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MASTER

# AN INVESTIGATION OF THE MECHANISM OF FLY-ASH FORMATION IN COAL-FIRED UTILITY BOILERS

Annual and Quarterly Report for the Periods

February 1, 1978 - January 31, 1979
November 1, 1978 - January 31, 1979


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PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY
Under Contract No. EX-76-C-01-2205

## I. OBJECTIVE AND SCOPE

Recent studies of fly-ash emitted from stationary combustion equipment suggest that substantial numbers of sub-micron particles are discharged even from units having electrostatic precipitators. This is the size fraction which is least efficiently collected and most damaging physiologically. Most previous work on ash formation has dealt with operating problems such as slagging and fouling caused by ash in the boiler itself. To attack both the operating and health problems in a more intelligent way, it is important to understand better the mechanism of ash formation and growth.

This group is studying the process from two directions. The first is a fundamental investigation of quench temperature, sticking coefficient, aggregate morphology, particle size distribution, electrical charge effects, and other phenomena that influence the formation and growth of pure and mixed metal oxide particles. This study is being conducted with the aid of a precision laboratory burner. Secondly, the growth of ash particles in a full-scale commercial utility boiler is being examined in an effort to determine fly-ash characteristics as a function of temperature and residence time in the unit. The cyclone-fired boilers at a nearby power plant have been made accessible for this work. Using results from the fundamental study, a model will be formulated to describe particle behavior in the commercial boilers. The ultimate aim of this three-year project is to develop a method for predicting the characteristics of ash particles produced in a coal-fired boiler based on furnace parameters and coal composition.

## II. SUMMARY OF PROGRESS TO DATE

Detailed discussions of technical progress during this third year's research are found in quarterly progress reports FE-2205-11, 12 and 14. This document is an overview of the year's work including a detailed analysis of the fourth quarter.

Based on the original proposal, a work statement was prepared by ERDA (before DOE was established). It identified the scope of this project according to the following tasks:

Task 1. A precision laboratory burner capable of producing pyrogenic silica and other oxides will be constructed so as to duplicate as closely as possible the conditions which occur in a commercial cyclone-fired, coal-burning utility boiler with respect to particle distribution and composition of fly ash formed. The growth rate, sticking coefficient, quench temperature, and particle size distribution for silica and other oxide particles formed by this burner will be determined as a function of feed composition and concentration, temperature and residence time.

Task 2. Using the Brownian growth model and the experimental data obtained in 1, a quantitative, theoretical model for fly ash aggregation and growth in a boiler will be formulated. Parameters and assumptions will be revised as data become available from 1 until predicted results agree with actual boiler samples. Associated laboratory data and theoretical conceptualizations, such as determinations of freezing points for sub-micron-size mixed oxide droplets, a model for particle nucleation, and a predictive program for obtaining concentrations of non-ideal condensed oxide mixtures in equilibrium with oxide vapors, will be obtained or formulated as required.

Task 3. The model devised in 2 will be tested for applicability by using it to predict fly ash parameters as a function of location, temperature, residence-time, and coal composition for existing commercial boilers.

Task 4. The feasibility of extending this program to include fly ash formation and growth in pulverized-coal burners will be examined.

Task 5. The principal investigator shall furnish consultation and advice on subjects related to his expertise, at such times and places as mutually agreed upon.

These tasks were translated into a series of objectives that are shown in Table 1 as it appeared in our first quarterly report. Experimentally, the projected program was divided into the two categories: 1) Basic Laboratory Studies and 2) Plant Studies. The laboratory segment was further subdivided into eight objectives and the plant effort into five. At this period in the contract, it seems appropriate to discuss the progress and status of each of these objectives.

## Basic Laboratory Studies

Each of the topics in this category relates to experiments with the precision laboratory burner.

