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BASIC COMBUSTION AND POLLUTANT FORMATION PROCESSES
FOR PULVERIZED FUELS

QUARTERLY TECHNICAL PROGRESS REPORT

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PATENT STATUS

This technical report is being transmitted in advance of DOE patent clearance and no further dissemination or publication shall be made of the report without prior approval of the DOE Patent Counsel.

TECHNICAL STATUS

This technical report is being transmitted in advance of DOE review and no further dissemination or publication shall be made of the report without prior approval of the DOE Project/Program Manager.

FORWORD

This report summarizes technical progress accomplished during the first quarter of a thirty month synthetic fuels study being conducted for DOE under grant DE-FG22-80PC-30306. This work period was 1 October 1980 to 31 December 1980. Work was accomplished under the direction of Dr. L. Douglas Smoot, project director, Dr. Geoffrey J. Germane, principal investigator, and Dr. Philip J. Smith, senior investigator. James D. Hickerson is the technical officer for DOE.

Graduate students who contributed to the technical progress accomplished at Brigham Young University were Stephen K. Kramer and David G. Sloan. Michael King, Elaine Alger, Tami Montgomery, and Karen Barrett have provided technican and typing services. Financial support for this research from Brigham Young University is acknowledged.

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SUMMARY

This contract study of basic combustion and pollutant formation processes for pulverized solid fossil fuels was initiated on October 1, 1980. The solid fossil fuels under consideration for this research include such solid fuels as non-bituminous coal types, solvent refined coal, combustion char, petroleum coke, oil shale and tar sands.

The current high demand for energy in the United States and the recent supply problems associated with oil imports have clearly shown the need to develop alternate energy sources. The potential industrial application of pulverized fuels other than coal provides some promise for relief from present and future conventional fuel shortages. Utilization problems with these fuels such as flame stability, fuel handling, pollutant emission and ash and slag formation in large-scale furnaces may be fundamentally addressed in laboratory reactors using properly scaled operating variables.

An extensive literature search was begun to assess current knowledge relative to utilization of these fuels. This review will provide a basis for selection of three solid fuels for testing. Pertinent information from industrial contacts will also be used in the fuel selection. The criteria to be used in the selection of these fuels include availability for economic industrial use, adaptability, grindability, flame stability, entrainability, uniformity, applicability to direct firing with air, solidity with heating, availability to the BYU Combustion Laboratory, cost, other physical characteristics affecting their use, industrial input and recommendations, and DOE approval.

The existing laboratory coal combustor at BYU will be modified to provide flexibility for a potentially wide range of operating characteristics with the selected solid fuels. The fuel flow rate will be reduced and reactor volume increased to improve particle residence time and burnout. A reactor wall temperature control will be installed to conduct steady-state tests and to help simulate large-scale furnace conditions. A computer system has been identified for interface both to the reactor for data acquisition and control of operating variables and to the main research computer for final data reduction and display.

INTRODUCTION

Background

The uncertain availability and potential scarcity of oil and natural gas for industrial energy requirements is causing a search for alternate forms of fossil fuels to meet energy needs. There is great potential for increased use of pulverized coal as well as other solid fossil fuels. However, the existing technology relates primarily to coal use in large, electric utility boilers. The potential application of alternate solid fossil fuels will likely require a wide range of combustor designs and burning techniques. The development of this hardware and techniques will require a more complete and improved understanding of fundamental combustion and pollutant formation reaction processes.

The use of laboratory combustors for pulverized solid fuels has been found to be a satisfactory way to obtain meaningful, detailed, fundamental combustion process information. However, the use of such combustors is not without problems. The variability of fuel feed stocks and types, the formation of nitrogen and sulfur pollutants, the emissions of trace elements, the effects of ash and slag formation on boiler operation and pollutant formation, and the requirements for procedures to optimize the design of furnaces and boilers, in order to maximize performance and minimize pollutant formation, have all been identified as technical problems associated with utilization of new solid fuels.

More recently developed solid fuels such as solvent-refined coal (SRC) and char, and other solid fossil fuels including oil shale, tar sands, anthracite and peat, may be used directly in combustors but

present handling problems as well as the aforementioned technical problems. Factors which affect the practical utility of such solid fossil fuels include their physical characteristics such as grindability and entrainability for direct firing applications and combustion properties such as flame stability and formation of particular pollutants. Cost, availability and other practical issues also affect the consideration of these alternate solid fuels.

