, along with minor modifications to existing equipment, can result in some energy savings, major process changes and capital expenditures are needed to achieve very large savings.

For the near term, the most attractive prospect for energy efficiency improvement is recovery or utilization of some of the 12 quadrillion Btu presently being exhausted to the environment. At an average value of about \$2 per million Btu, this waste heat represents a total value of more than \$24 billion in fuel costs. It is estimated that 10-20 percent of this energy can be economically recovered in the near term if some existing technical problems can be overcome (Reference 9-2).

One of the major technical problems is that of gas-side fouling of the heat exchangers involved in the recovery and utilization of this energy. Consideration of the unusually high fouling potential of fossil fuel flue gas streams and associated cleaning difficulties generally results in higher equipment costs, maintenance costs, and production costs. The two basic approaches to gas-side fouling are to: (1) modify the process involved to reduce the fouling, and (2) design the equipment to perform under the expected fouling conditions. Although process modifications are considered the most sophisticated approach, their development and implementation are generally of a long term nature. Modification of existing equipment designs to handle fouling conditions appears to be the most practical short term approach. If the fouling problems can be resolved, about 2 quadrillion Btu or \$4 billion in fuel costs annually are considered recoverable with current or near term technology.

In order to make these equipment modifications economically attractive, over design must be reduced and reliability increased. Presently, 5 to 10 percent of the cost of heat exchangers can be attributed to gas-side fouling considerations under the relatively clean conditions where they are being used. However, in some dirty applications where attempts have been made to increase efficiency, fouling considerations have nearly doubled the cost of the equipment. Thus, using an average equipment cost of \$15,000 per million Btu/hour transferred for relatively clean processes, fouling considerations could increase this cost by about \$10,000. On this basis, the cost of gas-side fouling considerations alone on equipment to recover 2 quadrillion Btu/year would be about \$3 billion.

In addition to the extra cost of the equipment, it is assumed that maintenance costs will also increase. Based on limited experience, annual maintenance costs are estimated at about 25 percent of the original equipment cost. This compares to about 10 percent for relatively clean flue gas applications. With an equipment cost of \$7 billion, the increase in maintenance costs due to fouling would be about \$1 billion annually.

Although the increased cost of the equipment and maintenance due to fouling is significant, the cost which is of most concern and nearly impossible to predict for most applications is that due to lost production when a piece of equipment fouls beyond design limits and causes reduced production or total shut down of the process. Such a loss can quickly exceed the original equipment cost.

So although the energy conservation benefits of increasing energy efficiency are significant, the economic benefits are difficult to predict because of the risks of equipment failure and attendant production losses resulting from gas-side fouling. At present, most of the information necessary to minimize the risks of gas-side fouling from fossil fuel flue gases is very limited and generally proprietary. Higher energy prices will continue to encourage improvements in operation and maintenance of existing equipment. However, more research, development and demonstration of equipment capable of economic and reliable operation in high fouling gas streams are necessary to minimize the risks involved with the overall production.

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- 9-2. "Development of the Strategic Plan for Industrial Energy Conservation," Report No. DOE/TOC-10002, U.S. Department of Energy, Office of Industrial Programs, Division of Industrial Energy Conservation, Washington, D.C., July 1978.

SECTION 10

EVALUATION OF WORKSHOP

QUESTIONNAIRE 3

Workshop Evaluation Form

Note: In Items 1 through 7, please indicate your response by circling the appropriate number. Note that in each case, 1 represents the most positive response and 5 the most negative response. Comment on Items 8 and 9 as appropriate, and use the back side of the the page if you need more space.

1. Technical presentations (Panelists, Banquet Speaker, and Group Leaders):
(Excellent) 1 2 3 4 5 (Very Poor)
2. Technical discussions in Workshop Groups:
(Excellent) 1 2 3 4 5 (Very Poor)
3. Technical discussions at final plenary session:
(Excellent) 1 2 3 4 5 (Very Poor)
4. Accomodations and facilities (Lodging, Meals, Social Hour, Banquet, Meeting Rooms):
(Excellent) 1 2 3 4 5 (Very Poor)
5. Overall organization and conduction of Workshop:
(Excellent) 1 2 3 4 5 (Very Poor)
6. Degree to which stated Workshop objectives were achieved:
(Excellent) 1 2 3 4 5 (Very Poor)
7. Degree to which your personal Workshop objectives were achieved:
(Excellent) 1 2 3 4 5 (Very Poor)
8. How could the Workshop have been improved?