A-1. Growth rates of silica particles and sticking coefficients for silica particles. Direct measurement of growth rates for silica particles in the laboratory flame was the intent here. Because of the time elapsed between submission of the original proposal and consumation of the contract, this work was actually completed before the contract period began on February 1, 1976 (Milnes, 1975). It was published, however, in 1976 (Ulrich, Milnes and Subramanian, 1976. See the list of project documents attached.) In this study, particle samples were extracted from the flame products at various residence times and characterized according to specific surface area. To fit the original theoretical model, an unrealistic sticking coefficient of .004 was required. Even at that, the fit was unsatisfactory. This objective was, however, satisfied or at least superseded by subsequent ones.

Table I. Status and Future: The Study of Fly-Ash Formation in Coal-Fired Utility Boilers at UNH. ERDA Contract No. (E49-18)-2205

| Objective Designation | Dates: Initiation | Dates: Estimated Completion | Project Description | Tangible Anticipated Results | Status (May 1976) |
|---|---|---|---|---|---|
| | | | Laboratory Studies | | |
| A-1 | Feb. 1976 | Dec. 1976 | Growth Rates of silica particles. | Durham Seminar-Jan. 1977 | |
| | " " | " " | Sticking coefficients of silica. | Technical Paper | Prepared, submitted and accepted for publication in Comb. Sci. & Tech. |
| A-2 | Feb. 1976 | Dec. 1976 | Fusion rates of silica particles. | Technical paper on theory of coalescence as a rate controlling process. | Prepared and submitted for oral presentation to Eastern Section, Combustion Institute, Laboratory Collection and analysis of data still in progress. |
| | " " | " " | Quench temperatures for silica particles. | | |
| A-3 | Feb. 1976 | Dec. 1976 | Particle size distribution. | | Priority lessened, study postponed. |
| A-4 | Jan. 1977 | Dec. 1977 | Aggregate-growth rates and formulation of an aggregation model. | Durham Seminar - January 1977 Technical paper on aggregate growth (Summer 1977). | Laboratory study in progress. |
| A-5 | Jan. 1977 | Dec. 1977 | Computer program to calculate vapor-liquid equilibrium compositions for ash-laden combustion gases. | Successful computation of vapor-liquid oxide equilibria for ideal oxide solutions. Extension to non-ideal solutions. | Not yet begun |
| A-6 | Dec. 1976 | June 1977 | Growth rates, sticking coefficients and quench temperatures of other oxides and oxide mixtures in the free-molecule regime (particles smaller than 0.05 micron). | Technical paper on growth of other oxides (Fall 1977). | No yet begun. |
| A-7 | June 1977 | June 1978 | Extension of growth measurements beyond the free-molecule aerosol regime through the transition and continuum regimes to a mean particle size of one micron or larger. | Durham Seminar-January 1977 Technical paper on growth in the continuum regime (Fall 1977). | No yet begun. |
| A-8 | June 1978 | June 1979 | Effect of ion-producing metallic additives on growth parameters. | | Not yet begun. |
| | | | Plant Studies | | |
| B-1 | June 1975 | June 1976 | Evaluation of particle parameters as a function of temperature and residence time in Merrimack boiler No. 2 | M.S. Thesis, Technical presentation | Thesis drafted, oral presentation proposed to Eastern Combustion Institute meeting. |
| B-2 | Aug. 1976 | Feb. 1977 | Evaluation of similar relationships for Merrimack boiler No. 1 and continued studies of boiler No. 2. | | Not yet begun. |
| B-3 | May 1976 | Feb. 1978 | Derivation of a model describing fly-ash formation in cyclone-fired boilers. | Technical paper on fly-ash in boilers. Durham Seminar 1978. | In progress. |
| B-4 | Jan. 1978 | June 1979 | Evaluation of particle-residence time characteristics of pulverized-coal utility boilers. | Durham Seminar 1979. | Not yet begun. |
| B-5 | Jan. 1978 | June 1979 | Development of a model describing fly-ash formation in pulverized fuel boilers. | Technical paper on fly-ash formation in pulverized fuel boilers (Fall 1979). | Not yet begun. |

A-2. Fusion rates of silica particles and quench temperatures for silica particles. Orignally visualized as two separate objectives, it became apparent that they are both significant elements of the same process. At one time, growth was perceived as a process controlled by Brownian collisions between spherical liquid droplets. We viewed aggregation as a final stage of the growth process. Examination of silica samples under the electon microscope revealed clusters or aggregates at all stages of growth (Subramanian, 1974). Thus, it was necessary to formulate a model for simultaneous fusion and collision. This was completed and documented in the paper by Ulrich and Subramanian (1977) plus an oral presentation (Ulrich, 1976). Based on an improved understanding of the growth mechanism, this program segment became an element of the aggregation model, Objective A-4.

