A REVIEW OF THE
FUNDAMENTAL COMBUSTION RESEARCH PROGRAM

April 25, 1980

Science Advisory Board
U.S. Environmental Protection Agency

EPA NOTICE

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PREFACE

There is a stated desire within EPA's Office of Research and Development (ORD) to have "peer reviews" of specific elements of its Program. The objective of such reviews is to ensure that these elements have the benefit of evaluative comments from a broader segment of the appropriate expert community than is normally involved in any specific research project. A peer review can take any of several forms. In the most continuing type, a program is reviewed at its conceptual phase, at several benchmarks and at its conclusion. In the single-exposure type, the program is evaluated by a group of experts, specially put together for the review.

A peer review of the Fundamental Combustion Research (FCR) program of the Industrial Environmental Research Laboratory (IERL) - Research Triangle Park, North Carolina, to provide an independent assessment of the program was requested by the management of ORD's Office of Environmental Engineering and Technology (OEET). The Technology Assessment and Pollution Control Committee (TAPCC) of the Administrator's Science Advisory Board was asked to conduct this review. TAPCC elected to perform this review and formed a special review group. The review group chose to

a) examine the objectives of the program within the context of the Agency's mission;

b) evaluate, to the extent possible, the technical quality and management of the research underway; and

c) assess future program direction with regard to Agency needs.

The members of the TAPCC review group were W. Leigh Short (chairman) and James H. Porter, and consultants Ralph H. Kummler, John M. Ross, and Paul W. Spaite. In addition, Stanley M. Greenfield and M. Massoudi of Teknekron Research, Inc. (Berkeley, CA) provided technical support. William N. McCarthy, Jr., Acting Executive Secretary of TAPCC, provided staff and administrative support.

As conceived, this review was to utilize the periodic projects-review meeting that had been scheduled by the EPA project officer, Steve Lanier. Background information for the assessment of the FCR program was acquired as follows:

a) Review of the briefing book provided by Mr. Lanier. This book describes the program, its objectives, the management system and the individual projects.

b) Attendance at three (3) days of program review discussions, during which the status of the research activities was presented and other investigators were able to comment on the Program, the results, the validity of experimental technique, etc. The agenda is found in Appendix A and the attendance is given in Appendix B. This meeting was held January 23-25, 1980 in Newport Beach, California.

c) Participation in an open meeting of the TAPCC review group at which program managers and research personnel associated with the FCR program responded to questions and comments from the group. This meeting was held on January 26 at the University of California, Irvine, campus.

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1.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations of the Technology Assessment and Pollution Control Committee's (TAPCC), Fundamental Combustion Research FCR review group are divided between the conclusions and recommendations of (1) a general program nature and (2) a specific technical nature and are as follows:

1.1 Program

Concerning the general program aspects of the review, the TAPCC FCR review group concludes that:

1. The FCR program of the Office of Environmental Engineering and Technology (OEET) is in general well-conceived and well-executed. Participants are competent, well-qualified, enthusiastic, and displayed a good understanding of the spectrum and complexity of the problems needing solution.

2. Funds expended for the program have produced results that are worth the cost.

3. The "Master Contract" approach has proven to be successful. The prime contractor is doing a good job of managing the subcontractors and is responsive to EPA's needs.

4. The EPA management team is well acquainted with the details of the on-going research, the problems which require solution, and the necessary interfaces with industry and other non-EPA sponsored research programs in the same area. The TAPCC FCR review group recommends that

- o Efforts should be made to insure that the competence and knowledge which have been developed by the FCR program be fully utilized and as widely disseminated as practicable.

5. Past and present work is aimed chiefly at understanding and minimizing the problems associated with controlling those NO_x emissions which are produced mostly by large coal and residual oil-fired boilers. This is considered to be a proper emphasis at this time for fundamental combustion research aimed at improving NO_x control.

