**DETAILED MODEL FOR PRACTICAL PULVERIZED COAL FURNACES
AND GASIFIERS**

Volume III

Data Book for Evaluation of Three-Dimensional Combustion Models

Final Report

**By
Steven D. Philips
L. Douglas Smoot**

August 1989

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**For
U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania**

**By
Brigham Young University
Provo, Utah**

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Volume III
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Contract No.: DE-FG22-85PC80752

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Notice

This report was prepared as an account of work sponsored in part by Babcock and Wilcox, Combustion Engineering, Inc., Consolidation Coal Co., Electric Power Research Institute, Empire State Electric Energy Co., Foster Wheeler Development Co., Tennessee Valley Authority, United States Department of Energy (Pittsburgh Energy Technology Center), and Utah Power and Light Co. Neither Babcock and Wilcox, Combustion Engineering, Inc., Consolidation Coal Co., Electric Power Research Institute, Empire State Electric Energy Research Co., Foster Wheeler Development Co., Tennessee Valley Authority, United States Department of Energy, nor Utah Power and Light Co., nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

Foreword

This report summarized technical accomplishments made during the entire four year reporting period for a study conducted for a consortium of governmental and industrial organizations. This period extended from 1 May 1985 to 31 August 1989. Work was accomplished under the direction of Dr. L. Douglas Smoot, project director, and Dr. Philip J. Smith, principal investigator. Dr. Scott Brewster, Dr. A. S. Jamaluddin, and Dr. Subrata Sen have been senior investigators on this contract. Subcontract work at Los Alamos National Laboratory was performed under the direction of Dr. Scott C. Hill.

Graduate students who have contributed to the accomplishments reported in the final contract report include Larry Baxter, Joseph Smith, Paul Gillis, Knute Christensen, Robert Colson, Steven Phillips, Paul Davies, and Mary Rasband. Michael R. King, Cindy A. Stevens, Ruth Dodson and May Tiu have provided administrative assistance, typing, and drafting services.

This study was a foundation for the development of a new Advanced Combustion Engineering Research Center (ACERC) which is funded by the National Science Foundation, the State of Utah, the U.S. Department of Energy, and twenty-five industrial organizations. ACERC was started on May 1, 1986, just one year after the initiation of work on this consortium study. All sponsors of this work automatically became associate members of ACERC for the three year remaining period of the consortium study to August 31, 1989. Further, new associate members in ACERC have immediate access to this set of consortium final reports and to the 3-D code. These members include Advanced Fuel Research Co., Dow Chemical U.S.A., Gas Research Institute, Morgantown Energy Technology Center, and Convex Computer Corp. This report is not available for external distribution by BYU except to ACERC members until released to the public domain.

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Nomenclature

Symbol	SI Units	Definition
F	kg/s-m^2	mass flux
m	kg/s	mass flow rate
MW_e	MW	megawatt electric
MW_t	MW	megawatt thermal
SCMS	m^3/s	abbreviation for cubic meters per second at standard conditions
V_x, V_y, V_z	m/s	velocity components in space
T	K	temperature in degrees Kelvin
x, y, z	—	subscripts representing the three coordinate directions in space
$X+, Y+, Z+$	—	labels used on some coordinate axes to indicate the direction of increasing values

Executive Summary

The need to improve efficiency and reduce pollutant emissions in commercial furnaces has prompted energy companies to search for optimized operating conditions and improved designs in their fossil-fuel burning facilities. Historically, companies have relied on the use of empirical correlations and pilot-plant data to make decisions about operating conditions and design changes. The high cost of collecting data makes obtaining large amounts of data infeasible.

Because of the advent of high-speed digital computers and lowered hardware and software costs, computer models of combustion have become feasible alternatives to collecting experimental data. Many two-dimensional combustion models have been developed around the world (Smoot and Smith, 1987). A compilation of 2-D data proved useful for evaluating PCGC-2, a combustion model developed at Brigham Young University (Smoot and Christensen, 1985). However, the complex, three-dimensional nature of commercial furnaces has led to the need for three-dimensional models. Comprehensive model evaluation has been limited for such systems. As more three-dimensional combustion models are developed, the need for comprehensive model evaluation will increase.

There is no known compilation of three-dimensional combustion data available, and a review of the available data has not been done. A compilation of relevant data can provide a data base for evaluating combustion models. A review of the state of three-dimensional combustion data can also provide an insight into data needs and a guide for future experimental work.

The main objective of the data book is to provide a single source of detailed three-dimensional combustion and combustion-related data suitable for comprehensive combustion model evaluation. Five tasks were identified as requirements to achieve the main objective. First, identify the types of data needed to evaluate comprehensive combustion models, and establish criteria for selecting the data. Second, identify and document available three-dimensional combustion data related to pulverized coal combustion. Third, collect and evaluate three-dimensional data cases, and select suitable cases based on selection criteria. Fourth, organize the data sets into an easy-to-use format. Fifth, evaluate and interpret the nature and quality of the data base.

Five categories of data were selected based on the complexity of the flow in the combustor: 1) non-reacting flows (cold flows), 2) particle-laden, non-reacting flows, 3) reacting gases, 4) pulverized coal combustion, and 5) entrained coal gasification. Any size of furnace or pilot plant was considered.

Five computer searches of the literature were made using the National Technical Information Service, Engineering Information, and Department of Energy data base retrieval services. Abstracts for 281 references were initially identified as relating to three-dimensional combustion and combustion-related topics. The most likely articles to contain experimental data or references to data were obtained for further evaluation. In addition to the literature search, a survey of sixty-six major combustion facilities was made to locate non-published and government reports with potentially useful data.

Every data set that was deemed relevant to three-dimensional model evaluation was requested. Data contained in journal articles and conference proceedings were not comprehensive enough to be useful without obtaining the full data set. Requests to authors were unanswered in all but one case. After elimination of data cases that were obviously not within the three-dimensional criteria, thirteen cases were selected for additional evaluation.

Eight categories, including boundary conditions, inlet conditions, and three-dimensional geometry or flow were established to evaluate the completeness of the data sets. Each data set was evaluated and assigned scores for each of the categories. Data sets with the highest cumulative scores that also included all the information required for computer modeling were chosen for use in the data book. Data accuracy was not used as a category for choosing the data although it is very important. None of the data sets provided enough information about accuracy for a relevant evaluation to be made. Six data sets were found to meet the selection criteria. Two cases were for cold flow, one for reacting gases, and three for pulverized-coal combustion. The companies taking the data were Combustion Engineering, Inc., Consolidation Coal Company, Institute of Gas Technology, and Energy and Environmental Research Corporation. Results from a recently initiated study by the Electric Power Research Institute (EPRI) were not yet available for this study. The EPRI study includes full-scale furnace measurements to evaluate the coal quality impact model (CQIM). Much of these data should be useful for evaluating three-dimensional combustion models.

An analysis of the general characteristics of the data in the data book was made to determine the extent to which the data book met the main objective of the study. The data book is somewhat incomplete since it does not include data from all five categories of data identified as useful for model evaluation. Three-dimensional data for particle-laden, non-reacting flows and entrained coal gasification were not found during the data searches. The data cases represent a wide range of sizes and furnace types. The data from the two non-reacting flow cases were taken in a tangentially-fired, lab-scale furnace model and a wall-fired, pilot-scale furnace. The reacting gas case was from a pilot-scale, refractory-lined, glass-melting furnace. The pulverized-coal data cases were from a wall-fired, pilot scale furnace (0.6 MW_g), a full-scale, wall-fired furnace (385 MW_g), and a full-scale, tangentially-fired furnace (405 MW_g).

None of the data sets in the data book is as complete or comprehensive as desired. The two cold-flow cases are the most comprehensive of all the data cases. Both cases were taken at a single operating condition. The reacting-gas data were taken over a range of fuel inlet velocities. The measurements emphasized effluent NO_x concentrations and wall temperatures. No spatial velocity profiles were obtained. All three of the pulverized-coal cases had spatial velocity, temperature, and gas concentration profiles. The test locations within the two full-scale furnaces were sparsely distributed. The pilot-scale furnace had spatially-resolved data evenly spaced on each of three test planes. The data in the pilot-scale furnace were the most extensive of all the combustion data sets. The data included particle-size and chemical composition analysis for each measurement location. The pilot-scale data set has restrictions regarding the release of furnace dimensions. The same restrictions apply to the pilot-scale cold flow data, however both cases were included in the data book because of their relatively high quality and completeness.

The accuracy of the data was evaluated using two sources of information. The first method used information from the reports from which the data were extracted. Limited information was available in reports about the error associated with the data. No error analyses were available with the cold-flow data sets or the reacting-gas data set. The estimated error in the data for two full-scale furnaces was estimated to be no larger than ± 30 percent for the velocity measurements. The error in the report for the pilot-scale data set stated the error to be generally within ± 10 percent. Limited information was available

about the repeatability of the data since only in the pilot-scale furnace combustion data were any measurements repeated.

The second method of estimating the error was to use the experimental data to perform material balance calculations. This method was also subject to some uncertainty. Since most of the data sets had sparsely located measurements, material balance calculations required assumptions about the flow in areas where no data were taken. In general, there is significant variation in the material balance calculations using data from different levels in a furnace.

Other problems with combustion data were observed during this study. One of the major problems with obtaining quality combustion data is proper control of the operating conditions over the test period. Furnace operations inherently change with time as wall surfaces and heater pendants become covered with soot and slag. Process equipment such as coal grinders, coal feeders, and fans for wind boxes have natural variation over time that also affect the furnace conditions. Care must be taken to account for system changes during data collection to ensure that data measurements and operating conditions are consistent. Another problem with data collection is access to the furnace interior. Careful planning is needed to obtain the best data within the limitations imposed by the structure.

Intrusive probes are not believed to have as significant an impact on flow within the furnace as in much smaller lab-scale facilities. However, most intrusive probes, such as pitot tubes, are thought to be less accurate compared to laser techniques and difficult to use because of the large diameter and probe length needed for testing in full-scale furnaces. Improvements in the cold-flow data could be obtained by using advanced measurement techniques such as laser-Doppler anemometry. Raman scattering techniques for species concentration profiles are also attractive alternatives capable of increasing accuracy and resolution. The disadvantages of the advanced optical methods is the high cost of equipment, high level of user expertise required, short optical paths in dirty environments inside furnaces, and difficulty using the equipment in the harsh environments surrounding furnace interiors.

In general, the data available for both non-reacting and reacting flows are lacking in accuracy and completeness. In specific, two major voids in combustion-related data are: 1) profile data of temperature, velocity, and gas concentrations in the lower regions of the furnace, especially near the burners, and 2) details of the furnace geometry. Velocity

profiles at the burner are not available. Because of the high particle load and intense heat near the burners, it may not be possible to obtain data in this region using conventional measurement techniques. A separate characterization of industrial-style burners may be necessary to obtain inlet profiles for the various burners used in furnaces.

A list of possible data measurements that could be taken in an experimental study of a combustion or cold flow facility was assembled and prioritized. The priority for each measurement is intended to be helpful for matching test plans to available resources to obtain the best data set possible for model evaluation. Recommendations are given for taking experimental data that will permit relatively accurate material balances to be performed.

The suitability of the data book for its purpose of providing an accurate data source for model evaluation is somewhat limited. All classes of data are not available. Data sets that are included are either incomplete or restricted in their usage. However, given the scarcity of data, the data book provides a first step towards obtaining the necessary data for model evaluation. Most importantly, the data book establishes criteria for selecting future data and provides suggestions for the data that are needed for model evaluation.

Work on 3-D data book collection should continue. A concerted effort is needed among industry, government, and academia to implement a program for collecting relevant data for model evaluation. Better use of existing facilities should be implemented where possible to avoid duplication of resources. New measurement techniques are needed to improve accuracy and ease of data collection. Government-funded projects need enforced guidelines concerning the availability of data taken during projects. Data in reports are often partially presented or reduced to a point of being unusable by others. The complete data set should be made available as part of project contracts.

Section 1

Introduction

1.1 Background

Fossil fuels such as oil, natural gas, and coal play the dominant role in providing for society's energy needs. Coal and natural gas are used extensively for power generation in large utility boilers and for heat/electricity co-generation in industrial facilities. At the near certain conclusion of the present oil surplus, the use of natural gas, and especially coal, can be expected to increase significantly as oil supplies dwindle, accompanied by a sharp increase in price.

Major aspects of using fossil fuels as an energy source include the need to minimize costs, maximize profits, and minimize its impact on the environment. While profits are important to the successful long-term operation of any utility company, the environmental impact of burning fossil fuels has become an increasingly important issue concerning energy production. National summits on acid rain caused by emissions of nitrogen oxides and sulfur oxides have brought international attention to the problem. Since 1971, when the New Source Performance Standards (NSPS) were instituted, nitrogen oxides emissions from coal, oil, and gas-fired utility boilers have been regulated. Another environmental concern over the use of fossil fuels is carbon dioxide accumulation attributing to the so called "green house effect" thought by some to be increasing the Earth's atmospheric temperature. Because of the growing concern with the environmental impact of burning fossil fuels, increased regulatory pressure to reduce emissions from utility boilers can be expected to continue.

Because of the regulations governing the operation of existing NSPS furnaces, and with even more stringent requirements covering the construction of all new furnaces, there is a real and urgent need to develop more efficient, cleaner-burning furnaces, and to improve the operation of existing furnaces. Improvements can be achieved by optimizing operating conditions, retrofitting furnaces with improved burner designs, over-fired air injection, and other methods that are constantly being developed.

Most design and operating decisions today are based on operating data, empirical correlations, and pilot-plant data. Although empirical correlations are useful to help make decisions, they cannot be used with confidence outside the operating conditions for which

the correlation data were measured. Because of the high cost of obtaining experimental data, available data are usually limited to a small range of operating conditions and a small physical area within a furnace.

With the advent of high-speed, digital computers over the past decade, computer models are a potentially valuable tool for achieving improved furnace design and operation. For a small fraction of the cost to build a pilot-scale furnace, or to take experimental measurements in an operating utility-scale furnace, a reliable computer model can give insights on design and operating changes affecting a given furnace's performance.

Models for two-dimensional combustion processes have been developed at many locations around the world and are beginning to play an important part in computational combustion studies. However, commercial utility boilers are typically three-dimensional with complex interactions between multiple burners and are not accurately described by axisymmetric, two-dimensional models. The complexity of commercial furnaces has led to the need for three-dimensional furnace models. Modeling of three-dimensional combustors is a major task at Brigham Young University's Combustion Laboratory and the Advanced Combustion Engineering Research Center as well as at several other research facilities as outlined in a review of combustion modeling by Smoot and Smith (1987). Several references to three-dimensional combustion models given in the review include papers by Gosman and Johns (1980), Gosman and Ioannides (1981), Mongia and Smith (1978), Bruce, et al. (1979), Boyson, et al. (1979), Blake, et al. (1979), Shida, et al. (1984), Zhou, et al. (1986), Boyd and Kent (1986), Robinson (1985), and Fiveland and Wessel (1986). Comprehensive evaluation of these codes has been limited (Smoot and Smith, 1987). As with any mathematical model of physical phenomena, confidence in the computed results is limited until the model has been thoroughly evaluated (Sampath, 1987).

According to Smoot and Smith (1985), various methods can be used to provide increased confidence in comprehensive combustion codes. Of the various methods possible, four were recommended as being essential to any rigorous model evaluation: (1) numerical evaluation, (2) sensitivity analysis, (3) trend analysis, and (4) comparison with comprehensive data. Three of these methods (excluding numerical evaluation) rely, at least in part, with the ability to obtain relevant and reliable experimental data. Sensitivity analysis, which evaluates the sensitivity of code predictions to changes in important model

parameters does not require experimental data in the strictest sense. However, using experimental data helps guarantee that the sensitivity analysis is being performed with consistent test conditions in an area of operational interest to industry.