A-3. Particle size distribution. This study was conceived during the time of the single droplet theory. With refinement of the model, the experimental feasibility and the relevance of this objective became less important. For these reasons, it was not pursued further and has been dropped from the program.

A-4. Aggregate growth rates and formulation of an aggregation model. Originally conceived as the final stage of particle growth, aggregation emerged as a controlling process at all stages of growth in situations where either the particle is viscous or the particulate loading is high. Acknowledged and explored to some extent in the work of Ulrich and Subramanian (1977), the need for dependable techniques to measure both primary particle and aggregate sizes was obvious. Use of specific surface area remained as a viable method for characterizing the former. Evaluation of aggregate mass was made possible through collaboration with John Riehl of Cabot Corporation who contributed his knowledge of laser light-scattering techniques to the effort. The result was a more comprehensive model for growth and one that correlates well with experimental data both for primary particle size and aggregate mass. Preliminary results were published in Ulrich, Riehl, French and Desrosiers (1978). They were also presented orally (Ulrich, June 1977). This segment of the program will be completed soon with the publication of final results (Riehl and Ulrich, to appear). Because this program element is closely related to other objectives; in particular, the development of a fly ash formation model, it has been featured prominently in other project presentations, i.e., Desrosiers, Riehl, Ulrich and Chiu (1979), Ulrich (FE-2205-14, Dec. 1978), Ulrich (oral, Feb. 6, 1979), and will undoubtedly appear in future ones.

A-5. Computer program to calculate vapor-liquid equilibrium compositions for ash-laden combustion gases. This element of the program was designed to permit prediction of compositions and concentrations of metal oxides vaporized from burning coal particles. With this information plus an appropriate nucleation model, condensation ash parameters can be predicted from our theoretical growth expressions. Equilibrium predictions are based on a computer code developed by Cruise and Associates of NOTS, China Lake, Calif. In our opinion, it is a superior code. Employing the complete JANAF thermochemical data file, equilibrium flame temperatures and compositions can be determined quickly and accurately from a minimum of input data, i.e. chemical compositions and enthalpies of reagents. The problem with the code, for our use, was its inability to treat condensed mixtures. Developed for rocket propellant evaluations where condensed species were usually pure, the program considers each as a separate compound having unit activity. For use in fly ash predictions, it was necessary to modify the program to treat real condensed-phase mixtures. This has been accomplished (Desrosier, FE-2205-5, 1977; Desrosiers, FE-2205-7, 1977). The program has been employed, subsequently, to support theoretical fly ash predictions (Ulrich, Riehl, French and Desrosiers, 1978; Desrosiers, Riehl, Ulrich and Chiu, 1979).

A-6. Growth rates, sticking coefficients and quench temperatures of other oxides and oxide mixtures in the free-molecule regime (particles smaller than 0.05 micron). As described above, initial laboratory studies were directed toward an understanding of the growth of pure silica. Since fly ash is an oxide mixture, this segment was designed to explore the growth of a simulated ash using the laboratory burner. Before shifting directly to a mixture, study of a pure oxide other than silica was proposed. An appropriate, well-studied and characterized compound is titania. Having an expected viscosity many orders of magnitude lower than silica, this compound would provide a rigorous test of the fusion-control theory. Initial efforts with this compound were begun in the fall of 1977, but a redesigned vaporizer became necessary. (Higher temperatures and corrosive conditions characteristic of $TiCl_4$ vaporization caused damage to seals and valves.) Redesign and construction were not justified for the study of titania alone, but were pursued in anticipation of similar problems with aluminum and iron compounds to be studied later. The vaporizer was completed by February 1978 but there were some minor problems with burner fouling. This effort has been stymied at that point for almost a year. Because of resources devoted to refining the theory, preparation of manuscripts, and writing a computer code, little time has remained for laboratory work. This elusive titania and mixed oxide study is scheduled to begin again in April.