6. There is growing national recognition that potentially hazardous emissions other than NO_x (e.g., sulfates, unburned hydrocarbons, trace metals) are likely being produced by small combustors. This implies that combustion conditions similar to those of small combustor operations should be studied, for these parameters are different from those currently being examined by FCR. The TAPCC FCR review group, therefore, recommends that

- o the FCR program be expanded to include studies that would lead to a reduction in the level of pollutants other than NO_x. This is not meant to suggest a program redirection, but rather a program expansion with commensurate resources as required.

- o the effort be expanded to identify future problems (5 to 10 years hence) which would lend themselves to analysis using experimental techniques which have been developed under the FCR program. A problem in this category, which might be appropriate for investigation, is the combustion of synthetic fuels produced from coal or shale oil.

- o studies should be conducted to determine whether these synthetic fuels are likely to produce potentially hazardous materials under normal combustion conditions.

1.2 Technical

Concerning the specific technical aspects of the program, the TAPCC review group concluded that

1. The technical work which has been accomplished to date is of high quality and is directed toward the solution of EPA regulatory problems.

2. Proper and thorough use of past literature has been made and the point of diminishing returns on further recalculations of old results has probably been reached.

3. Since there is insufficient funding for this program to underwrite the cost of obtaining individual rate constants and elucidating mechanisms with current technology, the emphasis on using kinetic code and reaction mechanisms developed elsewhere and testing their applicability for simplified combustion experiments is well placed.

4. More work is required to improve the kinetic codes to prove the uniqueness of a specific chemical reaction mechanism. The TAPCC review group recommends that

- the FCR program consider funding new fundamental flame studies, e.g., on flat flames or opposed jet flames, which are properly instrumented to provide reliable detailed spatial and temporal data on free radical species. These studies should preferably be done in existing equipment with augmented diagnostic capability.

5. Since no clear-cut methodology to treat the interplay of aerodynamics and kinetics in a turbulent environment was delineated, one apparently does not exist. As this is a most

difficult area and no solution is in sight, the TAPCC FCR review group recommends that

- o further investigation on the interactions of the combustion aerodynamics and the chemical kinetics in turbulent diffusion flames be carried out. Until this limitation is minimized, satisfactory design of an overall combustor model will not likely be possible.

6. Although, the FCR program has had a major impact upon the combustion engineering community, and much of the work published by the program is presently incorporated in engineering design, it does not appear that appropriate mechanisms for use of the fundamental data being generated in design of scaled-up equipment have as yet been identified. The TAPCC FCR review group recommends that

- o the principles and methodology which could be used to apply data being generated to the design of large-scale units or for modification of existing units be identified.

2.0 REVIEW OF PROGRAM OBJECTIVES

The broad objective of the Fundamental Combustion Research (FCR) program is to develop a basic understanding of fossil fuel combustion processes and to generate data needed to design combustors for minimum pollution. The specific objective of the FCR program currently is to develop an ability to predict oxides of nitrogen (NO_x) emissions considering a wide variety of fuel types and boiler types. Most work has been aimed at control of NO_x from large boilers burning coal or residual oil. The general approach taken by the FCR researchers to achieve these objectives is to concentrate on the generation of gas-phase reactants from the volatilization of solid and liquid fluids, gas-phase kinetic modeling, heterogenous reactions of NO_x reduction by char, and transport phenomena which are of relevance to combustion processes. To synthesize these components into a capability to predict emissions, the program employs mathematical modeling and ideal flame and furnace models such as the well-stirred reactor, the plug flow-reactor, the pre-mixed flat flame, the laminar axial diffusion flame, and the laminar opposed jet diffusion flame.

2.1 Adequacy of Program Objectives

Nitrogen oxides are a major pollutant species produced in combustion. Large boilers burning coal and residual oil are one category of the major sources of our Nation's pollutant emissions. Furthermore, minimizing NO_x through control of the combustion process is generally considered the most economically feasible route to initial control of these pollutants. Thus, the overall objective of the program is adequate. Additionally, the techniques that will be developed for predicting NO_x emissions will be useful in predicting other pollutant emissions from combustion processes. The task objectives of the present FCR program have during the life of the program been appropriate. However, recently developed information on the relative importance of energy consumption in all types of combustors coupled with a better understanding of potentially hazardous pollutants (e.g., unburned hydrocarbons, trace metals, and sulfates) have given rise to a need to reassess the overall problem of pollution from combustion and determine what additional fundamental combustion research is needed.