Trend analysis is used to compare changes (or trends) in model predictions (such as NO_x concentration at various locations in the furnace) when a test parameter (such as stoichiometric ratio) is systematically varied over a range of conditions. The ability of a model to correctly predict the magnitude and direction of change in response to a change in operating conditions increases confidence in its use. The ability to correctly predict trends in data is limited if the predictions are inaccurate. For example, simply knowing that a given change in operating conditions will increase the maximum temperature by 100°C is of little utility if the model incorrectly predicts the temperature by a significant amount.

Two types of data are available for evaluating combustion models. Effluent (stack or chimney outlet) data are useful for providing some idea of model validity, but fall short in their ability to evaluate the three-dimensional processes occurring within the furnace. Profile data, which are temporally and spatially resolved inside a combustor, give a more definitive evaluation of model accuracy, especially when several properties (species concentration, temperature, velocity, etc.) are "simultaneously" measured (Smoot, 1984). Not only does this provide the magnitude of the properties, but also information concerning the relationship between the various species and processes occurring in combustion.

Computer models can be given the highest degree of confidence when being used to predict results for operating conditions similar to those used successfully for model evaluation. The evaluation of a model over a wide range of operating conditions is useful for establishing the range of parameters for which the model is known to be accurate. However, the law of diminishing returns applies to evaluating the model. Data cases used for evaluation need to be carefully chosen using engineering judgement so that each case modeled provides the maximum information about model performance. Cases for operating conditions covering a wide range of values are desirable, but a large number of data sets is not required across the entire range. For example, evaluating a model at four stoichiometric ratios judiciously chosen gives essentially the same information about the effects of stoichiometric ratio as evaluation at 20 settings across the same range.

Rigorous model evaluation is no better than the data used to evaluate it. Meaningful evaluation of the comprehensive code requires accurate data. Acceptable accuracy depends on the availability of data. Ideally, all the data would be highly accurate and reliable, but when data are scarce, a few relatively accurate cases may be better than many inaccurate cases or no cases at all. Criteria for selecting data are needed for choosing data that are useful to model evaluation.

Developers of the earlier two-dimensional combustion models, such as PCGC-2 at this laboratory, found it useful to have a single, compiled source of experimental data with which to evaluate the model. A compilation of two-dimensional, axisymmetric data (Smoot and Christensen, 1985) was used to evaluate PCGC-2 over a period of several years (Rasband, 1988). Another source of two-dimensional data was compiled by the Combustion and Carbonization Research Laboratory of CANMET in Canada (Hughes, 1988). These compilations are useful for validating the three-dimensional model's numerical convergence methods, stability, etc. They are also useful as a check on the three-dimensional model's ability to reduce correctly to a two-dimensional solution. However, comparisons with data from axisymmetric cases gives only limited indication of the performance of the comprehensive model's three-dimensional capabilities.

There is no known compilation of three-dimensional data available, and a review of the available data has not been done. A compilation of relevant data (this document) provides a data base for evaluating combustion models. A review of the state of three-dimensional combustion data provides insights to future data needs and should be useful for guiding future experimental work. This review should prove useful to engineers and scientists working in the field of combustion, especially those involved with commercial systems.

Data collection at an 80 MW, (megawatt electrical) commercial facility, the Goudey Station in New York, has benefitted from information gathered during this project. A team of investigators lead by Cannon (1989) used recommendations about the data needs for evaluating combustion models to assist in organizing an experimental test plan for full-scale testing at the Goudey Station. The data collection took place from June 19 - 30, 1989, and included furnace in situ measurements of gas composition, temperature, velocities of gases and particles, particle cloud densities, size distributions, and radiation fluxes at

several locations in the furnace. Measurements were essentially confined to the radiant section of the furnace using several water-cooled probes of up to 0.10 m (4 inches) in diameter and 4.3 m (14 feet) in length. These data became available after the data book was in its final draft and were not considered for the data book. They will be considered in future updates of the data book.

The importance of the data-collection project reported herein has already been recognized by a scientific team from outside the laboratory. The report covering a recent visit to the Advanced Combustion Engineering Research Center stated:

The collection of field data and its integration into a source available for model evaluation is an important task. It seems to have been pursued vigorously in spite of the difficulties and the tedium inherent to the sifting of data from past, incompletely documented experiments...there is a special need to document the full size end of the experimental spectrum. This activity should also emphasize the design of experiments...to produce the data best suited to a close evaluation of the numerical model (Boni, 1988).

Although this National Science Foundation (NSF) evaluation report was written toward the end of this project, and refers to a larger scale program, its recommendations have been partially fulfilled by this thesis, which lays a foundation for future work in the area of three-dimensional furnace data acquisition.

1.2 Objectives

The main objective of the data book was to provide a single source of detailed three-dimensional combustion and combustion-related data suitable for comprehensive combustion model evaluation (Table 1.1). The five main tasks identified as requirements to achieving the main objective was: (1) to identify the types of data that are needed to evaluate comprehensive combustion models, and to establish a criteria for selecting data to use in the data book; (2) to identify and document available three-dimensional combustion data related to pulverized coal combustion; (3) to collect and evaluate three-dimensional data cases, and select suitable cases based on selection criteria; (4) to organize the selected data

Table 1.1
Objectives of Data Book

Main Objective: Provide a Single Source of 3-D Data for Comprehensive Combustion Model Evaluation

Tasks:

1. Identify Data Types Needed and Establish Criteria for Selecting Data
2. Identify and Document Available Three-dimensional Data Relating to Pulverized Coal-fired Furnaces
3. Collect, Evaluate, and Select "Best" Data Sets Based on Selection Criteria
4. Organize the Data into an Easy-to-Use Format
5. Evaluate and Interpret the Nature and Quality of the Data Base

sets into an easy-to-use format; and (5) to evaluate and interpret the nature and quality of the data base.

Task 1 required that a set of specifications be determined for selecting data to be included in the data book. Criteria have been established in previous two-dimensional studies (Smoot and Christensen, 1985). These two-dimensional criteria were evaluated and modified as needed for use as the three-dimensional data selection criteria.

Task 2 used two methods, literature searches and surveys, to identify potentially available data. A thorough search of the open literature for more than the past 20 years was completed using both manual and computer-assisted search methods. As expected, most of the available data were contained in the sub-literature such as unpublished company reports. A systematic survey of key combustion facilities determined which facilities had data and were willing to allow its use in this study. Results of the survey are given in section 2 of this document.

For Task 3, each data set was obtained and evaluated according to the criteria established for Task 1. A weighting scale which assigns points to data sets according to the number of criteria met was used to identify the "best" sets to be included in the data book. The results of the evaluation are given in Section 2.

The fourth task required that each set of data, including operating conditions, boundary and inlet conditions, and experimental measurements, be organized into an easy-to-use format with sufficient detail given to permit computer modeling of the data case. This

document, Three-Dimensional Combustion Data for Comprehensive Model Evaluation, was created in fulfillment of this task.

For Task 5, the data sets that were of sufficient quality and scope were evaluated, and the accuracy and reliability of the data base of combustion data were estimated. The evaluation identifies key data needs, important trends in the data, and key variables. Since the amount of data available was limited to a few cases of generally inadequate experimental quality, evaluation of the methods used to make experimental data available to the research community was made, along with suggestions on how to improve the transfer of information.

Section 2 Data Base

2.1 Data Search

2.1.1 Types of Data Desired

Before any literature search or surveys could be started, it was necessary to establish limits to the search and to define what types of data would be useful for comprehensive model evaluation. The two-dimensional data book (Smoot and Christensen, 1985) was used as a starting point for establishing a list of three-dimensional data needs. Items that were not relevant to three-dimensional combustion data were removed from the list and other items unique to three-dimensional data were added.

Five categories of data were selected based on the complexity of the flow in the combustor. Table 2.1 lists the five categories from the simplest flow (cold gaseous flow) to more complex combusting flows (Smoot and Christensen, 1985). The use of five categories corresponds well to model development and permits independent evaluation of major model components such as gas fluid mechanics, particle dispersion, reacting gases, and pulverized coal combustion. Gasification, which is essentially fuel-rich combustion, is added as a separate category for completeness.

Table 2.1

Classes of Combustion Data for Model Evaluation

1. Non-Reacting Gaseous or Liquid Flow (Cold Flow)
2. Non-Reacting Gaseous Flow (Particle Laden)
3. Reacting Gases
4. Pulverized Coal Combustion
5. Entrained Coal Gasification

The data are not restricted to pulverized coal and combustible gases (i.e. natural gas, methane, etc.) as fuels. Other types of data may be useful additions to the data book as more data become available or as interest in other types of flow systems increase. For example, three-dimensional data for combustion of liquid fuels sprayed through an atomizer, or coal-water slurries used as the fuel would be possible candidates. Since the three-dimensional combustion code will have the potential to model these types of combustion, it was decided

to document any references to these types of data but not include them in the data book. It is anticipated that these types of fuels may become plentiful enough to merit addition to the data book.

Another important aspect of the data is the size of the facility used for combustion. To evaluate the ability of the model to accurately predict results for both large and small furnaces, data from commercial, full-size boilers down to lab-scale combustors were desirable. Among full-scale furnaces, industry users often divide furnaces into small, medium, and large based on their electrical output. Although subjective, a small furnace is probably rated below 100 MW_e, a medium furnace would include up to 300 MW_e, and large furnaces would include those above 300 MW_e. Pilot-scale furnaces are typically one to two orders of magnitude smaller than small, full-scale furnaces with a load rating of approximately 1 to 10 MW_e or less. Data from any size combustor would be suitable provided they meet the other criteria discussed below.

2.1.2 Computer-Assisted Literature Search

Five computer assisted literature searches were conducted to find references to three-dimensional data for the five classes listed in Table 2.1. Three major technical data bases were searched: National Technical Information Service (NTIS), Engineering Information (EI), and Department of Energy (DOE) Energy Data Base. These data bases specialize in technical articles. The NTIS and DOE data bases include articles from technical journals and energy-related reports that have not been published in journals, such as contract reports funded by the DOE, NASA, or other government agencies.

Using the key word combinations shown in Table 2.2, 281 references were found during the data base searches. Abstracts were printed for the articles whose titles seemed most likely to have useful information. The 281 abstracts were reduced to those most likely to have three-dimensional experimental data. Details about the completeness or quality of the data were not a major concern at this stage of the data search. The criterion at this point was for the article to have potentially three-dimensional data.

Copies of the articles of interest were either found in the technical journals located in the Brigham Young University library or copies were purchased from the NTIS. Documents funded by government contracts were also obtained through the NTIS. Assessment of the availability of potential data found through the literature search is described below.

Table 2.2
Key Words Used in Literature Search

<u>Data Base</u>	<u>Period Searched</u>	<u>Key Words Used</u>	<u>No. of References Found</u>
Engineering Information	1970 - 1986	COMBUSTION AND 3(W)D OR THREE(W)DIMENSIONAL AND DATA	26
National Technical Information Service	1964 - 1986	COAL AND (FURNACE OR COMBUSTION) AND 3(W)D OR THREE(W)DIMENSIONAL	41
DOE Energy	1975-1988	UTILITY(W)(BOILER OR FURNACE? ?) AND REACTING(W)GAS OR GAS(W)COMBUSTION OR REACTING(W)FLOW OR GAS(W)FIRED	25
DOE Energy	1975-1988	FLOW AND (COLD OR NON(W)REACTING OR AIR(W)ONLY) AND FIRED OR TANGENTIAL?(W)FIRED OR COMBUSTER OR CROSS OR OPPOS? OR THREE(W)DIMENSIONAL OR 3(W)D OR FURNACE? OR BOILER?OR UTILITY AND MEASURE? OR DATA OR EXPERIMENT? OR PROFIL? OR FLOW(W) FIELD? ?	125
DOE Energy	1983-1988	COAL AND (PULVERIZED OR ENTRAINED) AND UTILITY(W)(BOILER OR FURNACE? ?) OR TANGENTIALLY(W)FIRED OR WALL(W)FIRED OR CROSS(W)FIRED OR 3(W)D OR THREE-DIMENSIONAL AND DATA OR EXPERIMENT? ?	64

2.1.3 Survey of Combustion Facilities

While reports from studies funded by the government are generally available through the NTIS and listed in the DOE energy data base, specific reports containing experimental data are not always easily identifiable for various reasons. Because of the great expense required to take three-dimensional combustion data, most available experimental data of interest to the three-dimensional data book, if it existed, were expected to be found in the "sub-literature" of government reports and unpublished reports created for internal use by

energy-related companies. The great expense of obtaining three-dimensional experimental data makes funding from commercial entities or government agencies likely.

To locate potentially useful data for the data book from the sub-literature, a survey of major combustion facilities was conducted. A list of likely facilities and individuals was made by extracting names from journal articles, a list of combustion facilities, and a mailing list of combustion-related individuals and companies. A questionnaire, shown in Figure 2.1, was mailed to a specific individual at each company or facility listed in Table 2.3. Table 2.3 indicates who received the questionnaire, who returned the questionnaire, and whether they have available data. A "no reply" in Table 2.3 indicates that no response was received after sending a first and second letter. Table 2.4 summarizes the responses to the questionnaires that were returned.

An additional source of information about data availability was through attendance and participation in combustion-related seminars and meetings. For example, personal communication with Wolfgang Richter, formerly with Energy and Environmental Research Corp. (EER), during the Western States section of the Combustion Institute led to the location of a major study performed by Energy and Environmental Research Corporation. Two other meetings used to seek data were a poster session during the Advanced Combustion Engineering Research Center (ACERC) annual review session attended by officials from many combustion-related companies, and a meeting of members of Working Group 6 from ACERC. Working Group 6 is responsible for data for model evaluation.

2.1.4 Available Three-Dimensional Data

After identifying potential sources of three-dimensional data, the data in tabular, digital format were requested from the various sources. Data referenced in journal articles were requested from the authors. Data collection was one of the most difficult parts of this project. Many known, potential sources of data were not obtained for the data book because of the unwillingness of potential sources to respond to correspondence.

None of the data in journal articles or articles of the proceedings of conferences and seminars found from the literature searches were complete enough to use in the data book. Requests to the authors of these reports were not answered, except for one case. The one response received indicated that the data of interest were "borrowed" from a colleague. This response may be indicative of why other authors did not reply. Three-dimensional

Three-Dimensional Combustion Data Questionnaire

Name _____ Position _____
 Company _____
 Address _____
 City _____ State _____ Zip Code _____
 Country _____ Phone Number _____

Please check each answer that applies to your facility.

1. Does your facility have combustion related experimental data which can be made available to the BYU Combustion Laboratory on a ☐ A. Restricted Basis ☐ B. Unrestricted Basis ☐ C. No Data Available

If your answer to question 1. was A or B, please complete the rest of this questionnaire. If you answered C, please fill in your name and address and return the blank questionnaire.

2. May we release your responses to this questionnaire in a report of this survey? ☐ Yes ☐ No

3. Does your facility have any of the following types of three-dimensional profile data (e.g., temperatures or velocities measured at various locations throughout the combustor)? On the left, indicate which classes you have (e.g., cold flow, reacting gases, etc.). Indicate which types of data are available in the boxes on the right (e.g., temperature, velocity, etc.).