9. General Comments:

QUESTIONNAIRE 3

Workshop Evaluation Form

RESULTS

							<u>Average Rating By Participants</u>	
1.	Technical presentations (Panelists, Banquet Speaker, and Group Leaders): (Excellent)	1	2	3	4	5	(Very Poor)	2.03
2.	Technical discussions in Workshop Groups: (Excellent)	1	2	3	4	5	(Very Poor)	2.06
3.	Technical discussions at final plenary session: (Excellent)	1	2	3	4	5	(Very Poor)	2.90
4.	Accommodations and facilities (Lodging, Meals, Social Hour, Banquet, Meeting Rooms): (Excellent)	1	2	3	4	5	(Very Poor)	1.94
5.	Overall organization and conduction of Workshop: (Excellent)	1	2	3	4	5	(Very Poor)	1.97
6.	Degree to which <u>stated Workshop objectives</u> were achieved: (Excellent)	1	2	3	4	5	(Very Poor)	2.41
7.	Degree to which <u>your personal Workshop objectives</u> were achieved: (Excellent)	1	2	3	4	5	(Very Poor)	2.41

SECTION 11

CONCLUDING REMARKS

Attendance at this Workshop has been an interesting learning experience. A large amount of knowledge and information has been exchanged among workers interested in gas-side fouling. Although there have been other forums where corrosion, fouling, and slagging from combustion gases have been the focal point, this Workshop is apparently the first meeting where the primary emphasis has been placed on gas-side fouling in fossil fuel exhaust environments with special emphasis on heat recovery systems. Unlike fouling in liquids, which has received considerably more attention, gas-side fouling is in a relative state of infancy.

In many ways, the topic of gas-side fouling in heat recovery systems presents an interesting study of contrasts. From a broad perspective, R. C. Weierman pointed out in Section 9 that some 12×10^{15} Btu/year are presently exhausted to the atmosphere through the industrial consumption of fossil fuels. Estimating the cost of this energy at \$2 per 10^6 Btu, the total value of this industrial waste energy is \$24 billion. If even 10 percent of this amount could be recovered, the potential value is still over \$2 billion which is a significant total. Clearly, it would be to the advantage of both industry and the people of the United States to recover as much of this energy as possible.

Certainly one of the principal difficulties involved in the recovery of heat from fossil fuel exhausts is gas-side fouling. The participants in this Workshop have done a good job of identifying the technical problems in this area which require further study. As might be expected for a billion dollar heat exchanger industry, the cost of needed research is in the tens of millions of dollars. Much of this work is in the area of applied research which, although very pertinent to real problems encountered by industry, is too risky to justify large expenditures by the industrial sector.

By contrast, the heat exchanger technology effort in the Physical Processes Project of the DOE-ECUT Program is limited to an annual budget in the range of \$500,000 to \$1,000,000. And this program covers considerably more than fouling; in fact, the effort in gas-side fouling is limited to less than \$200,000 per year. Thus, it is clear that the DOE-ECUT budget is not nearly adequate to carry out the kind of research program which the participants in this Workshop have called for. Furthermore, there are

indications that the present Administration may make further cuts in this program.

Perhaps one way to get more work done under the present budgetary constraints is to depend heavily on cost sharing by industry. Many attendees have expressed a favorable attitude toward such cost sharing, especially in the form of donating equipment and fabrication support. One of the pleas heard throughout the Workshop is the need for more experimental gas-side fouling data. It is also apparent that small lab and bench scale facilities do not always suffice, and that sometimes large scale testing is needed. Therefore, under these conditions it would seem very appropriate for DOE to establish a national center for fouling research, with equipment and facilities donated by industry, and operating funds provided by DOE. Clearly, there is a good spirit of cooperation between industry and the federal government in this field. What is badly needed is a mechanism for putting the recommendations of this Workshop into effect. Major research efforts at such a national center would produce non-proprietary gas-side fouling results which would be readily available to all interested parties and eventually lead to commercialization by industry. Thus, such a program would ultimately unlock many quads of energy which are presently being wasted and help to facilitate conservation efforts which are clearly in the best interests of this country.

SECTION 12

BIBLIOGRAPHY ON GAS-SIDE FOULING

This bibliography on gas-side fouling includes a total of about 175 citations grouped under the headings of books, reports, and papers. The latter category includes both presentations at technical meetings as well as publications in the permanent literature. The references were obtained from the files of the editors, the Workshop participants, and several computer-based literature searches. Special emphasis was placed on publications related to heat recovery applications.

About 70 of the references were obtained as the result of culling 574 references from a computer data base survey. The 574 references were obtained from the following three data bases:

1. NTIS, 1964-1981: 80 citations.
2. Engineering Index (Compendix), 1970-1981: 144 citations.
3. Department of Energy Data Base (DOED), through 1981: 350 citations.

Each data base was searched using the following procedure: Query 1: Print all references with the keywords "gas" and "fouling", and Query 2: Print all references which include the Group A keywords, but exclude all references which also include any of the Group B keywords. Group A keywords included: gas, fouling, exhaust, heat recovery, heat exchanger, combustion products, finned tubes, and waste heat. Group B keywords included: liquid, liquids, water, hydrocarbons, petroleum, refining, and feedstock.

No claim is made as to completeness, especially for literature published before 1970. The report "Corrosion and Deposits from Combustion Gases," Battelle Memorial Institute, Columbus Laboratories, Columbus, Ohio, 1970, is the best reference available for work done in this area prior to 1970. This report, which is included among the citations in the present Bibliography, includes abstracts for many of the references and should be considered a "must" for anyone seriously interested in gas-side fouling.

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