A companion approach to laboratory studies of the combustion properties of these fuels is the development of computer design models to help design reactors for maximum thermal efficiency while minimizing pollutant formation and reducing development cost. To be effective, these models must contain sufficient technical detail to accurately describe the mixing and chemical reaction processes governing pyrolysis, heterogeneous reactions and pollutant formation. The model must be carefully compared with experimental data to verify and validate the computerized description of the processes. The proven model may then be used as a powerful tool in large scale reactor design as a link between experimental results of fuels in laboratory combustors and expected performance in industrial scale furnaces with possibly different geometries and configurations than in the laboratory.

Objectives

In response to the stated objectives by DOE "to provide the technology base required to expedite the conversion of industrial processes from oil and gas to coal and other pulverized solid fuels," the following general objectives for this study have been outlined:

1. Provide basic experimental information on the effects of key test variables on combustion efficiency and nitrogen and sulfur pollutant levels for selected pulverized fossil fuels.

2. Determine the major basic physical and chemical processes that have the most impact on control of combustion efficiency and pollutant levels. These processes studied will include turbulent mixing of various inlet gaseous streams, the dispersion of pulverized fuel particles, heatup of the solid fuel particles, reaction of the fuel particles and production of sulfur and nitrogen pollutant species.

3. Provide detailed, space-resolved measurements of gas and particle composition and temperature during flow and combustion of pulverized fossil fuels for evaluation of predictive and scale-up codes.

4. Provide a comprehensive mathematical model for the detailed, space-resolved description of pulverized fuel combustors and to evaluate the model by comparison with space-resolved combustor measurements.

5. Facilitate the transfer of this basic combustion information to prospective industrial and governmental users through technical report publication, the use of a Technical Advisory Council, the publication and presentation of papers based on significant research results, and through periodic visits.

To accomplish these objectives, a series of tasks have been outlined as identified in the next section. The first tasks receiving emphasis in this program are to conduct a comprehensive search of the literature for information relative to the utilization of any solid fuels other than coal, and then to finalize the selection of three promising fuels for detailed study in the combustor.

PROJECT ORGANIZATION

Research Team

The resesarch team for this study is composed of three faculty researchers, graduate students and research assistants. During the first quarter, two Ph.D. candidates and one M.S. candidate were recruited to work on this study. One of the doctoral students will focus on modeling, while the other two students will work on experimental aspectrs. Figure 1 shows the research team organization. The complete research team meets each two weeks to discuss progress on program objectives and outline direction. The principal investigator meets with the graduate student research assistants on the alternate weeks to provide specific direction. Additionally, there are four monthly meetings which are included in a summary of all meetings in Table 1.

TABLE 1
SUMMARY OF MONTHLY RESEARCH MEETINGS

<u>Week</u>	<u>Wednesday Meeting</u>	<u>Thursday Meeting</u>
1	P.F. ¹ Research Team	All Combustion Lab Researchers
2	Principal Investigator/Students	All Faculty Researchers
3	P.F. Research Team	Combustion Lab Seminar
4	Principal Investigator/Students	All Combustion Lab Researchers

¹P.F. = Pulverized Fuels Research Team for this DOE Contract.

Figure 1. Project research team organization.

Time Schedule

The first quarter time schedule, covering October 1, 1980 to January 1, 1981, is shown in detail in Figure 2. Figure 3 shows the overall project management schedule, and identify tasks to be accomplished during the entire study.

Selecting and Obtaining Fuels

The fuels in this study will be selected from a range of primary (natural) and secondary (synthetic) fuel possibilities. The selection as to which specific fuels to use involves the determination of fuel categories, the establishment of fuel selection criteria, and the ranking of fuels by information obtained in a literature review. Once the fuels have been selected and approved by DOE, sufficient quantities for testing will be obtained.

Reactor Modification

The BYU reactor facility was designed for detailed tests of coal combustion. The potentially unusual handling and burning characteristics of the alternate fuels under consideration in this program necessitated a review of the facility capabilities. The facility, while adequate in its present configuration, will be modified for better control and measurement of fuel feed and for increased particle residence time and burnout. A computer will be interfaced with the combustor for data acquisition and control of operating variables including primary air flow, fuel flow and reactor wall temperature.

Combustion Tests

The Combustion Laboratory has extensive experience in conducting coal combustion and pollutant formation experiments and in mixing

Figure 2. First quarter tasks and time schedule, October 1, 1980 to December 31, 1980.

Figure 3. Overall project tasks time schedule.

processes. Following selection of the three test fuels, a test plan will be developed considering any special physical factors which may be associated with each fuel. The reactor will be flexible enough to allow variation in wall temperature, primary air flow, fuel input, secondary air swirl and other operation conditions to determine optimum efficiency settings for each fuel.