Some of the reasons why fundamental research might now be appropriately targeted, in part, on problems presented by small and intermediate oil-burning combustors are as follows:

a) Much of the Nation's supply of distillate oil is consumed in small boilers and residential furnaces. Operating and maintenance procedures for these units are such that poor combustion efficiency, resulting in discharge of unburned or partially burned hydrocarbons, can be expected.

b) Much of the residual oil is also burned in small boilers. Residual oil-fired boilers have been shown to emit much more direct sulfate per unit of sulfur content than do coal-fired boilers. Also residual oil-boilers have been shown to discharge trace metals, some of which are known to be toxic. Further, these boilers are known to discharge oil soot which is suspected to contain, at times, carcinogenic material.

c) Small boiler and residential furnaces are located in urban areas and discharge emissions at low levels. In addition, much of the material discharged from oil-burning boilers is known to be in the respirable size range.

If questions relative to small combustors are to be answered effectively, R&D on small scale systems will be needed. At present it appears that little or none is underway.

2.2 Ability to Achieve Program Objectives

As discussed above, the program objectives are clearly defined. The responsibility for achieving these objectives rests with the EPA program management staff and, to some extent, with the staff of the master contractor. Because of the large number of research contractors involved and the large number of areas currently under investigation, there will always be the potential for a substantial coordination problem. For the most part, the coordination appears to be as good as one could expect.

One of the primary communication mechanisms for the program is the "annual" meeting of the contractors, at which the research results are presented. At the most recent meeting, the one which the TAPCC FCR review group attended, less technical discussion took place than seemed warranted. There are two likely reasons for this:

a) The size of the meeting -- about 50 people were present.

b) The presence of the TAPCC review group -- which may have been an inhibiting factor in preventing the research results to be openly discussed and criticized.

The TAPCC review group believes that with regular and continuing attendance by essentially the same TAPCC reviewers the negative perception referred to in item (b) above would eventually disappear. Holding topic meetings which would be smaller in attendance would increase the interchange that was perhaps lessened with a meeting size of 50.

The briefing book prepared by the EPA program manager for the TAPCC FCR review group was very useful. Whether or not this type of peer review is continued, publication of a summary document briefing book on an annual basis would be very helpful to those not totally familiar with the program. The need for the publication also arises because portions of the program tend to be reported only in rather disparate journals and other low circulation publications.

2.3 Benefits to EPA

The benefits to be gained by EPA for appropriately funding this program are:

a) An understanding of the NO_x formation process in boiler operation that will permit both optimization of NO_x control and a quantification of the sensible emission limits for standard setting;

b) The knowledge gained will apply not only to the combustion of conventional fuels such as oil and coal but also to the utilization of synthetically derived fuels in boilers and to the thermal destruction of wastes (incineration);

c) The methodology to evaluate future problems will be developed.

3.0 REVIEW OF PROGRAM CONTENT

The program content was reviewed and evaluated in terms of relevancy, methodology and progress.

3.1 Relevance to Present Objectives

a) Chemical kinetics: The program includes a solid component of gas phase and heterogeneous chemical kinetics geared to interpretation of data taken both within and outside the FCR program, gaining insight into the complex reaction phenomena of fuel pyrolysis and subsequent combustion, and determining the kinetic constraints to the maximum limit of NO_x control attainable. More specific efforts to obtain the critical rate constants are clearly needed, but the level of effort required to obtain rate constant data is equally clearly beyond the current resources of the program. The effect of coal properties such as mineral composition, graphite content, and porosity on particle burnout time and the reaction mechanisms leading to NO_x formation should be addressed and experimentally investigated. The current emphasis on synthesis in the chemistry area is well placed. The additional emphasis on obtaining global rate-determining information pertinent to specific fuels is appropriate and highly relevant to the objectives of the FCR program.