A-7. Extension of growth measurement beyond the free-molecule aerosol regime through the transition and continuum regimes to a mean particle size of one micron or larger. Data have been obtained in the transition and continuum range as a byproduct of other program segments. Also, because of low concentrations, condensation ash grows primarily in the free-molecule regime. For these reasons this program element has been integrated into the preceding studies and will not be considered further as a separate objective.

A-8. Effect of ion-producing metallic additives on growth parameters. Electric charges, fields and their impact on particle growth are potentially important as growth enhancement or retardation devices. Not listed among the primary project tasks, the question of whether or not to pursue this objective will remain until other tasks are completed.

## Plant Studies

B-1. Evaluation of particle parameters as a function of temperature and residence time in Merrimack Boiler No. 2. This study was completed early in the project and documented in the M.S. thesis of French (1976). His work indicated that precipitation of sub-micron particles occurs in the superheater section of the boiler; Ulrich, Riehl, French and Desrosiers(1978). Subsequent doubts have arisen about sample quality and analytical techniques because of discrepancies between these findings and the theoretical model. This segment is dormant, however, as current questions are being examined under objective B-2.

B-2. Evaluation of particle parameters as a function of temperature and residence time in Merrimack Boiler No. 1 and continued studies of Boiler No. 2. Although examined sparsly in the past, this objective remains unfulfilled. Of prime importance to the total effort, it will receive the full attention of a research assistant during the next year. We are currently reevaluating probe construction, sampling techniques, and sample analysis to assure reliable results.

B-3. Derivation of a model describing fly ash formation in cyclone-fired boilers. This has been the primary object of attention for the past year. Results from segments A-1, 2,4, and 5 were combined recently to create some primitive predictions for sub-micron ash behavior in cyclone and pulverized-fuel fired boilers (Desrosiers, Riehl, Ulrich, Chiu, 1979, and Ulrich, oral, 1978). Predictions and observations (Chiu, 1978) agree quite well. Predictive tools have improved somewhat with the development of a computer code which considers all major variables. It accounts for particle-size distributions, aggregate collisions in the free-molecule, transition and continuum regimes of Brownian motion, simultaneous fusion; and allows for a programmed variation of temperature with residence time. (Ulrich, Fe-2205-14, December 1978, ULrich, oral, February 1979). Now that the predictive method exists, future work will focus on refining elements of the theory by testing it against plant data. At the same time, work is underway to improve our ability to characterize ash samples and provide a valid comparison.

B-4. Evaluation of particle-residence-time characteristics of pulverized-coal utility boilers and B-5. Development of a model describing fly ash formation in pulverized-fuel boilers. As the theoretical model matured, it became apparent that condensation-ash mechanisms are similar in pulverized-fuel and cyclone-fired boilers. Objectives B-4 and B-5 are alternatives that can be and have been included in documents cited under B-3 above. Because of their similarities, elements B-3, B-4 and B-5 have been combined into one objective for the balance of the project.

In a few words, activities of the past three years can be summarized as follows:

1976: Work was initiated. Within about six months, the research staff was assembled. In the laboratory, specific surface areas and aggregate sizes were measured for silica particles. Because of low combustion temperatures attributed, after the fact, to heat losses from the burner honeycomb, surface area changes were much smaller than had been anticipated. Poor reproducability was also a characteristic of these early results. Simple observations using a flashlight to illuminate the flame column revealed pronounced recirculation currents. These systems employed a concentric flowing curtain of cold air which was intended to eliminate recirculation. Buoyancy, however, was significant enough to cause back-mixing. Flames were completely stabilized and back-mixing eliminated when the air curtain was replaced with a guard flame.