Pollution Tests

The tests of pollutant formation will be conducted concurrently with the combustion tests according to the time schedule shown in Figure 3. The testing of pollutants involves a comparative literature search, combustor outlet and space-resolved sample train measurements, the analysis and updating of sample train methods, and the analysis and compilation of results. The data processing will be facilitated by a computer interface with the combustor and the existing analyzing equipment computer.

DETAILS OF TECHNICAL PROGRESS

Fuels Selection

Approach. Selection of solid fossil fuels to be tested is presently the key task being considered. The selected fuels will influence reactor modification, sampling methods, and the other operating variables such as particle size, burner configuration, stoichiometry, air preheat, solids loading and secondary swirl. Possible fuels have been categorized, criteria have been reviewed and established by which to rank the candidate fuels and a literature review was initiated to examine each fuel in detail.

Categorization. The candidate solid fuels considered for this study have been separated into three categories:

- 1) Primary fuels which can be combusted directly in the natural state. These directly-used reserves are often called "natural fuels."
- 2) Secondary fuels which undergo some processing step prior to direct combustion. These processed substances can either be the desired product, such as solvent refined coal (SRC), or an residual product, such as gasifier char or petroleum coke.
- 3) Composite fuels which are mixtures of primary or secondary fuels to achieve better combustion.

The classification of solid fuels into these categories is shown in Table 2. The fuels to be used in the study will come from the first two classes, preferably at least one fuel from the primary and secondary fuel categories. Composite fuels will be considered only if one of the principal fuels selected cannot burn by itself, but requires assistance in the form of coal or methane.

Selection Criteria. The choice of fuels to study is based upon criteria which were established from past experience of the group, the capacities of the research program, and basic engineering fundamentals. Table 3 summarizes these selection criteria. A description of the criteria follows:

1. The fuel is to be solid according to terms of the contract.
2. The fuel must have economic potential. Exploitable quantities of the fuel should exist that are not already being used.

TABLE 2
POSSIBLE SOLID FUELS

<u>Primary Fuels</u>	<u>Secondary Fuels</u>	<u>Composite Fuels</u>
Wood	Solvent-refined coal (SRC I)	Oilshale and coal
Agricultural wastes	Carbon black	Char and oil
Peat	Coal liquefaction residues	Others
Lignite	SRC-II	
Brown coal	Exxon	
	H-Coal	
Coal*	Coal gasification chars.	
Subbituminous	Winkler	
Bituminous	Koppers-Totzek	
Anthracite	Hy-Gas	
	Lurgi	
Tar Sands	Others	
Oil Shale	Tar sand residues	
Others	Oil shale pyrolitic residues	
	Petroleum coke	

*Because the BYU Combustion Laboratory lab is already studying these coal types, they will not be considered for this project.

TABLE 3
FUEL SELECTION CRITERIA

<u>Criterion</u>	<u>Considerations</u>
1. Solid	
2. Economic Potential	Reserves Present applications Future use
3. Adaptable	Grindability Flame stability Entrainability Uniformity
4. Current Technology	
5. Available to Program	Cost Nature
6. Unusual Characteristics	
7. Industrial Recommendations	
8. DOE Approval	

Direct combustion of the fuel needs to demonstrate a reasonable economic potential.

3. The fuel should be adaptable. Our test program is limited to direct, oxygen-fired, pulverized fuel combustion. Therefore, the fuel must be finely pulverized, sustain a stable flame, be easily entrained, and have a uniform nature.

4. There should be some need in the state of technology for combustion of this fuel. If the direct combustion of the fuel has been well studied, it is not necessary to repeat it.

5. The fuel must be available. Working with a limited budget, the fuel cannot be costly to obtain or transport. The aid of DOE might be required to obtain some fuels. The laboratory fuel must be in a solid form that it may be handled readily.

6. Unusual fuel characteristics must be considered. Any peculiarities of the fuel should be considered to ascertain potential problems.

7. Industrial recommendations must be considered. Any interest indicated by industry in a specific fuel should be taken into account.

8. Final approval will be obtained. The project manager must approve of the selections.

Literature Search

A literature review has been initiated to examine the categorized fuels in light of the above criteria. The first step in this review was a computer-assisted search using the Energy-line and Tulsa data bases which provided 635 possible references. These references were scanned and classed as to their usefulness and availability. Promising individual references are presently being obtained and carefully

examined. Also, the personal files of the research team that have been developed during their years in the field have been reviewed and appropriate references extracted. Finally, the BYU Library has been used as a source of texts that pertain to this field.

The literature search will be completed during the next quarter to determine the assets and liabilities of each fuel until sufficient information is collected relative to criteria to make the final decision. Following are preliminary results of the literature search.