b) Aerodynamics: The fluid flow, which dominates the combustion process in any industrial combustion system, is highly turbulent. Most coal flames in boilers are dominated by aerodynamic phenomena. The importance of combustion aerodynamics has led to the general belief that for diffusion flames the chemical reaction rate is not the rate-determining process. Spectroscopic investigations have shown that this is only true for the hottest part of the reaction zone. The preheating zones show interesting sequences of chemical reactions. The interplay of aerodynamics and chemical kinetics which is of practical importance in turbulent diffusion flames is presently inadequately treated in this program.

c) Equipment: There is a wide spectrum of equipment, beginning with laboratory scale and continuing through bench and pilot scale sizes. The specific selections have been wisely chosen to address the issues which have arisen in each individual project. However, the equipment and the techniques need to be standardized. In summary, the tasks selected appear to enable a reasonable probability of success in achieving the objectives.

d) Interface with applications: The interface of FCR activities with what happens in real furnaces has not been demonstrated clearly. For example, applying the results obtained in lab-scale stirred-reactor experiments to actual situations requires incorporating scale-up procedures which need to be elucidated. Efforts should be made to tie the end results into a furnace model incorporating the practical factors such as mixing, burnout time, and temperature variation in the furnace. At present, furnace behavior is determined by correlation factors derived from the reference fuels. While this has been an important contribution to the engineering-design community, a general model describing combustion processes in a furnace on the basis of practical variables is currently lacking. The TAPCC FCR review group recognizes, however, that such a model may be premature at this stage of the FCR program.

3.2 Methodology

a) In developing an overall model capable of scale-up and engineering design, many separate model components must be tested and validated. The FCR program is following the "validation by parts" methodology in which any portion of the model which can be separately tested is subject to independent scrutiny. The program frequently is divided into independent tasks in which one subcontractor develops a model and another validates it. This is an approach which is to be encouraged. Although this approach is desirable and necessary, it is not sufficient. Eventually, comprehensive tests of the overall model must be developed.

b) In evaluating model prediction using data obtained in the laboratory, emphasis should given to quantitative measures, such as correlation coefficients and statistical treatment, rather than to qualitative statements of agreement.

c) More emphasis should be placed upon criteria for determining model uniqueness, especially with regard to chemical kinetic mechanisms. Comparison of model prediction with concentration profiles for stable species, burning velocities, and final exhaust concentrations are useful, but not sufficient. Concentration profiles of reactive intermediates often provide a more rigorous test of model accuracy. Special emphasis should be placed upon programs to measure free radicals *in situ*. Of some 100 reactions considered exemplary of a general mechanism, perhaps only 20 will be critical, and the rate constant uncertainty in those 20 can cause difficulty. Detailed profiles of the reactive species such as OH, CHO, CN, etc. will help eliminate the uncertainty problem and will assist in defining mechanism uniqueness.

d) In the modeling strategy, care must be exercised in discarding literature data which do not fit the current kinetic models. Emphasis should be placed upon defining the range of model validity, including all of the relevant parameters (e.g., Over what range of temperature have kinetic parameters been measured, and over what range have the model components been validated?). Care must be taken to limit model use in engineering design to applicable situations and not to attempt to extrapolate into a region where the model has not been tested.

e) In using the jet-stirred combustor for development of kinetic packages, the program must address the adequacy of the well-stirred reactor equipment. Namely, the comparison of kinetic times, residence times and mixing times must be evaluated. Until quantitative measures of mixing times have been established for a given piece of equipment, it should not be used for kinetic comparisons. The example, a demonstration of log linear tracer behavior for residence times in cold flow which are an order of magnitude above combustor residence times, does not allow adequate assessment of micro mixing on the time scale of interest.