- ☐ Non-reacting gaseous flow (cold flow)
- ☐ Non-reacting particle-laden flow
- ☐ Reacting gases
- ☐ Pulverized coal combustion
- ☐ Entrained coal gasification
- ☐ Other (please specify) _____

PROFILE DATA						
Temperature	Velocity	Concentration of Gas Particles	Pollutants	Radiative Fluxes	Fouling and Slagging	Particle Properties

4. Does your facility have any of the following types of three-dimensional effluent data (e.g., temperatures or velocities measured at the combustor's outlet)? On the left, indicate which classes you have (e.g., cold flow, reacting gases, etc.). Indicate which types of data are available in the boxes on the right (e.g., temperature, velocity, etc.).

- ☐ Non-reacting gaseous flow (cold flow)
- ☐ Non-reacting particle-laden flow
- ☐ Reacting gases
- ☐ Pulverized-coal combustion
- ☐ Entrained coal gasification
- ☐ Other (please specify) _____

EFFLUENT DATA						
Temperature	Velocity	Concentration of Gas Particles	Pollutants	Radiative Fluxes	Fouling and Slagging	Particle Properties

(OVER)

Figure 2.1
 Three-Dimensional Combustion Data Questionnaire Used in Survey
 This questionnaire was sent out to combustion-related facilities
 inquiring about possible data that may be available

5. Please indicate what type of facilities were used for measurements and their size.

- ☐ Full-size combustor
☐ Pilot-scale combustor
☐ Lab-scale combustor

MW Level	Coal Feed Level

6. Who should we contact at your company concerning your combustion data?

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7. Please indicate other persons, facilities, or references where relevant data may be available.

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8. Other requests or comments.

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9. ☐ Please check here if you would like to receive a copy of this survey when complete.

Thank you for your cooperation. Please return this questionnaire to:

Dr. L. Douglas Smoot
BYU Combustion Laboratory - 270 CB
Brigham Young University

A representative from the BYU Combustion Laboratory will be contacting the person listed in question no. 6 in the next few weeks to arrange for the delivery of your data.

Figure 2.1 - continued

Table 2.3
Companies Receiving Data Questionnaire

<u>Company or Facility Name</u>	<u>Recipient</u>	<u>Response</u>
Acurex	Chang, Ramsay	No Reply
Allis-Chalmers Coal Gas Corp.	Garside, Peter	No Data Available
Altex Technologies	Kelly, John	No Reply
Amax Coal Company	Woessner, Paul	No Data Available
Avco Research Laboratory	Gannon, Richard E.	No Reply
Babcock and Wilcox, Alliance	Oberjohn, William J.	No Reply
Bituminous Coal Research	DeMarchis, John A.	No Reply
Blue Circle Industries Limited	Lowe, T. M.	No Reply
British Gas Corporation	Rhines, Jeff M.	No Reply
Central Electricity Generation Board - Marchwood	Sargeant, Malcolm	No Reply
Chevron Research Company	Taylor, B.W.	No Reply
Combustion Engineering, Inc.	Robinson, Gordon	Data available in public domain Proprietary data unavailable
Consolidation Coal Company	Harding, N. Stanley	Data available with restrictions Facility is pilot scale (0.6 MWe)
Corning Glass Works	McNally, Robert N.	No Reply
CSIRO Division of Fossil Fuels	Haynes, B. S.	No Reply
Dow Chemical USA	Henley, John	No Reply
Energy and Environmental Research, Inc.	Payne, Roy	Data available / Volume 2 received (Cetegen, 1987)
Elec. Comm. of New South Wales	Lowe, Alan	Letter returned - wrong address
Electric Power Research Institute	Eskinazi, David	Data available - no funds for extraction
Electric Power Research Institute	Mehta, Arun K.	Data available through Combustion Eng.
Empire State Electric Energy Research Co.	Mancini, Rick A.	Homer City Unit 3 data received (Anacki, 1980)
Factory Mutual Research Inst.	Markstein, George H.	No Reply
Florida Power and Light	Olen, K.R.	No Reply
Foster Wheeler Corp.	Bryers, Richard W.	Data available / data were not requested. Facility is pilot scale.
Gas Research Institute	Hill, Vernon	No Data Available
General Electric Company	Kimura, Gene	Data available with restrictions. Facilities are pilot- and lab-scale gas-turbine comb.
General Motors Corp.	Mongia, Hukam C.	No Reply
Hitachi Limited	Azuhata, Shigeru	Data exists but unavailable
Ishikawajima-Harima Heavy Ind.	Nakamura, Takeshi	No Reply
Imperial College	Whitelaw, J. H.	No Reply
Imperial College	Salooja, A. P.	No Reply
Imperial College	Lockwood, F. C.	Data available/ Data requested but not received; Lab scale facility (10 - 60 kg/h)
Indian Institute of Technology	Ganesan, Venkitachalam	No Data Available
Institute of Gas Technology	Khinkis, Mark J.	Data available / 2 reports received Facility is 0.6 MW pilot scale
Institute of Paper Chemistry	Grace, Thomas M.	No Reply
John Zink Company	Waibel, Richard T.	No Reply
KVB, Inc.	Cherry, Steven S.	No Reply
Los Alamos	Hill, Scott	No Data Available
L & C Steinmuller GmbH	Michelfelder, S.	Data available with restrictions. Contact - Dr. Walter Thielen; No data received

Table 2.3 - continued

Massachusetts Institute of Tech.	Beer, J.M.	Only 2-D and 0-D data available; Pilot scale (2 MW; 600 lb/hr)
Midwest Research Institute	Greene, Frank T.	No Reply
Nagasaki Technical Institute	Sakai, Masayasu	No Reply
Nagasaki Technical Institute	Shida, Hiroya	No Reply
Niagra Mohawk Power Corp.	Underwood, D.E.	No Data Available
Oklahoma State University	Lilley, David	No Reply
Ontario Hydro	Seckington, Blair	No Reply
Pittsburgh Energy and Tech. Ctr.	Spencer, F. Edward	No Reply
Pratt and Whitney Aircraft	Syed, Saadat	No Reply
Pyropower Corporation	Tang, John T.	No Data Available
Radian Corporation	Burke, Jack	No Reply
Riley Stoker	Lisauskas, Robert	No Reply
Science Applications Int.	Edelman, Raymond	No Reply
Shell Development-Westhollow	Tang, Harry S.	No Reply
Shell Research Ltd.-Thornton	Briffa, Francis	No Reply
Solar Energy Research Inst.	Milne, Thomas	No Data Available
Southern California Edison	Straughan, Ian R.	No Reply
Southern Research Institute	Beittel, Roderick	No Reply
Southwest Research Inst.	Ryan, Thomas W.	No Reply
State Elec. Comm. of Victoria	Juniper, L. A.	Letter returned - wrong address
Stone and Webster	Korosi, Alex	No Reply
Texaco, Inc.	Schlenger, Warren G.	Data exist but unavailable
Tennessee Valley Authority	Huang, Chao-Ming	No Data Available
University of Sydney	Kent, J. H.	No Reply
University of Waterloo	Rhodes, Ted	No Reply
Utah Power & Light	Rees, Dee P.	Data available / no data requested (400MWe)
Westinghouse R&D Center	Mechlin, George F.	No Reply

combustion data or flow data are scarce. The number of facilities with the ability to obtain three-dimensional data are mostly limited to commercial entities who are unwilling to share their expensively obtained data with competitors. Authors of journal papers usually appear to have borrowed data from commercial facilities with an agreement not to publish the details of the data, only the results of model comparisons, or some other limited use.

A list of all the data that were obtained for further evaluation is given in Appendix F. These data were briefly evaluated to determine if they were from a facility with three-dimensional geometry or flow characteristics. Data that did not meet these two preliminary criteria were immediately removed from consideration. Most of the data sets did not meet the three-dimensional geometry or flow criteria. The cases remaining at this point (Table 2.5) of the project were evaluated further as described in the next section.

Table 2.4

Compilation of Three-Dimensional Data Sources

Categories refer to profile and effluent data. Availability of profile data is shown on the first line and effluent data on the second line. Some data were available only with restrictions as indicated in the second column. The following keys and abbreviations apply to the table. Conc. = concentration, Temp. = temperature, NRG = non-reacting gas flow, NRPL = non-reacting particle laden gas flow, RG = reacting gas flow, PCC = pulverized-coal combustion, NA = not applicable, no data = nothing available, unknown = details not known. Furnace ratings were specified in MW electrical unless noted otherwise.

Survey Sources	Restrictions on Usage	Temp. Data (profile/effluent)	Velocity Data (profile/effluent)	Conc. of Gases (profile/effluent)	Conc. of Particles (profile/effluent)	Conc. of Pollutants (profile/effluent)	Radiative Fluxes (profile/effluent)	Fouling & Slagging (profile/effluent)	Particle Properties (profile/effluent)	Facility Scale/Rating (MW/e)
Consolidation Coal Co. (Havekotte, 1988)	Yes	NRG/ no data	NRG/ no data	NRG/ no data	NA/ NA	NA/ NA	NA/ NA	NA/ NA	NA/ NA	Pilot / 0.6
Consolidation Coal Co. (Havekotte, 1987)	Yes	PCC/ PCC	PCC/ PCC	PCC/ PCC	PCC/ PCC	PCC/ PCC	PCC/ no data	PCC/ PCC	PCC/ PCC	Pilot / 0.6
Institute of Gas Technology (Abbasi, 1983)	No	RG/ RG	no data/ no data	no data/ RG	no data/ no data	no data/ RG	RG/ no data	no data/ no data	no data/ no data	Pilot / 0.6 MW thermal
Institute of Gas Technology (Briceland, 1983)	No	PCC/ PCC	no data/ no data	PCC/ PCC	no data/ PCC	no data/ PCC	PCC/ no data	no data/ no data	no data/ no data	Pilot / 0.6 MW thermal
Utah Power and Light	No	none/ PCC	no data/ PCC	no data/ PCC	no data/ PCC	no data/ PCC	no data/ no data	PCC/ no data	no data/ no data	Full / 400
General Electric	Yes	NRG/ NRG	NRG/ no data	NRG/ NRG	NRG/ NRG	NRG/ no data	no data/ no data	NRG/ no data	NRG/ no data	Pilot / unknown
Energy and Environmental Research Corp. (Cetegen, 1987)	No	PCC/ PCC	PCC/ no data	PCC/ PCC	no data/ PCC	no data/ no data	PCC/ no data	no data/ no data	no data/ no data	Full / 420

Table 2.4 - continued

Survey Sources	Restrictions on Usage	Temp. Data (profile/effluent)	Velocity Data (profile/effluent)	Conc. of Gases (profile/effluent)	Conc. of Particles (profile/effluent)	Conc. of Pollutants (profile/effluent)	Radiative Fluxes (profile/effluent)	Fouling & Slagging (profile/effluent)	Particle Properties (profile/effluent)	Facility Scale/Rating (MW/c) (profile/effluent)
Reference										
NASA Contractor's Report (Lilley, D.G., 1986)	No	no data/ no data	NRG/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	Lab/ NA
Robinson, G.F. (1985)	No	RG/ RG	no data/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	Full/ 2000 & 303
Sakai, M. (1984)	No	no data/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	PCC/ no data	no data/ no data	no data/ no data	Full/ 725
Khalil, E.E. (1979)	No	RG/ no data	no data/ no data	RG/ no data	no data/ no data	no data/ no data	RG/ no data	no data/ no data	no data/ no data	Pilot/ unknown
Boyd, R.K. (1986)	No	PCC/ no data	no data/ no data	PCC/ no data	no data/ no data	PCC/ no data	PCC/ no data	no data/ no data	no data/ no data	Full/ 500
Sampath, S.	No	RG/ no data	RG/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	no data/ no data	Lab/ unknown

Table 2.5

Combustion Related Data with Three-Dimensional Characteristics Considered for Data Book

Investigator	Chem. System (pri/sec)	Number of Sets	Test Variables	Measured Properties	Geometry / Inlet Conditions Specified	Comments
Consolidation Coal (Havekotte, 1987)	Bituminous/Air	1	-	T, mass, V_x , V_z , CO, CO ₂ , O ₂ , SO ₂ , NO _x , slag anal., wall T, heat flux, particle properties	yes/yes	restrictions on use dimensions of furnace cannot be published
Consolidation Coal (Havekotte, 1988)	Air/CO	1	-	V_x , V_z , CO, wall temp.	yes/yes	restrictions on use dimensions of furnace cannot be published
CE/EPA (Koucky, 1988)	Air	1	-	V_x , V_y , V_z	yes/yes	additional information made available from CE
IGT (Briceland, 1983)	Bituminous/Air	5	Part. Size, Firing Rate	Visual Flame length, Flue Gas T, Walls T O ₂ , CO ₂ , CO, NO, NO _x , Slag and Ash, Dep. Rates	yes/yes	axially-fired square furnace.
IGT (Abbasi, 1983)	Natural Gas/Air	111	port design, firing mode, excess O ₂ , fuel inj. vel.	NO _x , O ₂ , CO, CO ₂ , NO, combustion air temp., roof temp., wall temp., flue gas temp., pressure	yes/yes	model of a glass melting furnace. mostly effluent data
Youssef (Youssef, 1967)	natural gas/air	1	-	axial velocity, temperature profile, tangential velocity	yes/yes	cylindrical turbine with 60° symmetry because of film cooling air injected axially from wall.

Table 2.5 (continued)
Combustion Related Data with Three-Dimensional Characteristics Considered for Data Book

Investigator	Chem. System (pri/sec)	Number of Sets	Test Variables	Measured Properties	Geometry / Inlet Conditions Specified	Comments
Sakai (Sakai, 1984)	Wyoming coal/air	3	furnace load	wall and cooling water temp. for heat flux calculations	yes/some	only heat flux reported, no temperatures
Duck Creek (Cetegen, 1987)	bituminous/air	5	furnace load, excess air, burner settings	temp profiles, wall deposits, CO, CO ₂ , O ₂ , SO ₂ , NO _x , V _x , V _z , incident radiative heat flux	yes/yes	wall fired furnace, tabular data
Coneville (Cetegen, 1987)	bituminous/air	6	load, excess air, burner tilt, firing configuration	temp. profiles, velocity, CO, CO ₂ , O ₂ , SO ₂ , NO _x , incident radiative, heat flux wall emissivity, wall charact. fly ash and ash comps.	yes/yes	tangent fired, tabular data
Shoffstall (Shoffstall, 1976)	CH ₄	1	-	gas temp. profiles, CH ₄ & O ₂ profiles	yes/yes	square, complicated burner design
Robinson (Robinson, 1985)	natural gas	7 & 8	firing rate, excess air, burner tilt	mean gas temp. in outlet, temp. profiles along several traverses, heat flux	mostly/partly	2 tangentially-fired, full-size gas furnaces
ESERCO Homer City Unit 3 (Anacki, 1980)	bituminous/air	27	load, excess air, location of burners gas recirculation	effluent CO, CO ₂ , O ₂ , SO ₂ , NO _x .	yes/yes	48 burners total on front and rear walls. 73'X51'X171'

The cases above represent the best data sets for which data were obtained. These data were chosen because they appear to have some three-dimensional characteristics. The analysis of the data sets at this point in the project was not in depth but merely a first screening of data to identify which appeared to have the bare minimum qualities necessary for the data book. The number of sets refers to the number of operating conditions for which data were taken.