Primary Fuels. Wood has a good potential, but must be formed into pellets to be economically shipped; these pellets are too large for an entrained flow combustor (1).

Peat is an abundant resource, suitable for gasification or combustion, but is 90% water, very fibrous and mostly found in the northern-most states (2).

Tar sands are found in great quantities in Canada and in substantial amounts in Utah and contain bitumen that can be extracted by solvent-washing and thermal processes. Direct combustion seems to not have been considered for this fuel, though in-situ combustion may be used to recover bitumen (3).

Oil shale has been used marginally successfully for years as a liquid fuel stock, though it may be more viable now with improved technology and declining oil reserves. Direct combustion of oil shale may be a practical alternative and is currently being practiced in the USSR, Germany and France (4).

Secondary Fuels. Solvent-refined coal (SRC-I) has been developed as a potential non-polluting fuel but has not been extensively adopted (5).

Coal liquefaction residues and gasification chars, though certain to be available in great quantities when coal liquefaction and gasification becomes important fuel feed stocks, seems to have been neglected in the studies of these processes.

Petroleum coke, a by-product of petroleum refining processes, remains when gases and liquids are driven from the coke in a coking furnace. The coke has high carbon content with low concentrations of hydrogen. A 150,000 barrel per day U.S. refinery produces 2,000 tons of petroleum coke per day (6), approximately 4% of the incoming crude oil, which represents a significant source of solid fuel.

A preliminary list of fuels from which final selection will be made includes petroleum coke, gasification chars, pyrolysis char, SRC oil shale, and tar sand.

Reactor Facility

Modifications. Consideration was given to the possibility of constructing a new combustor for completing the proposed tests in this study. After a review of several existing facilities and combustor design criteria, it was decided to modify the existing reactor to accommodate a wide range of solid fuels. Facilities at Aerotherm/Acurex (7), MIT (8), University of Texas at Austin, University of Utah, Conoco and Exxon were studied to identify any features which could be implemented to scale as closely as possible wall effects, fuel flow rate, residence time, geometry and other design criteria on the combustion and pollutant formation processes. A study of industrial test conditions and design criteria (9) for meaningful results in a laboratory combustor, shown in Table 4, indicated that the existing BYU reactor significantly complies and would be adequate for use with

TABLE 4
LABORATORY REACTOR DESIGN CRITERIA FOR
LARGE SCALE MATCH OF RESULTS

<u>Criterion</u>	<u>Conditions to Match</u>
Stoichiometric ratio	15-25% excess air
Superheater temperature	2200°F gas temperature at first set of boiler tubes
Primary stream velocity	50-100 ft/sec
*Particle residence time	3-5 sec
Stack emissions concentration	SO ₂ : 1.2 lb/MBTU; NO _x : 0.7 lb/MBTU
Solid loading	8-12% primary air mass
Primary air preheat temperature	180°F
Secondary air preheat temperature	600°F
Particle size	70% through 700 mesh
Overall geometry	Inverted "J" shape
*Burnout	99.99%
Boiler tube material	Stainless or black pipe

*Modifications to existing reactor necessary to obtain necessary flexibility with wide range of pulverized solid fuels.

alternate solid fuels. Modifications to the reactor to increase particle residence time and burnout will be sufficient to adapt the facility to testing the solid fuels under consideration. Figure 4 shows a schematic drawing of the BYU combustor.

The planned modifications include reducing the primary jet diameter and fuel flow rate and increasing the reactor length with additional cylindrical sections to improve particle burnout. A mass flow device sensitive to changes in Coriolis acceleration of a particle-laden flows will be utilized with the existing pressurized feed system to accurately measure the input rate of the fuels being tested. A water jacket will be attached to the exterior of the reactor to obtain more precise control of the combustor wall temperatures during steady-state tests to better simulate operating conditions in a large furnace.

Computer Interface. A digital, microprocessor-based computer will be dedicated to the combustion facility for data acquisition and operating variable control. The computer, with disk storage and printer, will also be used for preliminary data processing and display. The computer will be interfaced with the main BYU research computer for final data analysis and plot displays.

The computer will initially be used to collect temperature and pressure data during combustor tests of the fuels at various internal radial and axial locations. The solid and gaseous pollutant concentrations will continue to be measured in a separate sampling system. Plans for further development include interfacing the pollutant sampling and measuring system, with the combustion facility, for complete data acquisition with a single computer.

Figure 4. BYU laboratory combustor.

An on-line, single-tuning parameter PID adaptive controller for a digital computer, previously developed at BYU, will be implemented to control combustor wall temperature, primary air flow and fuel feed according to prescribed levels for steady-state operation. Such controls interfacing will allow rapid multi-variable combustor operation for optimization of particle burnout and pollutant formation.