This is not to say that a partially stirred reactor will not be a useful tool. However, data from such a combustor cannot be used to test kinetic codes.

f) Additional areas requiring some attention include:

(1) a good working definition of "mixing,"

(2) fuel decomposition rates and products,

(3) a definition of mixing histories as related to product yield,

(4) N-H kinetics,

(5) establishment of a "sample" data base. Filters, product, etc. should be preserved by EPA for future study should priorities change. A well defined set of samples together with their combustion histories would be useful. This

might avoid redoing studies if future interest results in new pollutant studies.

3.3 Progress Toward Achievement of Goals

The FCR program has clearly had a major impact upon the combustion engineering community. Numerous examples of each contribution can be cited:

a) The importance of fuel-combined nitrogen in total NO_x production first was demonstrated by the FCR researchers. Their work showed that NO_x control for low-nitrogen fuels should be accomplished by minimizing peak temperatures through control of mixing, heat transfer and diluent addition. For fuels with high-fuel nitrogen, a strategy which involved limiting oxygen availability in staged combustion was indicated. These general principles are now accepted and are being widely applied.

b) The FCR researchers were the first to find that fuel nitrogen contained two fractions, one "volatile" and one "refractory," the latter being burned much later in the flame during carbon burnout. Pilot scale work confirmed the importance of the two types of fuel nitrogen and led to the design of low-NO_x burners which controlled the flame shape and carbon burnout. The designs which were developed have been demonstrated effectively on large scale equipment in the lab.

c) Bench scale studies show that both nitrogen distribution and type of reactor affect NO_x levels in combustion gases. Growing understanding of these relationships has led to encouraging progress in work underway to correlate field results with bench reactor and pyrolosis testing of volatile nitrogen.

d) Kinetic studies involving ammonia, hydrocarbon, and a low-Btu gas system indicate that design of combustors using coal-derived low-Btu fuels having a high content of nitrogen should provide for a fuel-rich first stage with controlled stoichiometry and a rapidly mixed second stage to minimize NO_x formation. This was confirmed subsequently by experimental work which also indicated that the same combustor configuration is appropriate for other high-nitrogen fuels including oil from shale, residual oil, and all coal-derived liquids.

e) Study of residential furnace oil burner performance resulted in EPA's patenting a burner design which yields a 65 percent NO_x reduction including, reduced carbon emissions and improved system efficiency.

f) Studies involving a first principles model for study of catalytic combustion led to design of a patented graded cell catalyst. The novel design gives order of magnitude increases in heat release rates which are expected to permit design of smaller, more efficient combustors with minimum pollution. This work was extended to the development of and patent on the design of a high-efficiency radiative water tube boiler which can control to very low NO_x emissions.

g) Kinetic studies were used to assess emissions expected from magnetohydrodynamic (MHD) systems. Results indicated that equilibrium levels of NO_x would be attained in the burner section. Also it was indicated that decomposition rates were too low for available residence times. Contrary to previous expectations, NO_x levels would not likely be reduced sufficiently to meet standards during subsequent passage through the radiant furnace. This suggested the need to redirect the work to focus on process changes at the burner end.

4.0 REVIEW OF PROGRAM MANAGEMENT AND COORDINATION

4.1 Adequacy of Staff

The "Master Contract" approach appears to be working well. Although there will always be the potential for conflict of interest, the close contact with EPA in the decisionmaking process minimizes this potential. The TAPCC FCR review group is impressed with the organization. The EPA program manager has assembled a very high quality team of researchers. They are very knowledgeable of the work in the field and open to suggestions on other ways to attack the various problems of extramural activity. The technical capabilities of the people associated with this program appear, in general, to be excellent.

The morale is high and their dedication good. The indepth technical understanding of the program by the associated EPA staff is evident and assures the required Agency technical overview, control, and guidance.

There would appear to be a need for additional capabilities in the area of mathematical modeling if research is to be initiated in solving the Navier-Stokes equations for swirling atomizers. Additional manpower resources may also be necessary if work is begun in a study of scale-up fundamentals.

This is one of the few research programs within EPA that has been managed via a master contract. The prime contractor is also responsible for the very large fraction of the work passed through to subcontractors both firms and consultants. It is the TAPCC FCR review group's judgment that the prime contractor has done a good job of managing the overall contract. In this particular instance of program implementation via the master contract technique, EPA has been well served.