2.2 Data Selection and Evaluation

2.2.1 Selection Criteria

Once data were collected from their original source documents, each case required screening and evaluation to determine which data were suitable for three-dimensional model evaluation. A general set of criteria, Table 2.6, was established for evaluating each of the data cases that were obtained. The general criteria were divided into eight categories to qualitatively assign scores to the data sets based on completeness (Table 2.7). The eight categories, explained below, are boundary conditions, inlet conditions, specified and desired geometrical configuration, test conditions, profile data, effluent data, and parametric data. Categories for accuracy were considered initially as a selection criteria. However, after reviewing the several data sets being considered, it was decided not to use accuracy as a criterion at this time since few of the data cases provided sufficient information about the accuracy of the data to make any conclusions. As more data become available, information about material balances, energy balances, reproducible results, and error analysis included with each data set should be considered as a selection criterion. Each of the categories are explained below.

Table 2.6
Criteria for Evaluating and Selecting Three-Dimensional
Combustion Data for Model Evaluation

- A. Required
  - 1. Three-dimensional Geometry
and
  - 2. Detailed Profile Data
    - a. Gas Temperature
    - b. Wall Temperature
    - c. Gas and Ash Compositions
    - d. Velocities
  - or
  - 3. Systematic Parametric Variation
- B. Desired
  - 1. Complete Boundary Conditions
  - 2. Several Measured Properties
  - 3. Complete Data Set
  - 4. Data Accuracy Information
    - a. Material Balances
    - b. Estimation of Errors
  - 5. Data in Tabular Form

Table 2.7

Summary of Detailed Data Evaluation Based on Selection Criteria

Data were evaluated using criteria discussed in chapter 2. A score of 3 means the data were essentially complete in the category being evaluated. A score of 2 means that some information was not available. A 1 means that only some information was provided, and a 0 means no information was available for the category being evaluated. Cases with an asterisk by them were chosen for the data book.

Case	Scale	Boundary Conditions	Inlet Conditions	Detailed 3-D Dimensions	Test Conditions	Profile Data	Effluent Data	Parametric Data	Composite Score	Comments
Cold Flow Cases										
CE/EPA* (Koncky, 1988)	pilot	3	3	3	3	3	2	0	17	extensive profile data at seven test planes
Consolidation Coal Company* (Havekotte, 1988)	pilot	3	3	3	3	3	0	0	15	dimensions of furnace restricted. operating conditions carefully monitored.
Reacting Gas										
Institute of Gas Technology* (Abbasi, 1983)	pilot	2	2	2	3	1	3	2	15	boundary and inlet conditions fairly well described. parametric effluent data over a range of several parameters.
Youssef (Youssef, 1967)	lab	1	2	1	2	1	0	0	7	geometry is not fully three-dimensional. measurements show no three-dimensional characteristics.
Shoffstall (Shoffstall, 1976)	lab	1	2	1	2	0	0	1	7	furnace has square geometry but is axially fired. data are symmetrical.
Robinson (Robinson, 1985)	full	1	1	1	1	1	0	2	7	insufficient information given about furnace dimensions.

Table 2.7 - continued

Case	Scale	Boundary Conditions	Inlet Conditions	Detailed 3-D Dimensions	Test Conditions	Profile Data	Effluent Data	Parametric Data	Composite Score	Comments
Pulverized Coal Combustion										
Institute of Gas Technology (Briceland, 1983)	pilot	3	3	3	3	1	3	2	18	furnace geometry is rectangular but axially fired profile data is limited to centerline measurements effluent data vs. coal particle size, 2-D flow.
Consolidation Coal Company* (Havekotte, 1987)	pilot	3	3	3	3	3	2	0	17	furnace dimension restricted from publication. Data well documented. Coal particle analyses taken at many locations, single oper. condition.
Sakai, et al. (Sakai, 1984)	Full	1	1	1	2	1	0	1	7	insufficient information about inlet conditions. data limited to heat flux.
ESEERCO/Homer City (Anacki, 1980) (Hunter, 1987)	Full	2	1	1	2	0	3	3	12	lacks details about operating conditions. includes devolatilization rates of coal, effluent pollutants and wall temperatures given.
Coneville* (Cetegen, 1987)	Full	2	2	3	2	3	2	1	15	large report, many operational details difficult to determine from report and must be estimated.
Duck Creek* (Cetegen, 1987)	Full	2	2	3	2	3	2	1	15	large report, many operational details difficult to determine from report and must be estimated.

Completeness of the data set is essential for useful model evaluation. Key information such as inlet conditions and specified geometry must be available. Other criteria, such as whether parametric data are provided, are less critical since they do not prevent a case from being modeled. They do add to the quality of the data set as a whole and are therefore included as an indication of the overall quality.

It is important to note that most data sets were not collected with comprehensive model evaluation as the main objective of the study. Therefore, cases identified in this study as having limitations for combustion model evaluations may have been completely within the objectives of the studies from which they were taken.

Boundary conditions, as a selection criterion, refer to information about wall temperatures and effluent conditions. Information such as inlet conditions and geometry, which are generally considered to be part of the boundary conditions, were separated into additional categories because of the importance of this information for modeling purposes. Lack of information about some boundary conditions is not critical since acceptable estimates of this information based on engineering judgement can be provided or because a parameter may affect the model only slightly or not at all.

Inlet conditions include inlet velocity or the flow rate and inlet geometry. Other required information includes the swirl characteristics, fuel characteristics such as particle size and ultimate analysis, temperature of inlet gas or fuel, etc. Most of the inlet conditions are required for reliable modeling since the model predictions are more sensitive to changes in inlet conditions than other parameters such as wall temperature.

Specified geometry is also required since flow patterns are dependent on the wall boundary location, intrusions, etc. Geometry is much more complex in three-dimensional furnaces than in two-dimensional furnaces. Two-dimensional geometries were considered in some cases, however. If inlet conditions consisted of a complex flow resulting in a three-dimensional flow pattern, these cases were evaluated. An example of a two-dimensional geometry with three-dimensional flow is an axially-fired furnace with radially-injected fuel from non-annular inlets as in a turbine combustor.

The category of test conditions refers to any additional information about the experimental procedure or operating conditions that may be useful for modeling or understanding the experimental data. The last three criteria under completeness (profile data, effluent data, and parametric data) refer to the completeness and characteristics of the measured data

rather than the specification of operating conditions. Detailed profile data are particularly useful in model evaluation. Profile data are spatially and/or temporally resolved in a reactor and thus give local properties for model comparison. Effluent data are measurements taken at the furnace outlet. These data can also be useful in model evaluation, particularly where effluent properties are measured as test variables are changed. Isolated effluent data cases by themselves do not provide as useful a foundation for model evaluation. Single-point effluent data were not selected for inclusion in this data book. The parametric data are measurements taken either at the effluent or as profile data at more than one operating condition. Typically, a single parameter such as stoichiometric ratio has been varied over some useful range to show the effects on dependent variables such as coal burnout, pollutant concentrations, temperature, etc. Parametric data are useful for determining if the comprehensive model gives predictions that follow experimental trends. This information is often useful even if model predictions are not exact in magnitude.

The second group of criteria is for evaluating the accuracy of the data. Accurate data are desired when used in model evaluation. Computer modelers consider this to be a most important criterion for data for evaluation of comprehensive models (Smith, 1988). Without accurate data, comparison of model predictions to experimental data can be misleading as an indicator of model accuracy. Confidence in the accuracy of model predictions can be no greater than the confidence in the data with which the model is evaluated.

Material and energy balances are the typical engineering methods used to verify that experimental data satisfy energy and mass conservation laws. Data reproducibility is useful for gaining confidence that operating conditions or measuring apparatus have not changed over the course of an experiment. Multiple measurements also permit greater confidence to be placed in data based on statistical criteria. Error analysis should be part of any experiment. At least part of any error analysis should be done by those most familiar with an experiment since they have the best chance of identifying non-random errors caused by changing operating conditions, equipment malfunction, etc. Even an engineering estimate of the magnitude of any possible errors is helpful for others who use experimental data at a later time based solely on reported values.

2.2.2 Minimum Specifications

Meaningful model predictions of a furnace requires that varying degrees of information be supplied to the computer code describing the operation and furnace characteristics, such as the geometry of the furnace, the fuel flow rates and compositions, and the wall temperatures. Some information, such as fuel flow rates, is critical for meaningful calculations to be performed, while other less critical facts, such as wall temperature profiles, can be estimated without seriously degrading the model predictions. The input requirements for the code specify the variables that the model uses. All variables must have values supplied for the code to function properly. Table 2.8 lists the variables required for the three-dimensional code. Variables required for the cold-flow parts of the code were supplied by Gillis (1989). The combustion-related variables were taken from the user's manual for PCGC-2 (Smith and Smoot, 1982). The two-dimensional variables will be similar for the three-dimensional code. Each variable is ranked as "Required" or "Estimate", with the former meaning the variable must be correctly specified for meaningful modeling results to be obtained, and the latter meaning that the variable can be estimated without making the predictions meaningless. In the next section, the data sets are evaluated for completeness of several types of input parameters. Data sets missing essential information received low scores and were eliminated from consideration. Some essential variables may only be partially specified, but have enough information given to permit estimation of the parameter. For example, a case may specify the coal flow rate, ultimate analysis, and stoichiometric ratio without specifying the air flow rate. However, with this information, the approximate flow rate can be estimated by calculating the quantity of air required to provide the specified stoichiometric oxygen. A measured flow rate would be preferable to an estimation, but the latter is acceptable. The inability to estimate accurately a key parameter would make the data set unacceptable.

2.2.3 Data Selection

Each of the data sets listed in Table 2.7 were rated on a scoring system of zero to three, with three being the best, for each of the selection criteria. By scoring the different criteria, sets that were deficient of key information were identified and eliminated from inclusion in the data book. The scores of one, two, and three were based on the following criteria. A three

Table 2.8
Input Parameters and Required Detail for Three-Dimensional Combustion Code

<u>Input Parameter</u>	<u>Detailed Specification</u>
diameter of primary streams	Required
diameter of secondary streams	Required
dimensions of chamber	Required
flow rates of primary streams	Required
flow rates of secondary streams	Required
density of primary streams	Estimate
density of secondary streams	Estimate
turbulent intensity of primary streams	Estimate
turbulent intensity of secondary streams	Estimate
swirl number of primary streams	Required
swirl number of secondary streams	Required
location of inlets and outlets	Required
laminar viscosity	Estimate
absolute pressure	Estimate
velocity profile at inlets (optional)	Estimate
injection angle for secondary stream	Required
fuel composition	Required
wall emittance	Estimate
particle swelling parameter	Estimate
number of particle sizes	Estimate
particle composition	Estimate
solids loading in primary stream	Estimate
solids loading in secondary stream	Estimate
wall temperatures	Estimate
thickness of tube walls between primary and secondary streams	Estimate
outlet gas temperature approximation	Estimate
primary gas stream temperature	Estimate
solids temperature	Estimate
secondary gas stream temperature	Estimate

"Required" means that detailed information must be provided for meaningful model calculations to be made. "Estimate" means that a good estimate will be sufficient for modeling purposes. A parameter that is specified as "Estimate" would still be better for modeling purposes if the information were specified exactly.

score indicates that the essential information for that category was completely and explicitly specified. No estimations of essential parameters is required for model input. A two score means that all essential data are either explicitly given or enough alternative information was given so that key input parameters could be estimated with satisfactory confidence. A score of one means that some information was available but not sufficient for supplying key input parameters. A zero means no information was available. Some sets which are not listed in Table 2.7 (see Appendix F) failed a pre-screening evaluation to eliminate sets that were obviously unacceptable because of wrong geometry, no data given,

etc. Data sets that could not be readily classified as unacceptable were evaluated further using the selection criteria.

A score of one or zero for any of the first four categories (boundary conditions, inlet conditions, specified three-dimensional dimensions, and specified test conditions) eliminated the data set from further consideration. A score of two or three was deemed acceptable since this score indicated that enough information was available to permit modeling parameters to be input to the computer program. Any data case (of the six cases remaining after assigning scores for the first four categories) with a two or three for profile data was acceptable for the data book. A score of two or three for effluent data was acceptable only if the parametric data score was also a two or three. Effluent data for a single operating condition was not acceptable. The cumulative score for each data case was not a critical factor for accepting a data set. A cumulative score of 10 was the minimally acceptable score given that the key categories had sufficient information. Scores higher than ten were possible for data sets that would have been unacceptable. For example, if a data set had detailed profile data, effluent data, and parametric data in a completely specified three-dimensional geometry, but zeroes for boundary conditions and inlet conditions, the score would be over ten, yet the data set would be unacceptable. Cumulative scores could have been used to choose the best case from among several cases with similar characteristics. However, given the limited number of data cases obtained, there was no need to choose between similar cases. The remaining sets with scores less than two for both profile data and effluent data were also eliminated.

Six data sets were found to be sufficiently documented to meet the required data-selection criteria. Two of the data sets are for cold flow, one for reacting gases, and three for pulverized-coal combustion. Each data set consists of one case or operating condition, except for the reacting-gas case, which includes a parametric study utilizing various firing port configurations and fuel staging to control NO_x emissions. Since it was the only reacting gas case of marginal completeness, the reacting-gas data set was included in the data book even though its score for inlet conditions and geometry were below three.

During data set scoring, engineering judgement was used to avoid being overly critical and thereby eliminating all the data because of less than ideal data quality and completeness. This approach was necessary since none of the data sets presented adequate information on accuracy of the data. Because of the great expense and time to obtain large-

scale three-dimensional data, few measurements were ever repeated during the course of an experiment. Energy and material balances were not complete or not considered in any of the data sets obtained. Accuracy was not a major factor for data selection since questions regarding accuracy were applicable to all of the data considered. If cases were eliminated because of a lack of information about accuracy, no cases would have been selected. Assessment of data reliability and accuracy should be a high priority in future large-scale, three-dimensional measurements.

2.3 Data Cases Selected

2.3.1 Introduction

Six data sets were chosen for use in the data book. These sets had at least the minimum required input information based on the data selection criteria. Table 2.9 summarizes the types of data included by furnace type, rated capacity, firing method, etc. Table 2.10 summarizes the operating conditions represented in the data book. Each of these sets is described below. Three-dimensional perspectives showing the coordinate system for each furnace is shown in Figure 2.2. Drawings and dimensions for each data case selected are given in both the 3-D data book (Phillips and Smoot, 1989) and this thesis. The detailed data from each case are given only in Phillips and Smoot (1989).

2.3.2 Cold Flow

Case A1. - CE/EPA (Koucky, 1988)

The first cold flow data set in the data book comes from an Environmental Protection Agency study performed by Combustion Engineering, Inc. (CE). The main objective of the study was to develop design criteria for the injection of dry sorbents into tangentially-fired furnaces for the control of sulfur oxides emissions. A small part of the study was to physically model CE's Boiler Simulation Facility (BSF) using a geometrically-scaled flow facility. The purpose of the cold flow test was to determine the best locations, based on flow patterns and velocities, to inject sorbents into the BSF.

Combustion Engineering used their Large Scale Furnace Aerodynamics Test Facility (LSFATF) for the cold-flow studies. The LSFATF was geometrically scaled (using a scaling factor of 0.46) to model the entire BSF furnace from the hopper bottom to the economizer outlet. The model was built mainly of plexiglas to permit flow visualization.

Table 2.9

Description of Cases Included in Data Book

In the Case column, each data set is given an identification code used in the remainder of the report in place of the name and reference. The letter in the ID represents either: A - Cold Flow, B - Particle Ladened Cold Flow, C - Reacting Gases, D - Pulverized-Coal Combustion, and E - Entrained-Coal Gasification. The number in the ID represents different cases within the same type of data (ie. cold flow, reacting gases, etc.).