Measurements of aggregate mass were accurate from the start. They revealed an abrupt shift in the growth curve that we did not expect. Further analysis revealed this to be the transition from free-molecule to continuum Brownian behavior. According to our knowledge of the literature, these data represent the best documentation to date of coagulation in this range of Knudsen numbers for any colloidal or aerosol system.

During this year, a shift to oxides other than silica was anticipated but not accomplished. In the plant studies, samples were extracted from various locations in the Merrimack No. 2 boiler. Specific surface area measurements implied significant precipitation of sub-micron ash in the convection section. Chemical analysis revealed little difference in composition according to size. This was probabily a result of poor size discrimination.

Work on the comprehensive ash-formation model was focused on the problem of calculating condensed-phase equilibria.

1977: To promote more significant surface area growth, a jet burner was developed which yielded temperatures near that of the adiabatic flame. Several series of probe samples were collected and evaluated. As expected, surface area changes were much more pronounced at the higher temperatures. Light-scattering studies of the jet burner confirmed the aggregate growth rates that had been measured previously. Rudimentary temperature profiles were measured using fine-wire thermocouples in silica-free flames. They confirmed the differences that were expected between honeycomb-stabilized and jet burners. Attempts to study $TiCl_4$ were thwarted by problems with the vaporizer. A new vaporizer was constructed and used successfully, but the study was postponed for other reasons. A laser-doppler velocity technique was developed and used to measure flow velocities of combustion products. Intended as an indirect method for temperature measurement, it remains to be exploited further.

The method for calculating ash-vapor equilibrium was completed and employed to indicate the relative significance of ash vaporization in a cyclone-fired boiler.

Samples of ash from the hopper of Merrimack Unit No. 2 were separated by inspection and filtration for characterization of the submicron fraction.

1978: Laboratory flame measurements, equilibrium predictions, and a char-ash vaporization mechanism were employed to generate primitive predictions for the size, quantity and composition of condensation ash in cyclone and pulverized-fuel fired boilers. These were compared with characteristics of the submicron fraction separated from plant samples. Agreement was good in terms of particle size, morphology, and concentration. The predicted depletion of aluminum and enrichment of silicon were also observed, but the measured depletion of iron was contrary to predictions. Hopper ash from the Monroe Station, a PF unit burning coal similar to the Merrimack Station, was examined briefly. The submicron fraction was negligible compared to that in the Merrimack unit. The difference was attributed to lower combustion temperatures employed in PF firing. Predictions for the two boilers confirm these findings.

The growth model was further refined with completion of a computer code which predicts primary-particle and aggregate growth. It encompasses a broad range of conditions in both Brownian regimes and the transition ranges.

During the contract period, three annual seminars have been held in Durham to explain the progress of the program and discuss related phenomena and practical problems. Other meetings were attended and papers prepared as noted in the list of project documents and oral presentations attached.

## III. FUTURE ACTIVITIES

Based on progress and modifications described above, the original program illustrated in table I has been reduced to the current objectives shown in table II. Specifically, we plan to document laboratory data with a comprehensive paper on particle and aggregate growth. Laboratory efforts will include the study of titania, alumina and alumina-silica mixtures. Inclusion of iron, to complete the list of matrix elements in condensation ash, will be attempted if time permits. The study of electrical phenomena may or may not be possible within the year. Plant efforts will be focused on the collection of and characterization of a series of sample sets taken at various positions in the Merrimack No. 1 and No. 2 boilers. Data from all these interrelated activities will be employed to test and refine the growth model. One element of the model which deserves more attention is the influence exerted by porosity on the ash vaporization rate.