4.2 Adequacy of Program Budget

The budget is well-managed and has been well-utilized. The mix of money among various program elements has been well thought out and is consistent with the program priorities and objectives. If the above recommendations to expand the program beyond its present objectives are adopted, an expansion of the budget will be in order.

APPENDIX A

AGENDA FOR THE FCR CONTRACTORS' REVIEW MEETING
Marriott Hotel, Newport Beach, CA -- January 23-25, 1980

Wednesday 23 January

8:30 a.m. Registration

9:00 a.m. The CRB Fundamental Combustion Research Program
W. S. Lanier - EPA

9:30 a.m. Session 1 - GAS PHASE CHEMISTRY AND HETEROGENEOUS NO REDUCTION

Chairman - C. T. Bowman, Stanford University

1. Kinetic Modeling Needs -- A. Sarofim, MIT
2. Development of a Kinetic Mechanism to Describe the Fate of Fuel Nitrogen in Gaseous Systems -- T.L. Corley, EER
3. NO_x Formation in the Flat Laminar Opposed Jet Diffusion Flame -- W. A. Hahn, University of Arizona
4. The Formation and Destruction of Nitrogeneous Species During Hydrocarbon-Air Combustion
D. W. Blair, Exxon
5. Application of the FCR Mechanism
J.O.L. Wendt, University of Arizona
6. NO Reduction by Char -- A. F. Sarofim, MIT
7. Mechanisms of NO Reduction on Solid Particles
G. G. De Soete, IFP

Thursday 24 January

8:30 a.m. SESSION II - THERMAL DECOMPOSITION - CHEMICAL AND PHYSICAL EFFECTS

Chairman - A. F. Sarofim, MIT

1. Inert Pyrolysis of Oil and Coal
R. Gay, Rockwell
2. Drop Tube Experiments on Oils and Coals
J. M. Beer, MIT

APPENDIX A (Continued)

3. IR Analysis of Coals and Coal Volatiles
   P. Solomon, UTRC

4. Physical and Chemical Effects Occurring During the Thermal Decomposition of Coal Particles
   R. W. Seeker, EER

1:30 p.m. SESSION III - BENCH SCALE REACTOR STUDIES

Chairman - J. P. Longwell, MIT

1. Back-Mixed Liquid Fuel Fired Reactors
   M. Murphy, Battelle Columbs Laboratories

2. Back-Mixed Solid Fuel Fired Reactors
   P. Goldberg, Acurex

3. The Impact of Fuel Characteristics on NO_x Formation -- M. P. Heap, EER

4. Pollutant Formation During Fixed-Bed and and Suspension Coal Burning
   D. W. Pershing, University of Utah

Friday 25 January

8:30 a.m. SESSION IV - TWO PHASE TURBULENT DIFFUSION FLAMES

Chairman - W. S. Lanier, EPA

1. Droplet Combustion in Shear Layers
   A. Vranos, UTRC

2. Spray Characterization -- G. S. Samuelsen, U of CA, Irvine, and C. Hess, SDL

3. Fluid Mechanics of Swirl Induced Recirculation Zones -- J. Swithenbank, University of Sheffield

4. Pollutant Formation in Long Turbulent Pulverized Coal Diffusion Flames -- R. Payne, IFRF

1:30 p.m. SESSION V - MODEL DEVELOPMENT

Chairman - T. J. Tyson, EER

1. Development of a Coherent Flame Model for Turbulent Chemically Reacting Flows
   F. E. Marble, California Institute of Technology

2. General Kinetic Analysis Codes -- E. J. Kau, EER

APPENDIX B

ATTENDEES AT THE FCR CONTRACTORS REVIEW MEETING
Marriott Hotel, Newport Beach, CA -- January 23-25, 1980

Professor J. M. Beer
MIT.