Case	Location	Capacity (MWe)	Firing Configuration	No. of Burners	Width, Depth, Height, (m)	Heat Release /Volume, (MW/m ³)	Inlet Flow Type	
							primary	secondary
A1. CE/EPA (Koucky, 1988)	Windsor, CT	NA	tangential corner fired	4	1.55, 1.32, 5.40	NA	air	air
A2. Consolidation Coal Company (Havekotte, 1987)	Library, PA	NA	wall fired	4	restricted	NA	air/CO/CO ₂	air
C1. Institute of Gas Technology (Abbasi, 1983)	Chicago, IL	0.6 thermal	end fired	1	1.37, 4.27, 0.914	0.207	natural gas	air
D1. Consolidation Coal Company (Havekotte, 1987)	Library, PA	0.44 thermal	wall fired	4	restricted	0.126	Northern West VA. bitum. coal	air
D2. Coneville (Cetegen, 1985)	Coshocton, OH	420	tangential corner fired	20 - 5 levels per corner	15.8, 13.4, 51.2	0.167	High volatility bitum. coal	air
D3. Duck Creek (Cetegen, 1985)	Canton, IL	420	wall fired	24 4 rows of 6 burners each	16.8, 11.6, 50.4	apprx. 0.27	Crown II mine bitum. coal	air

Table 2.10
Summary of Test Operating Conditions for Data Book Cases

Case	Load (MW)	Stoich. Ratio	Fuel Flowrate (kg/s)	Primary Air Flowrate (kg/s)	Secondary Air Flowrate (kg/s)	Windbox Air Temp. (K)	Theoretical Swirl Number
A1. CE/EPA (Koucky, 1988)	NA*	NA	NA	9.5	NA	297	0
A2. Consolidation Coal Company (Havekotte, 1987)	NA	NA	NA	0.0301	0.192	373	3.0
C1. Institute of Gas Technology (Abassi, 1983)	0.60 (thermal)	1.11	0.0106	0.198	NA	1439	0
D1. Consolidation Coal Company (Havekotte, 1987)	0.60 (thermal)	1.41	0.0104	0.0228	0.134	617	3.0
D2. Coneville (Cetegen, 1987)	405 (electrical)	1.21	42.1	78.36	334.5	593	0
D3. Duck Creek (Cetegen, 1987)	385 (electrical)	1.18	42.8	57.46	367.8	1057	1.0

*NA = not applicable

Figure 2.2

Three-Dimensional Perspectives of the Five Furnaces Included in the Data Book. The furnace drawings are not to scale. Each furnace drawing is superimposed on an X-Y-Z coordinate system. The coordinates are used to identify measurement locations and geometrical features in the furnaces. The information for the furnace drawings came from the sources listed with the furnace names above. Additional furnace information is available in the appendices.

The inlet and outlet ductwork were made of sheet metal. All upper furnace heat transfer surfaces were fabricated using masonite and wood dowels. A large FD fan capable of 850 m³/min provided air to the inlets. The fan was equipped with a control damper and flow measurement instrumentation.

An automated transversing system capable of placing instrumentation around or within the model surrounded the flow facility. For the cold flow testing, a calibrated, commercially available five-hole pitot tube was used to measure three-component velocity vectors. The pitot tube was operated using the transversing system. A computer program controlled the pitot tube spatial position and axial position. The computer caused the pitot tube to be rotated until maximum pressure differences were detected indicating that the probe was positioned correctly. The data were automatically read into a computer for further processing. The drawings, dimensions, and detailed data are given in Appendix A.

Case A2.- Consolidation Coal Company (Havekotte, 1988)

The second cold flow data set was obtained from Consolidation Coal Company. It is fully documented in Appendix A. The facility was Consolidation's pilot-scale combustor. For proprietary reasons, Consolidation Coal Co. has requested that some information about their furnace, specifically the detailed geometry and dimensions, be restricted from publication. Because of the overall lack of available data, the Consolidation Coal Company data set was included in the data book, although it cannot be modeled as given. However, the data provide useful information about cold flow in a pilot-scale furnace. Enough information is provided to allow modelers to determine if the data merit contacting Consolidation Coal Company for the missing information. The drawings of the furnace included herein have all dimensions in dimensionless units from 0 to 1. Except for the scarcity of quality data for model evaluation, the restrictions on publication of furnace details would have eliminated the use of this data set.

Two types of measurements were taken: velocity and gaseous concentration. A CO/CO₂ tracer gas was injected through three of the four burner inlets. Gases exiting from the secondary inlet tubes had reported swirl numbers of 3.0. At each measurement location, a gas sample was taken for analysis, and the velocity was measured using a pitot tube.

2.3.3 Particle Ladened Cold Flow

No data were available for this category.

2.3.4 Reacting Gases

Case C1, the only case available using reacting gases, was a study conducted by the Institute of Gas Technology for the Gas Research Institute (Abbasi, 1983). The purpose of the experiments was to provide data that would help industrial, glass-related companies to reduce NO_x emissions from natural-gas-fired melters. The experimental parameters were different firing methods, different inlet fuel velocities, and different stoichiometric ratios. The measured data were essentially NO_x emissions at the furnace outlet and temperatures along the roof and walls. Heat loads were also measured using water-cooled heat exchangers located in the floor under a layer of molten glass, refractory brick, and silica sand. The multi-layer floor set-up was made to simulate a molten glass flow through a melter furnace.

The tests were conducted in a 4.22 m^3 pilot-scale furnace using flat-floor and inclined-floor firing ports with a firing rate of approximately $590,000 \text{ J/s-m}$. Only the data set using the flat-floor port were included in the Data Book. The combustion air was approximately 866 K . Drawings, dimensions, and data are found in Appendix C.

2.3.5 Pulverized-Coal Combustion

Case D1. - Consolidation Coal Company (Havekotte, 1987)

The first data set for pulverized coal combustion was provided by Consolidation Coal Company. Restrictions on detailed disclosure of the Consolidation furnace dimensions apply to this data set. As discussed in the section for Case A2, the restricted data were included in the data book to allow potential users to know of their existence and to allow them to decide if the data merit pursuing from Consolidation Coal Company. Regardless of the detail given, the data provide useful information about coal combustion in a pilot-scale furnace.

The coal used in this test was from northern West Virginia, ground on site to nominal power generation size. The furnace was allowed to heat up using natural gas, followed by coal feed when the wall temperatures reached 1089 K . The furnace operated for 24 hours to reach a steady-state condition.

Data measurements were taken over a three-day period. Velocity measurements were taken using one of three different sizes of pitot probes, depending on the velocity. The gas temperature was taken using a shielded thermocouple. Gas and particle samples were taken using a water-cooled probe. The data measurements taken were velocity, temperature, O_2 , SO_2 , NO_x , CO, and CO_2 gas concentrations. Unrestricted drawings, dimensions, and data are included in Appendix C. Restricted information is available only by permission of Consolidation Coal Company.

Case D2. - Coneville (Cetegen, 1985)

The Coneville boiler (unit 5) is a 420 MW_e, tangentially-fired electricity generating station placed in service in 1978 and located near Coshocton, Ohio. The furnace was built by Combustion Engineering, Inc., and the owner is American Electric Power Corporation. The furnace has five burner levels with each burner set located in a corner of the furnace. The alignment of the burners is such that the fireball rotates counter-clockwise when viewed from the top of the furnace. In normal operation, only four burner levels are used, and the nominal full load output is 405 MW_e. The boiler is capable of producing 1.4 million kg/hr superheated steam at 175 atm and 813 K.

Gas temperatures were measured with a suction pyrometer, and velocity was measured using a two-hole impact probe. Radiative heat flux incident to furnace walls was measured using an ellipsoidal, total radiation pyrometer, and gas species concentrations were measured using continuous monitors. Drawings, dimensions, and data are given in Appendix D.

Case D3 - Duck Creek (Cetegen, 1985)

The third set of pulverized coal combustion data comes from a large study funded by the Environmental Protection Agency and performed by Energy and Environmental Research Corporation (EER) of Irvine, California. The primary objective of the study was to investigate the adequacy of a modeling approach to predict boiler thermal environment and flow field. Two full-scale furnaces were used to collect data for use in evaluating EER's three-dimensional General Boiler Thermal Analysis Code (GBTAC). Although five different operating conditions were used during the study of the wall-fired boiler, only one of the sets of data had sufficient information to be included in the data book. Measurements

at the other operating conditions were sparse and the inlet conditions were incompletely documented. For example, Case 3 of the EER study was at reduced coal-firing load with a detailed test measurement matrix. The amount of air introduced into the fire box was unknown because of leaks in the air registers that were closed for the burners that were not being used at reduced load. A significant amount of air entered the furnace and altered the expected stoichiometric ratios at each burner. The uncertainties introduced because of leaks makes use of this case for model evaluation unacceptable.

The data case being described in this section came from study of the Duck Creek Unit 1 boiler owned and operated by Central Illinois Light Company (CILCO). Unit 1, built by Riley Stoker Corporation, is a 420 MW_e boiler located near Canton, Illinois. It is front-wall-fired with 24 burners arranged in four rows of six burners each. The burners are supplied with pulverized coal from three Riley Stoker, low-speed, ball-tube mills.

Super-heat and reheat cycles capable of producing 1,363,600 kg/hr of steam at 178 atm were used for steam generation. Both super-heater and reheater were designed to produce steam at 813 K. The coal burned in Unit 1 is high-volatile bituminous coal with approximately 4 percent sulfur. The coal was mined in the Crown II mine in Illinois.

Gas temperatures were measured with a suction pyrometer, and velocity was measured using a two-hole impact probe. Radiative heat flux incident onto furnace walls was measured using an ellipsoidal, total radiation pyrometer. Gas species concentrations were measured using continuous monitors. The drawings, dimensions, and detailed data are available in Appendix D.

Section 3

Data Evaluation

3.1 Introduction

Section three is an evaluation of the data in the data book. First, an evaluation of the general characteristics of the data is given. Included in this analysis are the types of facilities, the measurements, and the operating conditions for data which are included. The second subsection gives a case-by-case general characterization of the physical and chemical aspects of the data in the data book. Characterization of the data includes key observations and trends in the data, ranges of temperatures, velocities, and other general information.

The third subsection provides an evaluation of the accuracy of the data based on analyses given with the original data source and independent analyses performed as part of this project. Indicators of data accuracy such as material balances are presented, and their significance to the quality of the data base is discussed. Finally, the section concludes with a discussion of the limitations of the data in the data book as well as with combustion-related data in general. Future data needs and suggestions for prioritizing data measurements are given.

3.2 General Characterization of the Data

The three-dimensional data book is incomplete in that it does not include data from all the categories that are desired. Of the five classes of data listed in Table 2.1, only non-reacting gaseous or liquid flows (cold flow), reacting gases, and pulverized-coal combustion data are represented. The other two classes of data were not available in a form adequate for use in the data book.

Each data set selected for use in the data book is relatively complete in comparison to the list of required information for the computer code input values. Table 3.1 shows how each case compares to the input parameter list.

3.2.1 Furnace Characteristics

Both cold-flow cases (A1 and A2), the reacting gas case (C1), and one coal combustion case (D1) are from pilot-scale facilities (see Tables 2.9 and 2.10). Cases D2 and D3 were

from large-scale, commercial utility furnaces. The range of furnace volumes varies from about 3.7 m³ to over 2800 m³, an 800 fold increase. Although the furnace sizes vary greatly, the volumetric firing rates varied only from 124,000 J/s-m³ up to 207,000 J/s-m³. Firing rates did not correlate to the furnace size; the two smallest furnaces had the largest and smallest firing rates of the four coal combustion furnaces.

Table 3.1
Comparison of Code Requirements to Data Set Variables.
Specified = S, Calculated from Specified Information = C,
Estimated = E, or Not Applicable = NA

Input Parameter	Detailed Specification	Case Identification					
		A1	A2	C1	D1	D2	D3
diameter of primary streams	Required	S	S	S	S	S	S
diameter of secondary streams	Required	S	S	S	S	S	S
dimensions of chamber	Required	S	S	S	S	S	S
flow rates of primary streams	Required	S	S	C	S	E	E
flow rates of secondary streams	Required	NA	S	NA	S	E	E
density of primary streams	Estimate	C	C	C	C	C	C
density of secondary streams	Estimate	C	C	C	C	C	C
turbulent intensity of primary streams	Estimate	E	E	E	E	E	E
turbulent intensity of secondary streams	Estimate	E	E	E	E	E	E
swirl number of primary streams	Required	S	S	S	S	S	S
swirl number of secondary streams	Required	S	S	S	S	S	S
location of inlets and outlets	Required	S	S	S	S	S	S
laminar viscosity	Estimate	E	E	E	E	E	E
absolute pressure	Estimate	E	E	E	E	E	E
velocity profile at inlets (optional)	Estimate	E	E	E	E	E	E
injection angle for secondary stream	Required	S	S	S	S	S	S
fuel composition	Required	S	S	SE	S	S	S
wall emissivity	Estimate	NA	NA	E	E	E	E
particle swelling parameter	Estimate	E	E	E	E	E	E
number of particle sizes	Estimate	NA	NA	NA	S	E	E
particle composition	Estimate	NA	NA	NA	S	SE	SE
solids loading in primary stream	Estimate	NA	NA	NA	S	S	S
solids loading in secondary stream	Estimate	NA	NA	NA	S	E	E
wall temperatures	Estimate	NA	NA	S	S	E	E
thickness of tube walls between primary & secondary streams	Estimate	NA	S	NA	S	NA	S
outlet gas temperature approx.	Estimate	NA	NA	S	S	S	S
primary gas stream temperature	Estimate	S	S	S	S	S	S
solids temperature	Estimate	NA	NA	NA	S	S	S
secondary gas stream temp.	Estimate	NA	S	NA	S	NA	S

Tangentially-fired and wall-fired furnace models were used in the cold-flow cases. Tangentially-fired, wall-fired, and end-fired furnaces were used in the combustion furnaces. Overall, a wide variety of furnace types and sizes are included in the data book.

3.2.2 Fuel Characteristics

The reacting-gas case (C1) used natural gas as the fuel. The specific breakdown of the gas composition was not given and must be estimated from "typical" natural gas. Coal types used in the three pulverized-coal data sets were Northern West Virginia coal (D1), and high volatile bituminous coal from the Crown II mine in Illinois with approximately four weight percent sulfur in Case D2. The source of the bituminous coal used for Case D3 was not given; however, the chemical analysis of the coal is provided. The fineness of the coal was approximately 70% through 200 mesh for all three cases. Particle size distribution was available only for Case D1.

3.2.3 Test Conditions

Table 2.10 summarized the operating conditions represented in the data book. For the two cold flow sets, the total air flow rates range from 0.22 kg/s up to 9.5 kg/s, greater than an order of magnitude difference. The flow patterns in the two cases are vastly different since one case is wall-fired and the other is tangentially fired. The reacting gas case, being a parametric data set, includes several operating conditions where a single parameter was chosen for study over a wide range of conditions. The cases were chosen so that the trends could be deduced from the data. For example, if eight cases were run over a range of inlet velocities, only three or four cases were selected from across the range. Some of the test conditions include varying the side-of-port firing angle, injection velocities, and fuel port type. The pulverized-coal cases span a large range of operating conditions. The wall-fired Duck Creek furnace (D2) and Coneville furnace (D3) loads are over 600 times greater than the pilot-scale case from Consolidation Coal Company (D1). Although the loads are different, the stoichiometric ratios are between 1.18 and 1.4, and the volumetric firing rates differ by only 30 percent. The fuel and air flow rates are approximately the same for the two full-scale facilities, even though the firing methods are different. As expected, the full-scale furnaces have much greater flow rates than the pilot-scale furnace. However, the average inlet velocities are similar.