## IV. PERSONNEL

Gail D. Ulrich, associate professor, is the principal investigator. Dr. John Riehl of Cabot Corporation continues as an advisor and consultant, but because of other duties, he is no longer intimately involved

Table II. Status and Future: The Study of Fly-Ash Formation in Coal-Fired Utility Boilers at UNH. ERDA Contract No. Ex-76-C-01-2205

| Objective Designation | Dates | | Project Description | Tangible Anticipated Results | Status February 1979 |
|---|---|---|---|---|---|
| | Initiation | Estimated Completion | | | |
| | | | **Laboratory Studies** | | |
| A-4 | Feb. 1976 | July 1979 | Aggregate-growth rates and formulation of an aggregation model. | Technical paper with detailed analysis of aggregate behavior (July) 1979). | Preparation of paper in progress. |
| A-6,7 | Sept. 1977 | Dec. 1979 | Growth rates, sticking coefficients and quench temperatures of other oxides and oxide mixtures in the free-molecule transition and continuum regimes. | Technical paper on growth of other oxides. | Laboratory study interrupted. To resume in April 1979. |
| A-8 | Dec. 1979 | Feb. 1980 | Effect of ion-producing metallic additives on growth parameters. | | Not yet begun. |
| | | | **Plant Studies** | | |
| B-2 | Aug. 1976 | Feb. 1980 | Evaluation of particle parameters as a function of temperature and residence time in Merrimack boiler No. 1 and continued studies of boiler No. 2. | | In progress. |
| B-3,4,5 | May 1976 | Feb. 1980 | Derivation of a model describing fly-ash formation in cyclone- and pulverized-fuel fired boilers. | Presented at the 17th Int. Symp. on Combustion, Leeds, England, Aug. 1978. Oral presentation, Caltech, Pasadena, Calif., Feb. 1979. | Primitive model derived and presented. Refinement to continue. |

in the laboratory work. Dr. Raymond Desrosiers, a post-doctoral research associate, departed after two years on the project to join the DOE Solar Energy Research Institute in Golden, Colorado. He was replaced by Mr. Frank Palella who is responsible for collection and characterization of plant samples. Shu-Mu Hsieh continues as a graduate research assistant. He was joined this year by Shadia Aly and Jer-Yann Hsieh.

## V. INDUSTRIAL SPONSORSHIP

Because of adequate funds and scarcity of time, there were no efforts to expand the level of industrial support. Since 1972, $22,000 has been contributed to our work by four industrial sponsors: Cabot Corporation, Public Service Company of New Hampshire, New England Electric System and Babcock and Wilcox. Our congenial relationship with people in these firms remains even though all contractual arrangements will end soon.

## VI. BUDGET STATUS

The condition of the budget is illustrated in table III. Because of a six month lag between project initiation and initial staffing we are considerably below the $223,740 estimated for the three year contract which was scheduled to end January 31 of this year. A no-cost extension of the contract was requested and granted for one more year. Because of a somewhat reduced student staff at various times plus other savings, the budget appears adequate for the next year. If finances permit, reallocation of funds will be requested next fall for academic-year release time for the principal investigator. An additional request for no-cost extension of the contract will be explored as the financial situation crystallizes in the fall.

## VII. PUBLICATIONS

Publications and oral presentations are included in the list of project documents and presentations attached.

## VII. PROGRESS DURING PAST QUARTER

There was no activity with the laboratory burner this quarter. A manuscript for oral presentation (Caltech Conference, February 6, 1979) was prepared. The particle-growth computer code was corrected and improved. In plant-related activities, attempts to isolate and analyze condensation ash continued. Separation has been accomplished by filtering liquid dispersions of ash (ultrasonically prepared) through graded nucleopore filters. The major problem has been chemical analysis of minute sample quantities. A new, highly sensitive AA procedure (Flameless or Graphite Furnace AA, Eggiemann and Betzer, Analytical Chem., 48, p. 886, May 1976) was attempted but with poor success. If local efforts are not successful soon, we will seek help from outside the University.