PLANS FOR NEXT STUDY PERIOD

Fuels Selection

By the end of the next study period, at least two of the final three fuels will be selected and ordered. Candidates for the third will be identified, also, potential problems and prospective approaches will be considered for each of the fuels.

Literature Search. Completion of the literature search will be a major thrust of the next quarter. The following tasks will be accomplished to do this:

1. All the references obtained by the computer search that are relevant, will have been examined.

2. Industries and other programs using these fuels will be contacted for their experiences.

3. If necessary, another computer search will be undertaken.

Furthermore, the literature search will be expanded to support the developing phases of the program: combustion tests, pollutant formation tests, analysis, etc.

Industrial Input. The Laboratory's Industrial Advisory Committee will be asked to participate in fuel selection. Representatives from Babcock and Wilcox, Combustion Engineering, Foster Wheeler, Riley

Stoker, research departments at several public utilities, governmental departments and other industrial firms serve on the Technical Advisory Council for the BYU Combustion Laboratory. Table 5 outlines the advisory council as presently constituted for pulverized fuel combustion. Input has already been given by Utah Power and Light Co. (10) and Tosco (6) relative to specific sources and commercial value of combustion char, petroleum coke and other solid fuels. The final fuel selection will be made with strongly encouraged input from representatives from industry.

Experimental Approach. Testing new solid fuels will involve developing new procedures for their handling, combustion, and analysis of products. As the final selection of desired fuels are made, the plans for necessary combustor modifications will be made. Designs will be drawn up to adapt present equipment, and methods will be planned. This will be done with the advice and experience of Combustion Laboratory members.

Obtain Fuels. After clearance from the DOE project director is obtained, fuels will be ordered and processed sequentially as they are determined. Shortly, one fuel will be ordered, after DOE approval, with a second fuel two months later and a third within three months after that. Contacts will be made with DOE and industry if needed to obtain the fuel.

Combustion Facility

Several modifications to improve correlation of results between lab-scale and industrial-scale solid fuels combustion processes have been outlined in the DETAILS OF TECHNICAL PROGRESS section of this report. The reactor volume will be increased by adding additional

TABLE 5

TECHNICAL ADVISORY COMMITTEE FOR BYU COMBUSTION LABORATORY

Pulverized Fuel Combustion

<u>Member</u>	<u>Company/Position</u>
Stephen Johnson	Babcock & Wilcox/Senior Research Engineer Alliance, Ohio
Thomas Hamilton	C-E Power Systems, Combustion Engineering Inc. Windsor, CN
Ben Breen	Research Cottrell/Director of Energy and Technology Projects Irvine, CA
Dominic Cagliostro	Los Alamos Scientific Laboratory Los Alamos, NJ
Bert Rawdon	Riley Stoker Corp./Director of Research Worcester, MA
William Crandall	PSSE&G Research Corp./Research Program Director Newark, NJ
Robert Kendall	Acruex Corp./Vice President Mountain View, CA
Val Finlayson	Utah Power & Light Co./Director of Research and Development Salt Lake City, UT
John Dimmer	Electric Power Research Institute Palo Alto, CA
Surjit Singh	U.S. Department of Energy, Morgantown Energy Technology Center Morgantown, WV
Dwight Boesiger	Phillips Petroleum Co. Bartlesville, OK
Richard Bryers	Foster Wheeler Development Corp./Technical Director Livingston, NJ

cylindrical sections. This flexibility was originally intended with the design of a modular reactor, with an instrumentation section which could be placed in any axial location along the length of the combustor. The combustor which will be used in the tests of the solid fuels for this study was shown in Figure 4. Residence time will also be increased by reducing the air and fuel feed to the combustor. These two modifications will improve the degree of particle burnout for the wide range of fuel characteristics which could be encountered.

Computer Interface. The computer will be obtained and analog to digital and digital to analog capability will be installed for data acquisition and control. The necessary signal conditioning circuitry for transducer interface to the computer will be designed and construction begun. Software will also be outlined and coded to accomplish the data acquisition and reduction. Hardware for control of combustor operating variables will be identified and interface requirements determined for utilization of the computer for closed loop set point control.

Combustion Model Development

Development of combustion submodels for the synfuels cannot begin until the fuel types have been identified. During this quarter, a Ph.D. student in Chemical Engineering was recruited to work on the modeling tasks of this study. Modeling and code development has continued at this laboratory during this report period under separate EPRI and DOE contracts. This modeling work has focused on resolving numerical difficulties and identification of pollutant formation mechanisms in turbulent combustion. Modeling and code development for this contract will begin February 1, 1981.

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