The Case D3 uses cornered-fired inlets to create essentially one large swirling fire ball around the inside of the fire box. The two wall-fired cases both use swirling secondary flows to stabilize the flame for each burner. The large fire ball is formed from the combination of each flame created at each burner. The swirling flow from each burner is in the same direction (clockwise) in the Consolidation Coal case (D1). The swirl is alternated from clockwise to counter-clockwise across a row in the Duck Creek furnace (D2). Essentially, each burner has a swirl direction that is counter to every burner adjacent to it.

3.3 General Aspects of Data Book

None of the data sets in the data book are as complete or comprehensive as desired. The most complete data sets are the two cold-flow cases. The relative ease of collecting cold-flow data in a pilot-scale facility made extensive data collection more feasible compared to pulverized-coal combustion in a large furnace. However, the two cold-flow cases are limited to a single operating condition. A parametric study varying the flow rates, the number of inlets being used, or the swirl number would enhance the value of the data for evaluating the cold-flow capability of combustion computer codes over a range of conditions.

Case C1 includes the most operating conditions in a single furnace. Unfortunately, the measurements were limited mainly to effluent-type NO_x data and wall temperatures. Profile data would have enhanced the value of this data set for the purpose of model evaluations.

Case D1 from Consolidation Coal Company is the most complete data set of the three sets in this data class. This case includes particle analysis at locations throughout the furnace as well as wall temperatures at varying depths into the furnace walls. The extent of completeness of Case D1 data can be attributed to the careful design of the furnace, which was intended for taking experimental measurements. While useful for evaluating the combustion model, Case D1 has too few data points to fully characterize the flow throughout the furnace or across a single plane. No points were sampled in the burner regions.

Case D2 and Case D3 data are less comprehensive than the data in Case D1. Many important facts about the boundary conditions, such as wall temperatures, must be

estimated since the furnaces were not designed to measure conditions in walls. Another problem with the data is the number of measurement locations. Because of the large size of the furnace, many locations were either inaccessible, or because of cost restraints, not included in the test location matrix resulting in many parts of the furnace being uncharacterized.

3.4 Key Observations

3.4.1 Cold Flow

Case A1

On the lowest measurement level, below the burners, the vertical component of flow is downward near the front and rear walls and upward in the center of the furnace (Figure 3.1). The center of the furnace is approximately in the center of the rotating flow pattern (Figure 3.2).

By the third level, which is located slightly more than fifty percent of the distance from the bottom to the top of the furnace, a vertical recirculation pattern has developed again in the left and right rear corners of the furnace (Figure 3.3). The flow pattern in the left rear corner appears to have a horizontal component of circulation also (Figure 3.4).

The extreme change in vertical flow along the back wall from positive to negative could cause a significant error in mass balance calculations if it were undetected because of a smaller test location matrix. For example, if the measurement matrix had been limited to locations between 0.2 to 0.8 (normalized) in both of the two horizontal dimensions, the recirculating flow would have been missed. The calculated flow rate passing through the plane would therefore be too large. The importance of the test location matrix for calculating material balances is discussed in the data accuracy section.

Test plane number 7 is the last measurement location in the exhaust duct. By this location in the furnace, the axial flow is fairly uniform across the duct. However, as discussed later, the material balance calculations for test plane 7 give flow rate values approximately 30 percent higher than expected.

Case A2

The Consolidation Coal Company data represent another cold-flow case. The inlet gases have high swirl numbers and high inlet velocity which result in several areas with

Figure 3.1

Case A1 - 3-D Surface Plot of Axial Velocity at Level 1

Three-Dimensional Surface Plot of Axial Velocity in the X-Y Measurement Plane at Level 1 ($Z=0.174$) for Case A1. See Figure 2.2 for the Correct Furnace Orientation in Relation to the X-Y-Z Axes. The X, Y, and Z Axes are Normalized by the Furnace Width, Depth, and Height, Respectively.

Figure 3.2

Case A1 - Velocity Vectors in X-Y Plane at Level 1

See Figure 2.2 for the Correct Furnace Orientation in Relation to the X-Y-Z Axes. The X, Y, Z Axes are Normalized by the Furnace Width, Depth, and Height, Respectively.

Figure 3.3

Case A1 - 3-D Surface Plot of Axial Velocity at Level 3

Three-Dimensional Contour Plot of Axial Velocity in the X-Y Measurement Plane at Level 3 ($Z=0.563$) for Case A1. See Figure 2.2 for the Correct Furnace Orientation in Relation to the X-Y-Z Axes. The X, Y, and Z Axes are Normalized by the Furnace Width, Depth, and Height, Respectively.

Figure 3.4

Case A1 - Velocity Vectors in X-Y Plane at Level 3

See Figure 2.2 for the Correct Furnace Orientation in Relation to the X-Y-Z Axes. The X, Y, Z Axes are Normalized by the Furnace Width, Depth, and Height, Respectively.

recirculating flows. However, the flow spreads quickly to fill the combustion chamber, resulting in low-velocity flow of less than 0.8 m/s in the vertically upward direction (Figure 3.5).

The concentration data indicate that the tracer gas introduced to the furnace through the primary inlets mixes rapidly so that the profiles are essentially flat across the furnace chamber.

3.4.2 Reacting Gas Combustion

Case C1 provides only effluent values, which were varied together with selected key parameters. The primary effluent measurements for case C1 were gas species, temperatures, and heat flux. The heat flux through the glass load was measured indirectly by measuring the change in water temperature through heat exchangers buried under refractory and molten glass on the furnace floor. At each of the test conditions, CO levels generally remained at less than 50 ppm, indicating independence from injection velocity (Figure 3.6). However, NO_x emissions decreased from 2590 ppm at the highest velocity down to 860 ppm at the lowest injection velocity. Changes in NO_x concentration at low injection velocities was more sensitive to injection velocity changes than at high injection velocities.

Changing from an input velocity of 46 m/s to 15 m/s, a 66% change, decreased NO_x emissions by 50%. This compares to a 30% decrease in NO_x emissions when the injection velocity is decreased from 155 m/s to 52 m/s (a 66% change). The heat flux (Figure 3.7) and temperatures did not appear to change significantly with changes in injection velocity. Overall, the 67% decrease in NO_x emissions was achieved without adversely affecting the furnace operation.

3.4.3 Pulverized Coal Combustion

Case D1

On the first level, a recirculating flow pattern is evident with gases flowing upward on the left side and downward on the right side of the furnace (Figure 3.8). The temperature varies slightly across the test plane as seen in Figure 3.9. The mass-flux measurements, which correspond to locations with high velocities, are nearly an order of magnitude greater on the right side of the furnace relative to the middle and left side. The O_2 , CO_2 , NO_x , and SO_2 concentrations have relatively flat profiles across a test plane and vary little throughout

Measurement Level 3 ($Z=0.715$)

Measurement Level 2 ($Z=0.579$)

Measurement Level 1 ($Z=0.438$)

Figure 3.5
Case A2 - 3-D Surface Plots of Axial Velocity for Levels 1 to 3
 Axial Velocity, Three-Dimensional Contour Plots for all Three Measurement Levels in Case A2. See Figure 2.2 for the Correct Furnace Orientation in Relation to the X-Y-Z Axes. The X, Y, and Z Coordinates are Normalized by the Furnace Width, Depth, and Height, Respectively.

Figure 3.6

Case C1 - NO_x Emissions vs. Fuel Injection Velocity.
Emissions for Case C1 with side-of-port burner angle set to 45°. Excess oxygen was 2.5%. Data taken from Abbasi (1983).

Figure 3.7

Case C1 - Heat Flux through Floor vs. Distance from Burner.
Heat flux was measured using water-cooled heat exchangers under a layer of molten glass. Data were taken from Abbasi (1983).

Figure 3.8

Case D1 - Velocity Surface Plots for Levels 1 to 3

Vertical velocity profiles shown above for test levels 1 through 3 in the Consolidation Coal Company furnace are arranged from bottom to top, respectively. Levels 1, 2, and 3 correspond to elevations of 0.44, 0.58, and 0.72, respectively. See Figure 2.2 for furnace orientation relative to X-Y-Z coordinate system. The pattern on the surface plot is used to enhance the 3-D effect of the plot. Data for plots were taken from Havekotte, (1987).

Figure 3.9

Case D1 - Temperature Surface Plots Levels 1 to 3.

Temperature profiles shown above for test levels 1 through 3 in the Consolidation Coal Company furnace are arranged from bottom to top, respectively. Levels 1, 2, and 3 correspond to elevations of 0.44, 0.58, and 0.72, respectively. See Figure 2.2 for furnace orientation relative to X-Y-Z coordinate system. The pattern on the surface plot is used to enhance the 3-D effect of the plot. Data for plots were taken from Havekotte, (1987).

SO₂ concentrations have relatively flat profiles across a test plane and vary little throughout the furnace. The CO concentration appears to have the most variation of the measured gas species as shown in Figure 3.10. On the first level, two local maximums in the surface plot of the CO concentration are evident. The maximum CO concentration and CO variation across a test plane decreases on the two higher elevations in the furnace.

Case D2

The measurement locations in the Coneville case are so sparsely distributed that it is difficult to make any conclusions about spatial trends in the data. Peak velocities in the vertical direction (upward) varied from 15 m/s in the bottom half (radiant section) of the furnace to 24 m/s in the super heater area where the cross section is smaller.

Peak temperatures vary from 1733 K at the first test plane to 1903 K in the test level that is 50 percent of the distance from furnace bottom to top. At furnace levels above the radiant section and in the area of the heat transferring super-heater pendants, the temperature drops rapidly to as low as 905 K. In the higher levels of the furnace the O₂ concentration drops to between 0.4 percent and 4.6 as expected for the specified excess air. The overall CO peak is on the 38 m measurement plane where the concentration varies significantly across the plane from 281 ppm up to 8000 ppm.

Case D3

In the burner region of the furnace ($Z=0.075$) the peak temperature was 1573 K (Figure 3.11), and the peak velocity in the vertically upward direction was 7.6 m/s (Figure 3.12). The O₂ concentration appears to follow inversely with the temperature; high temperature locations have low O₂ concentrations. This is expected since areas with the highest temperatures should correspond to areas where the coal has consumed more oxygen in the combustion process. Pollutants are higher in the regions of lower O₂ concentration. This is also expected since the pollutants are by-products of the coal combustion process. NO_x does not follow the same trends as SO₂, CO₂, and CO. NO_x appears to follow changes in temperature only when the temperature was above approximately 1500 K. Since fuel-nitrogen is the dominate source of NO_x in coal combustion and is less dependent on temperature, this trend is not unexpected.

Figure 3.10

Case D1 - CO Concentration Surface Plots for Levels 1 to 3.

CO profiles shown above for test levels 1 through 3 in the Consolidation Coal Company furnace are arranged from bottom to top in the figure. Levels 1, 2, and 3 correspond to elevations of 0.44, 0.58, and 0.72, respectively. See Figure 2.2 for furnace orientation relative to X-Y-Z coordinate system. The pattern on the surface plot is used to enhance the 3-D effect of the plot. Data for plots were taken from Havekotte, (1987).

Figure 3.11

Case D3 - Temperature Surface Plot for Level 1.

Measured temperatures were taken where the peaks are. The flat area of the plot is where no measurements were taken. The coordinates are normalized by the width and depth of the furnace. See Figure 2.2 for the furnace orientation relative to the X-Y-Z axes. Level 1 corresponds to $Z=0.29$. Surface patterns on the plot are used to enhance the 3-D effect of the plot. Data for plot were taken from Cetegen, (1987).

Figure 3.12

Case D3 - Vertical Velocity Surface Plot for Level 1.

Measured velocities were taken where the peaks are. The flat area of the plot is where no measurements were taken. The coordinates are normalized by the width and depth of the furnace. See Figure 2.2 for the furnace orientation relative to the X-Y-Z axes. Level 1 corresponds to $Z=0.29$. Surface patterns on the plot are used to enhance the 3-D effect of the plot. Data for plot were taken from Cetegen, (1987).

3.5 Data Accuracy

3.5.1 Introduction

The accuracy of the data can be estimated by two methods. The first method uses the report from which each set of data is extracted. Each of the EER pulverized-coal data sets (Cetegen, 1985) had sections discussing possible sources of error and the estimated accuracy of the data based on the accuracy and precision of the measurement equipment. Consolidation Coal Company (Havekotte, 1987) reported material balance closure for ash and several other species as an indication of the data accuracy but lacked estimations of equipment accuracy and precision.

The second method used to estimate data accuracy are the mass balance calculations performed as part of this study. The calculations were based on experimental data and the specified inlet conditions. This method worked reasonably well for the cold-flow data sets. Data from Case A1 was extensive enough to allow calculations to be made with a high degree of confidence that any significant errors were not the result of the procedure. The remaining cases were subject to considerable estimation error because of the limited number of measurements taken in a single test plane.

The estimated accuracy of each data set is presented below using information from original reports as well as calculations performed for this work. Material balances were calculated for each of the data sets in essentially the same manner. The material balance is based on the concept that for a steady-state system, the mass flow rate entering a fixed volume must equal the mass flow rate leaving the volume, as shown by equation 1.

$$m_{in} = m_{out} \quad [1]$$

The steps to applying this equation to the various furnaces or flow models were (Figure 3.13):

- 1) select a control volume that just contains a measurement plane.
- 2) calculate the gas density at each measurement location using temperature and pressure measurements or estimations.
- 3) use either a trapezoidal or Simpson numerical integration technique to average the mass flux (velocity x gas density) data for each section of the plane. This smooths the data between measurement points.

Figure 3.13

Illustration of the Procedure Used for Estimating Material Balance across a Measurement Plane.

Four steps are used to estimate the material balance. The steps are numbered one through four above. Examples of the equations used to calculate the material balance are given in Appendix E.

4) multiply the average mass flux for each section by the area of the section. This gives the mass flow rate for the section.

5) total the mass flow rate for all sections to obtain the total mass flow for the plane.

The mass flow entering the fixed volume must equal the mass flow leaving the volume for test planes between the inlet and outlet of the furnace. The mass flow entering the volume is assumed to be the total mass entering the furnace less any material, such as bottom ash, that does not leave through the exhaust of the furnace. For systems with no mass accumulating in or leaving through the bottom of a furnace, the net mass flow passing through a cross-sectional plane below the inlet must be zero, provided there are no leaks or exhausts in the bottom of the furnace.

The detailed calculations of data accuracy are shown in Appendix E. The results of the calculations for each case are summarized in Table 3.2. The methodology used to estimate the mass balances is one of several methods that could have been used. Other methods may give different results depending on the degree of extrapolation or interpolation of the data. Typically, the more extensive the data, the better the estimation. Estimation methods may be subject to significant error. An estimation of the "goodness" of the material balance is given with each data case.

3.5.2 Cold Flow

Case A1

The CE/EPA cold flow data were measured as part of a larger study to determine the optimum sorbent injection location in tangentially-fired coal furnaces. The cold flow facility was a scale model of a tangentially-fired Boiler Simulation Facility (BSF) rated at 15 MJ/s. The purpose of the cold flow data was to estimate the flow patterns in the BSF. As such, there was no analysis of error for the cold flow data given in the report.