Table III

University of New Hampshire

ERDA Contract EX-76-C-01-2205

Financial Statement

| | Budget (2/1/76-2/1/80) | Expended (2/1/76-1/31/79) | Balance |
|---|---|---|---|
| Salaries | $108,695.00 | $ 76,109.12 | $ 32,585.88 |
| Travel | 1,600.00 | 1,162.86 | 437.14 |
| Supplies | 16,900.00 | 19,763.46 | (2,863.46) |
| Equipment | 12,508.00 | 2,353.77 | 10,154.23 |
| Computer | 600.00 | 2,348.00 | (1,748.00) |
| Fringe Benefits | 7,350.00 | 5,709.25 | 1,640.75 |
| Indirect Costs | 76,087.00 | 53,105.17 | 22,981.83 |
| Totals | $223,740.00 | $160,551.63 | $ 63,188.37 |

| | |
|---|---|
| Amount Billed | $160,551.63 |
| Amount Received | 138,802.50 |
| Balance Due | $ 21,749.13 |

"I certify that all expenditures reported (or payment requested) are for appropriate purposes and in accordance with the agreements set forth in the application and awards document."

Feb. 21, 1979
Date

Marilyn A. Sanders
Marilyn A. Sanders
Ass't. Grant and Contract Officer

## PROJECT DOCUMENTS


Desrosiers, R.E. (March 20, 1977). "Computer Techniques for Determining Flame Temperature and Composition," DOE Report FE-2295-5.

Desrosier, R.E. (May 18, 1977). "Chemical Equilibrium in Ash-Laden Coal Combustion Systems," DOE Report FE-2205-7.

Desrosiers, R.E., Riehl, J.W., ULrich, G.D. and Chiu, A.S. (1979). "Submicron Fly-Ash Formation in Coal-Fired Boilers," Seventeenth Symposium on Combustion, Univ. of Leeds, The Combustion Institute.

Chiu, A.S. (1978). "Characterization of Submicron Fly-Ash from Cyclone-Fired Boilers," M.S. Thesis, Department of Chemical Engineering, University of New Hampshire.

French, B.R. (June, 1976). "Fly-ASh Formation in a Coal-Fired Boiler," M.S. Thesis, Department of Chemical Engineering, University of New Hampshire.

Milnes, B.A. (1975). "An Experimental Study of Particle Growth in Oxide-Forming Flames," M.S. Thesis, Department of Chemical Engineering, University of New Hampshire.

Riehl, J.W. and Ulrich, G.D. (in preparation). "Aggregation and Growth of Submicron Oxide Particles in Flames."

Subramanian, N.S. (1974). "Growth of Oxide Particles in Flames: A Theoretical and Experimental Study of Silica-Forming Flames," Ph.D. Thesis, Department of Chemcial Engineering, University of New Hampshire.

Ulrich, G.D., Milnes, B.A. and Subramanian, N.S. (1976). "Particle Growth in Flames - II. Experimental Results for Silica Particles," <u>Combustion Science and Technology</u>, <u>14</u>, pp. 243-249.

Ulrich, G.D. and Subramanian, N.S. (1977). "Particle Growth in Flames - III. Coalescence as a Rate-Controlling Process," <u>Combustion Science and Technology</u>, 17, pp. 119-126.

ULrich, G.D., Riehl, J.W., French, B.R. and Desrosiers, R.E. (1978). "Mechanism of Sub-Micron Fly-Ash Formation in a Cyclone, Coal-Fired Boiler," in <u>Ash Deposits and Corrosion Due to Impurities in Combustion Gases</u>, ed. by R.W. Bryers, Hemisphere Pub. Corp.

Ulrich, G.D., (Dec. 5, 1978). "Computer Code to Predict Submicron Particle Behavior," DOE Report FE-2205-14.

## ORAL PRESENTATIONS

Ulrich, G.D. (November, 1976). "Particle Growth in Flames-III. Coalescence as a Rate-Controlling Process," Eastern Section Combustion Institute, Philadelphia.

Ulrich, G.D. (June, 1977). "Mechanism of Submicron Fly-Ash Formulation in a Cyclone, Coal-Fired Boiler," ASME International Symposium on Corrosion and Deposits from Combustion Gases, Henniker, N.H.

Ulrich, G.D. (August, 1978). "Submicron Fly-Ash Formulation in Coal-Fired Boilers," Seventeenth Symposium on Combustion, University of Leeds.

Ulrich, G.D. (February 6, 1979). "Particle Coalescence," Caltech. Conference on Coal Combustion and Emission Control, Pasadena, Calif.