Mr. George Bennett
U.S. EPA, RTP, NC

Dr. David Blair
Exxon Research & Engineering Co.
Linden, NH

Dr. D. Blazowski
Exxon Research & Engineering Co.
Linden, NH

Professor Tom Bowman
Stanford University

Dr. J. E. Broadwell
TRW Systems
Redondo Beach, CA

Mr. Dick Carnes
U.S. EPA
Cincinati, OH

Mr. T. Corley
Energy & Environmental Research
Corp., Irvine, CA

Dr. Gerard De Soete
Institut Francais du Petrole
France

Dr. J. Drewry
GRI
Chicago, IL

Dr. R. Gay
Rockwell International
Canoga Park, CA

Dr. P. Goldberg
Acurex Corporation
Mountain View, CA

Dr. S. Greenfield
Teknekron, Berkeley, CA

Dr. W. Hahn
University of Arizona

Mr. Robert Hall
U.S. EPA, RTP, NC

Mr. Simon Hansen
MIT

Dr. M. P. Heap
Energy and Environmental
Research Corp. Irvine, CA

Dr. C. J. Kau
Energy and Environmental
Research Corp. Irvine, CA

Dr. R. Kendall
Acurex Corporation
Mountain View, CA

Dr. R. Kummler
Science Advisory Board
U.S. EPA, RTP, NC

Mr. W. S. Lanier
U.S. EPA, RTP, NC

Professor T. Lester
Kansas State University

Mr. Arthur Levy
Battelle Columbus
Laboratories
Columbus, OH

Dr. Joel Levy
MIT

Professor J. P. Longwell
MIT

Dr. Andre Macek
National Bureau Standards

APPENDIX B (Continued)

Mr. G. B. Martin
U.S. EPA, RTP, NC

Dr. M. Massoudi
Teknekron
Berkeley, CA

Mr. William N. McCarthy, Jr.
Science Advisory Board
U.S. EPA, Washington, DC

Dr. M. Murphy
Battelle Columbus
Columbus, OH

Dr. T. O'Brien
Department of Energy
Morgantown, WV

Dr. Roy Payne
IFRF
Holland

Professor D. Pershing
University of Utah

Dr. J. Pohl
Sandia Laboratories
Livermore, CA

Dr. J. Porter
Science Advisory Board
U.S. EPA

Dr. J. Ross
Science Advisory Board
U.S. EPA

Professor S. Samuelsen
University of California
Irvine, CA

Professor A. F. Sarofim
MIT

Dr. W. R. Seeker
Energy & Environmental Research
Irvine, CA

Dr. L. Short
Science Advisory Board
U.S. EPA

Professor F. E. Marble
California Institute of
Technology

Professor D. Smoot
Brigham Young University

Dr. P. Solomon
UTRC
East Hartford, CT

Dr. Paul Spaite
Science Advisory Board
U.S. EPA

Dr. Robert Statnick
U.S. EPA, Wash., DC

Professor J. Swithenbank
University of Sheffield
England

Dr. J. D. Trolinger
Spectron Development Labs
Costa Mesa, CA

Dr. G. Tucker
U.S. EPA, RTP, NC

Dr. T. J. Tyson
Energy & Environmental
Research Corp., Irvine, CA

Dr. A. Vranos
UTRC
East Hartford, CT

Professor J. O. L. Wendt
University of Arizona

Dr. L. Weitzman
U.S. EPA, CIN, OH

APPENDIX C

ATTENDEES AT THE TAPCC FCR OPEN MEETING
University of California, Irvine -- January 26, 1980

Professor J. M. Beer
MIT

Professor Tom Bowman
Stanford University

Dr. R. Gay
Rockwell International
Canoga Park, CA

Dr. S. Greenfield
Teknekron
Berkeley, CA

Dr. John Hart
KVB, Inc.
Tustin, CA

Dr. M. P. Heap
Energy & Environmental Research
Corp., Irvine, CA

Dr. Kim Hunter
KVB, Inc.
Tustin, CA

Dr. R. Kummler
Science Advisory Board
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Mr. W. S. Lanier
U.S. EPA, RTP, NC

Mr. G. B. Martin
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