These cold-flow data consist of a large number of measurements across a plane compared to other data sets included in the data book. The extensive measurement grid used for taking these data provided for reliable material balance calculations to within the accuracy of the data since there are no large areas where the flow direction and magnitude were unknown. This is not to say that the data are accurate, only that calculations used to estimate the consistency of flow rates among test planes are based on a complete, comprehensive set of data.

Table 3.2
Estimations of Accuracy Based on Material Balances and Data

Case ID	Measurement Location	Measurement being Compared	Calculated from Data	Given*	% Difference
COLD FLOW					
A1. CE/EPA (Koucky, 1988)	level 1	total vol. flow, m ³ /s	1.57	0.0	NA
	level 2	total vol. flow, m ³ /s	10.0	8.0	25
	level 3	total vol. flow, m ³ /s	7.17	8.0	-11
	level 4	total vol. flow, m ³ /s	8.16	8.0	2
	level 5	total vol. flow, m ³ /s	10.7	8.0	34
	level 6	total vol. flow, m ³ /s	8.27	8.0	3
	level 7	total vol. flow, m ³ /s	10.5	8.0	31
A2. Consolidation Coal Company** (Havekotte, 1988)	level 1	total mass flow, kg/s	0.313	0.226	38
	level 2	total mass flow, kg/s	0.225	0.226	0.6
	level 3	total mass flow, kg/s	0.256	0.226	13
PULVERIZED COAL COMBUSTION					
D1. Consolidation Coal Company** (Havekotte, 1987)	level 1	total mass flow, kg/s	0.115	0.164	-30
		Carbon mass flow, kg/s	0.00643	0.00819	-22
	level 2	total mass flow, kg/s	0.0967	0.164	-41
		Carbon mass flow, kg/s	0.00542	0.00819	-34
	level 3	total mass flow, kg/s	0.0770	0.164	-53
		Carbon mass flow, kg/s	0.00429	0.00819	-48
D2. Coneville (Cetegen, 1987)	41.4 m	total mass flow, kg/s (no species flows avail.)	10.2	7.76	32
D3. Duck Creek (Cetegen, 1987)	37.9 m	total mass flow, kg/s	8.08	7.95	1.6
		Oxygen, kg/s	1.41	1.51	-6.7
		Carbon, kg/s	0.396	0.411	-3.7
		Sulfur, kg/s	0.0187	0.0371	-50
	44.7 m	total mass flow, kg/s	8.08	7.95	1.6
		Oxygen, kg/s	1.65	1.51	9.2
		Carbon, kg/s	0.450	0.411	9.5
		Sulfur, kg/s	0.0233	0.0371	-37

* - Values were either given explicitly in the source or estimates were made using related data such as coal feed rates and theoretical air.

** - These mass balance values differ from those determined by Consolidation Coal Co. (C.C.C.). C.C.C. used extrapolated values of velocities into regions where no data were available, based on curve fits to available data. In this study, average velocities in the region were used where no values were measured. The C.C.C. method provided improved mass balance agreement.

Measurement Technique. Measurements were made with a five-hole pitot tube operated by a computer-driven mechanical system. The computer was interfaced with the pitot tube pressure transducers. Based on formulas relating the pressure drop across the probe, the computer controlled the rotational position of the probe. All three flow vectors were calculated from the differential pressure readings. The computer-controlled system helps relieve the tedium of manual data collection and made possible the extensive data. The computer probably positions the probe as well or better than manual methods for positioning the probe in the "correct" position.

In spite of the sophisticated system for measuring velocity profiles, the system is still limited by the accuracy of the pitot tube. The pitot tube will have some effect on the flow of gases around it. Because of the geometrical relationships between probe angles and pressure drops used to calculate the three flow vectors, a small error in angular position of the probe can result in significant errors in individual velocity vectors. Frequency response in turbulent flows further limit the precision of the pitot tube. These sources of error, among other unknown errors, appear to be evident in the material balance calculations made for each of the seven test planes used in the study.

Material Balance. The data for this case are extensive enough to permit the material balance estimations to be made with a high confidence of being indicative of the data accuracy. Test planes one through three are located in the fire box region of the furnace where flow is expected to be strongly turbulent and non-uniform across the plane. Test plane one is below the inlets to the furnace and should therefore have zero net flow in the vertical direction. Calculations show that there was an overall error of $1.57 \text{ m}^3/\text{s}$ or about 16% of the inlet flow rate. The non-zero value indicates that vertical flow components were relatively greater in magnitude than the negative flow components. Since no leaks were mentioned in the report, it should be assumed that the error is due to the measurement technique, especially since the flow was likely to be very turbulent near the inlet. Test planes two and three had errors of 25 percent and -11 percent based on the total inlet flow of $8.0 \text{ m}^3/\text{s}$ given by Combustion Engineering (Table 3.2).

Higher locations in the furnace are expected to have more uniform flow patterns as the turbulence dissipates and the flow becomes more streamlined. Test plane four, located at

the furnace nose elevation, and test plane six, located at the uniform cross-sectional area of the exhaust duct, had agreement to within three percent of the reported inlet flow rates. The improved agreement may be attributed to the smaller cross-sectional test plane and more uniform flow. However, other areas where good agreement was expected proved otherwise. Test planes five and seven each had errors of over 30 percent. The flow may have been disturbed by the pendants hanging down in the duct affecting the measurements. Another possible reason could be that the reported inlet flow is closer to $9.9 \text{ m}^3/\text{s}$ instead of $8.0 \text{ m}^3/\text{s}$. Three of the planes (Table 3.2) are closer to the higher value. Another possible explanation is that none of the estimations are valid, and the excellent agreement on levels four and six were fortuitous.

Completeness and Reproducibility. Case A1 data are the most extensive cold-flow data available. The comprehensive coverage of each test plane eliminated the uncertainties caused by sparsely located measurements. No measurements were repeated to give an indication of repeatability of the data. The cold-flow data from the CE case are as good as can be expected for studies using a pitot tube and without taking several repetitions of the data to determine the statistical variation in the measurements. The furnace operating conditions appear to have been kept at steady-state conditions. The weakest part of the data-collection system appears to be the pitot tube. Higher spatial resolution would not yield much more information about the flow across a plane. The next step to better data would require non-intrusive techniques such as laser velocimetry methods.

Case A2

Measurement Technique. The Consolidation Coal Company cold flow data were taken with a pitot tube and a suction probe for measuring velocity and gas species, respectively. No indication of the accuracy or precision of the equipment was included in the report. Typically, the accuracy of pitot tubes depend on the resolution of the manometer or pressure transducer used to measure the pressure drop in the tube (Perry, 1973).

Material Balance. No indication of data accuracy was given in the cold-flow data report. The data calculations for material balances across a horizontal plane indicate errors of approximately 38 percent for the lowest plane immediately above the burner inlets, 1

percent at the second measurement level, and 13 percent at the top level. The excellent agreement at the second level is probably, to some degree, fortuitous considering the measurements were taken with a pitot tube in a low velocity flow field. A sufficient number of measurements was taken across a plane to make a reasonable estimate of the flow across the plane in the vertical direction. Each plane had a measurement density of 2.0 measurements per square foot of cross section which is much fewer than the CE data case (A1). The points are far enough apart that recirculating flows could have been missed, introducing significant error. Considering the relative good agreement of the estimations on the middle and top levels, it is estimated that the individual velocity data measurements are accurate to within the accuracy of the pitot tube, which is between ± 5 to ± 10 percent.

The Consolidation Coal Company data also included furnace mixing characteristics obtained by injecting tracer carbon monoxide through three of the four burners and measuring the CO content at each of the sampling locations. Material balance calculations across each of the measurement planes showed the amount of CO accounted for in the samples to be low, compared to inlet CO flow rates. Researchers at Consolidation Coal Company indicated that there was uncertainty in the CO concentration measurements because they were in the parts-per-million range and sensitive to error. Thus, CO mass balances are not reported. The procedure used to calculate the material balances is given in Appendix E.

Completeness and Reproducibility. The Consolidated Coal Company cold-flow data appear to be relatively complete. Fifteen measurements were taken on each level. None of the measurements were shown to be repeated in the source material. Data near the burners would be extremely useful.

3.5.3 Reacting Gases

Case C1 - Measurement Technique

The gas samples were taken with a water-cooled suction probe. The probe was heated at the cool end (the end outside of the furnace interior) to about 88 °C to prevent condensation. The gas samples passed through a millipore filter to remove solid particles and a Permapure dryer to remove moisture. Gas analyzers were used to determine the concentrations of oxygen, nitrogen oxides, carbon monoxide, and carbon dioxide. The

combustion air temperatures were measured upstream of the inlet port using a bare bead type-K thermocouple. Tests using water-cooled probes showed that radiation did not significantly affect the temperature measurements using an unshielded thermocouple in the small cross sectioned, heavily insulated air duct. Combustion gases in the furnace flue were measured using a suction pyrometer with a type-R thermocouple located within a ceramic radiation shield. Internal wall surface temperatures of the refractory were measured using ceramic-shielded type-R thermocouples mounted in the wall.

Case C1 - Material Balance

No information about flow rates exiting the furnace were given to allow overall material balances to be performed. The accuracy of the data can only be estimated. Much of the error is estimated to come from positioning the pitot tube in a turbulent flow field where large velocity and temperature gradients can cause significant sensitivity to probe orientation. Comparing the similar techniques used in cases C1 and C2, the measurement error is estimated to be the same in both cases. In case C2 the reported error is estimated to be better than ± 30 percent.

Case C1 - Completeness and Reproducibility

Multiple measurements were not taken at each operating condition to give any indication about reproducibility. However, since this data set is a parametric study, data trends are given for varying input parameters. Generally, the trends appear to correlate to the input changes, indicating that changes in data measurements are being detected, although there is no indication of data accuracy.

3.5.4 Pulverized Coal Combustion

Case D1

Measurement Technique. Data collection was made using a pitot tube for velocity, a water-cooled gas sampling probe for measuring gas concentrations, and a shielded thermocouple for measuring gas temperature throughout the furnace. Additional thermocouples were embedded in the walls to measure wall temperatures. The report gives no indication of the estimated error associated with these measuring tools.

Material Balance. The Consolidation Coal Company pulverized coal combustion data set specified all the inlet conditions in the original report. This provided a value for checking total flow rates through the furnace. Calculated mass flow rate varied from 0.115 kg/s (913 lb/hr) on level 1 (bottom level) to 0.077 kg/s (611 lb/hr) on the top level. These values for mass flow compare poorly to the given inlet mass flow rate of 0.168 kg/s (1329 lb/hr).

Assuming complete carbon burnout in the coal, the theoretical CO_2 concentration, assuming the amounts of carbon in the ash, CO gas, and soot are negligible, is 0.0305 kg/s (242 lb/hr) compared to the calculated value of 0.0231 kg/s (183 lb/hr) (-24 percent) on level 1 and 0.0156 kg/s (124 lb/hr) (-49 percent) on level 3. The data indicate that the first two assumptions are correct, and it is reasonable to expect only a small amount of carbon to be present in the soot relative to the total carbon entering the furnace. A carbon balance, neglecting carbon in soot but including ash and CO, estimated carbon to be -22 percent and -48 percent of the total carbon at the inlet for levels 1 and 3, respectively. The carbon balance agrees closely with the CO_2 balances.

As seen in Table 3.3, the ratio of level 1 measurements to level 2 measurements, and level 2 measurements to level 3 measurements, are typically between 1.2 and 1.4. The values for higher levels in the furnace are lower than the level below it by approximately 20 to 40 percent. Possible explanations for the trend to smaller values at higher levels are 1) that there is some systematic error in the data collection equipment, or 2) the operating conditions gradually changed from the initial operating conditions, or 3) the estimation method used here is inaccurate. The top radiant section, level 3, was tested on the first day, followed by the second and first levels on the second and third days of continuous operation, respectively. If the inlet conditions drifted over the course of the three operating days such that the air and/or fuel input increased, the differences between test planes could be accounted for, but would not account for the differences between reported inlet conditions and calculated material balances based on measurements. Since all the mass balances except for solids and ash depend on the velocity measurements, it is probable that the error is with the velocity measurement. The gas species mass flow rates vary directly with changes in the velocity. Mass flux values were measured independently of the velocity and permitted particle material balances to be calculated separately. Estimations for ash balance indicated values that were approximately 30 percent lower than the specified inlet amounts.

Table 3.3
Variations in Data between Furnace Elevations in Case D1

Measurement being Compared	Ratio of level 1 to level 2	Ratio of level 2 to level 3
Total Flow, kg/s	1.2	1.3
CO ₂ , kg/s	1.2	1.2
SO ₂ , kg/s	1.2	1.3
O ₂ , kg/s	1.1	1.2
CO, kg/s	1.7	2.0
NO _x , kg/s	1.3	1.3

Consolidation Coal Co. reported their own values for mass closure. For the most part, they obtained much better results for closure than were calculated for this report. The maximum error for closure reported by Consolidation Coal Co. was 119 percent for iron. Most other measurements were estimated to be within ± 10 percent. The discrepancy between the two sets of estimations is not surprising when comparing the methods used to estimate the balances. Consolidation Coal Co. used a different method than was used in the current study. A cubic spline was fit through the three data points in each measurement transverse of the furnace. The cubic equation was integrated for each transverse. The three resulting values were then fit to another cubic spline and integrated again to account for the other dimension. The spacing of the data in the furnace was such that the furnace was evenly divided into nine square sections. If a square were drawn through all the measurement locations closest to the walls, the area within the square would only represent 46 percent of the cross sectional area in the measurement plane. The other 54 percent of the area requires extrapolation of the data to estimate the flow rates and compositions. By using cubic splines, Consolidation Coal Company was able to make estimations of furnace flows in the outer region of the measurement plane which may explain the better agreement to specified values. The current method made no attempt to guess the flow patterns in unknown regions, but instead assumed that the average flow for the known areas extended into the unknown areas. More data across the plane, especially closer to the walls would be very useful for better predicting the flow across a measurement plane.

Completeness and Reproducibility. The Consolidation Coal Company data are the most complete of the pulverized coal data sets. This data set is the only pulverized coal data set that gives spatially resolved particle analyses. Although sparse in number, the test locations

were equally distributed across a test plane such that "blind spots" were reduced. Duplicate measurements were taken at the center location on each level to help verify the reproducibility of the data. Particle analysis showed that the particle composition changed little between original and duplicate measurements. However, some gas species changed significantly between repetitions, most notably CO which changed 42 percent between first and second measurements.

Case D2

Measurement Technique. Velocity direction and magnitude were measured using a pair of pressure taps located on opposite sides a water-cooled suction pyrometer probe. Gas analysis was performed using continuous emissions monitors. Details of the measuring techniques are given in volume 2 of Cetegen (1985).

Material Balance. The two pulverized-coal cases from EER had quality control methods implemented to achieve the highest quality data possible within the restraints of their budget and equipment. Neither case had estimates for error based on post-experimental calculations and data. By EER's own estimates, the velocity measurements are subject to a maximum of $\pm 30\%$ error. The large areas of furnace where no measurements were taken made it impossible to make accurate material balance calculations with any confidence. For example, on one test level measurements were taken on only one side of the radiant section in the furnace. The mass flux vertical to that plane can be calculated for the half with the measurements, but the other half could have flows that are negative because of recirculation, or flows that are positive. An estimate was made for the 41.4 m level assuming that the average flow rate calculated for the areas with data also applied to the areas without data. In the higher elevations of a full-scale furnace where turbulence has mostly dissipated, and away from wall boundaries that could cause recirculation, the assumption of average flow being equal across a test plane is probably fairly good. The calculated flow rate was 27 percent too high. It is within the estimated error of the velocity measurements.

The measurement techniques used in all of the data cases were with suction probes or pitot tubes. These measuring devices are known for their inherent error due to large fluctuations in the flow field, tips that plug with solids, non-isokinetic suction, and

disturbance of the flow field by introduction of the probe. In small-scale facilities often used in two-dimensional studies, the size of the probe is usually large relative to the cross section of the furnace. In a furnace with a 200 square meter cross section, a 0.10-meter diameter probe would be expected to have less influence on the overall flow field.

Completeness and Reproducibility. The locations of measurements in the furnace are sparse. Many test planes have all the measurements taken on one half of the furnace's cross section. This does not necessarily limit the data for use in evaluating the three-dimensional model, but it does limit the ability to determine data accuracy based on material balances across the entire plane. Great care was taken to keep operating conditions as constant as possible. Flue gases and particles were analyzed, and much of the raw data taken during the tests was included in the second volume of the report. The greatest inaccuracies in the data set are due to the unknown inlet conditions, such as measured gas and solids flow rates at each inlet, and a lack of details for the burner geometry.

The two-hole impact probe used in the study does not permit all three components of the velocity vector to be determined from a single measurement, therefore, only two components of the flow (one vertical and the other in one of the two horizontal directions) at any point were reported. None of the tests was repeated to determine the reproducibility of the data.

Case D3

Measurement Technique. The same techniques used in the Coneville tests apply to the Duck Creek test. A quality assurance program was used to minimize errors in the data. From Volume 2 of the original data source, most data measuring techniques for chemical analysis have errors less than 10 percent. The velocity data were estimated to be no worse than ± 30 percent. Temperatures were measured using a suction pyrometer with a suction velocity of 150 m/s or greater. Radiative heat flux was measured using an ellipsoidal radiometer. The estimated accuracy of the radiometer is ± 20 percent. The precision of all measurements, based on the capability of the equipment, was typically less than ± 1 to ± 2 percent standard deviation. Standard deviations from measurements were not reported but are probably much greater because of fluctuations caused by turbulence in the furnace.

Material Balance. No material balances were given in the original data source. Only limited calculations were possible because of the spatial distribution of measurements across any test plane. Two planes had sufficient data to make calculations for mass balance. The mass flow at the test plane at 37.9 m from the furnace base was only 11 percent lower than the inlet mass flow. The mass balance calculation at 44.7 m was 4 percent higher than the inlet flows. Inlet flows were not measured as part of the test but were calculated from coal flow rates and stoichiometric ratios. These flow rates were used to estimate the flow rates at each burner inlet.

Carbon, oxygen, and sulfur balances were calculated for the plane at 44.7 m. The percent difference between the given (calculated from inlet information) values and the values calculated from measurement data are 9, 10, and -37, respectively.

Completeness and Reproducibility. Specific information about the furnace was limited. The swirl level for the secondary stream was not given, although the angle of the swirl blades can be used to estimate the extent of swirl. Velocity profiles across inlets are unknown. There is a gas flow bias across each row of burners which is unknown. EER estimated the stoichiometric ratio for each burner from temperature measurements in the furnace. These estimations by EER were used to estimate the flow rates at each burner. This is a source of inaccuracy in the inlet conditions that cause the greatest concern about the suitability of the data for model evaluation. Wall temperatures are not known for the boundary conditions. The temperatures need to be estimated for modeling purposes.

In summary, the data measurements throughout the furnace and at the inlet are fairly complete. The inlet conditions are incomplete and create large uncertainty for accurate modeling of the furnace. Many of the conditions used in the data book were taken from the variables used by EER for their modeling work since they had the best understanding of what operating conditions were being used. Their estimates made from first hand knowledge of the furnace operation should be more reliable than estimates made subsequently from incomplete information. No repeat measurements were made to confirm reproducibility in the data.

3.6 Data Limitations

3.6.1 Non-steady State Conditions

One of the major problems with obtaining quality combustion data in large-scale systems is proper control of the operating conditions over the long periods during which data are taken. The inherent nature of combustion facilities is to vary over time, even at a single set of operating conditions. Fouling and slagging of wall and heat-transfer surfaces combined with periodic soot blowing of surfaces changes the radiation heat transfer as well as the heat transfer through the walls or super-heater platens with time. Natural variations in the equipment used to supply the furnace with coal, grind the coal, and move air through the wind box all add to process variation over time. Full-scale combustion facilities are typically operated 24 hours per day to avoid the inefficiencies of shut down and start up. During daily periods of low electricity usage, furnaces firing rates are decreased to lower the steam production rate. Changing the load conditions daily requires adjusting secondary-air registers, closing burner-air registers, and changing the overall operating conditions.

Measurements made at each test location can take over 30 minutes or more. Several days or weeks are required to take measurements from throughout a furnace, even for small-scale facilities. Establishing steady-state conditions is a problem as is determining how the data measurements change because of process variations. An engineer experienced with full-scale furnace operation suggested four hours as the longest period of time to consider furnace conditions as "steady" (Radulovic, 1989) unless a special effort is made by the furnace operators to hold conditions constant. Measurements taken at increasingly longer times during a test should be associated with the operating conditions prevalent during the data collection of those measurements.

The steady-state problem is resolved best in small pilot-scale or lab-scale facilities where the operating conditions can be more easily controlled and measured. The difficulty in collecting steady-state data increases as more burners are used and as the load varies frequently.

3.6.2 Access to Furnace Interior

Typical commercial furnace design is a major impedance to obtaining data over a wide area inside the furnace. Considering the size of a typical large-scale furnace (200 square

meter cross-section) it is obvious that probes must be very long to access the middle of the furnace. A long probe is very heavy and requires chains and other supports, as well as several people, to maneuver. Temperatures can reach 325 K (130 °F) in the walkways next to the furnace walls, making extended hours of work difficult or impossible. A small number of access ports limit the number of locations where a probe can be inserted. Furnace owners are not generally in favor of cutting new holes through the water-cooled walls to make a new port. Furnace access problems are essentially eliminated in pilot and lab-scale reactors since access is generally designed into the facility and measurement probes do not need to be big and bulky.

Access to furnace interiors can dictate to some degree the number of measurements that can be taken across a plane. Unfortunately, there is no set number of points that will necessarily give sufficient information for an accurate material balance. Three points correctly situated may in some instances give better results than ten points located in the wrong locations. The number of points needed to make calculations of material balances depends on the complexity of the flow which is generally unknown prior to testing. For example, a uniform flow through a duct would be accurately estimated with a single measurement point. Recirculating flow in the same duct may take a hundred points to accurately estimate. For making material balance calculations, it is useful if the end points of a measurement transverse of a plane include the areas near the walls. The flow is obviously zero at the wall but may become large at points near the wall. Measurements taken within the first and last ten percent of the furnace width are useful for improving the material balance calculations based on data. This provides information in the region closest to the walls that can make up the majority of the cross-sectional area. Often, recirculating flows will be next to walls. Missing information from this region can introduce large errors in material balance estimations. A possible useful approach to taking data would be to plan test location matrices based upon preliminary model calculations. Model predictions may show regions where more measurements would be useful for accurately predicting material balances. Areas where flow profiles are expected to be flat could be measured with one sample, and areas where flow is complex could have several closely-spaced locations sampled. Fortunately, for model evaluation, a material balance is not required to use the data.

3.6.3 Use of Non-Intrusive Probes

Radulovic (1989) states that one of the problems with measuring inlet conditions is the measurement probe. Suction probes and pitot tubes become easily plugged by the large amounts of solids present near the burners. Another problem is the intense heat that quickly destroys measurement probes. As mentioned previously, a probe inserted into a large furnace does not significantly affect the flow field in the furnace relative to the disturbances found in a smaller reactor caused by a probe. However, impact and suction probes are inherently poorer devices for measuring velocities, temperatures and other properties compared to advanced laser techniques. Properly orienting a probe in turbulent flows is difficult to do. Small variations in the probe angle can markedly change the measured value for the three components of flow. Errors in the velocity measurements make material balance calculations incorrect.

The problems with the various types of probes make use of non-intrusive methods, such as laser Doppler anemometry for velocities and Raman scattering techniques for species concentrations, more attractive. The major problems with the non-intrusive techniques are high relative cost for a system compared to probes, difficulty in using advanced systems (requires highly trained users), and inability to use laser techniques in full-scale facilities because of reduced optical path caused by soot and other particulates. Once again, the use of optical measuring techniques favor smaller facilities over full-scale facilities.

New methods for measuring properties in full-scale facilities need to be developed. Laser-based instruments may be able to solve part of the problems encountered in full-scale facilities. High costs and technical difficulties, such as gap breakdown along high-power laser paths, are involved in such testing. However, the advantages of taking data in a full-scale facility over using a pilot-scale facility may merit the effort. Better, less expensive methods need to be developed. A possibility may be probes that use optical methods with light signals carried over water-cooled fiber optics. Laser-based methods for particle velocity were applied with some success in the Goudy utility furnace tests (Cannon, 1989).

3.7 Data Needs

3.7.1 Perceptions on Availability of Combustion Data

Reviewing the state of combustion data in the literature and in project reports has led to definite perceptions regarding three-dimensional data needs in combustion facilities for

evaluating comprehensive, three-dimensional combustion models. The most important qualities that have been identified to be missing in data for both cold (non-reacting) flows and reacting flows are accuracy and completeness. There are two areas where complete information is lacking and yet of utmost importance: 1) profiles of velocity, concentrations, and temperature in the lowest part of the furnace (fire box), especially near the burners, and 2) detailed geometric data describing the furnace (walls, nose, intrusions, etc.) and burner (quarls, angle of tilt, etc.) configurations.

Most test matrices for taking combustion data that were reviewed appear to distribute the measurement locations throughout the furnace, starting at some point above the burners and moving up until the outlet is reached. Often, the distance between elevations is quite large such that a large proportion of measurements are taken in the upper half of the furnace. However, most of the "action" takes place in the lower half of the furnace. In the upper portions of the furnace, velocity, concentration, and temperature profiles are relatively flat and, in the case of velocity, parallel to the furnace walls. In the lower portions of the furnace, there are recirculation zones, swirling inlets, vigorous combustion, mixing, and large changes in species concentrations, temperatures, and velocities.

Incomplete furnace details make accurate predictions impossible to achieve with any confidence. For example, several burners tilted at 10° will change the flow pattern considerably in the fire box. Burners with quarls will behave differently from burners that are flush with the furnace wall. Without accurate inlet data such as measured swirl number and direction, velocity profiles at the inlet and fuel characteristics, it is impossible to accurately predict what will happen in the rest of the furnace. Therefore, at the present stage of model development, it is preferable to have complete, accurate data taken at one or two operating conditions rather than to have incomplete data taken at several conditions.

In light of the issues mentioned above, it is recommended that the majority of the measurements be taken in the half of the furnace nearest the inlets. The location and number of measurements taken on a given horizontal plane in the lower portion of the furnace should be closer together and more numerous than in the upper part. For example, if measurements are to be made at 50 locations throughout the furnace, perhaps 10 would be taken in the upper part and 40 taken at strategic locations throughout the lower section (not necessarily evenly spaced). Velocity profiles taken as near as possible to the burner outlets traversing the width of the furnace would be very useful in verifying the inlet conditions.

Measurement locations will most likely be restricted because of limited access to the inside of the furnace.

Detailed information about the furnace geometry and burner settings are needed to properly set the boundary and inlet conditions in the computer model of the furnace. Most of this can be provided from working plans used during design and construction of the furnace. Settings that are set according to the desired operating conditions must also be specified. These settings include items like burner tilt, over-fired air, flow rates, excess air, etc. To summarize, Table 3.4 lists characteristics of the furnace and operating conditions for each test that should be documented as completely as possible, when results are to be used for model evaluations.

Table 3.4
Operating Conditions Information Needed for Model Evaluation

1. Fuel Characteristics

- a. coal type, mine, and seam
- b. particle size distribution
- c. devolatilization rates (not often available)
- d. char oxidation rates
- e. proximate and ultimate analyses
- f. heating value
- g. ash fusion temperature

2. Furnace Specifications

- a. swirl number and direction at each burner inlet
- b. velocity profiles across inlets (not usually available)
- c. primary and secondary inlet temperatures, flow rates, compositions, solids loadings, overfire air rates, etc. for each burner
- d. detailed burner dimensions (primary and secondary)
- e. detailed burner positions and mounting (burner tilt, quarls, etc.)
- f. detailed dimensions of furnace including locations of intrusions (nose, inlets), wall materials and conditions
- g. wall temperature profile
- h. wall surface conditions
- i. initial turbulence intensity

3.7.2 Types of Data Measurements Needed

A long list of possible data measurements can be assembled. Table 3.5 lists four classes of data that would be useful for evaluating three-dimensional combustion models. Under each class of data (i.e. cold flow, particle-laden cold flow, gas combustion, pulverized coal combustion) are listed the types of data that are needed. Since funding may not permit every type of measurement to be made during a testing project, each data type has been ranked as to importance by the numbers 1, 2, and 3 (1 being most important and 3 least important) to help prioritize the measurements included in the test matrix. Quality data in all categories are needed. To help estimate the accuracy of the data taken during a test, measurements of several properties are needed to calculate material and energy balances. Measurements for mass balances include all inlet quantities and concentrations, quantity and analysis of bottom ash and fly ash, and quantity and concentration of gaseous products exiting the furnace. Energy balances require the same information as the mass balance in addition to the temperatures of all exiting materials. The steam quantity and properties are needed to account for energy leaving the furnace through water-cooled walls and superheater platens.

3.7.3 Particle-laden Cold Flow Data Needs

Particle-laden flow is very useful for evaluating the effects of solids on flow without chemical reaction, but somewhat impractical to obtain. Obtaining particle-laden flow data in large-scale facilities is difficult because of the problems involved with blowing coal dust throughout the facility and collecting it again in the air filters in the baghouse. Typical baghouse design is for collecting fly ash, which constitutes a small fraction of the coal particles entering a furnace, not tons of coal dust or other particulate material. The solids loading is therefore limited to a fraction of that found during typical operating conditions.

The problems associated with particle-flow data practically limit data measurements to small-scale facilities. The same data needs listed for non-reacting flow in Table 3.5 apply to particle-laden, non-reacting flow with the single addition of particle properties profiles as a high priority need.

Table 3.5
Types of Data Needed for Data Book for Evaluation
of Three-Dimensional Combustion Model

The following types of data are needed for evaluation of the 3-D data book. The data types listed apply to both single operating condition data sets as well as data sets taken for several operating conditions with one or more variables varied in a systematic manner.

A. Non-reacting Flow

1. Velocity Profiles 2. Concentration Profile (this requires that a known concentration and flowrate of some inert tracer such as CO₂ or CO be injected along with the gas).	3. Temperature Profiles (this measurement requires that inlet streams at widely different temperatures, one hot and one cold, be injected into the furnace).

B. Particle-Laden, Non-reacting Flow

1. Velocity Profiles 1. Particle Properties Profiles 2. Concentration Profile (this requires that a known concentration and flowrate of some inert tracer such as CO₂ or CO be injected along with the gas).	3. Temperature Profiles (this measurement requires that inlet streams at widely different temperatures, one hot and one cold, be injected into the furnace).

C. Gas Combustion

1. Velocity Profiles 1. Temperature Profiles 1. Wall Radiative (& Convective) Heat Flux	1. Concentration Profiles 2. Wall Temperatures 2. Effluent Temperature 2. Effluent Species Concentration

D. Pulverized Coal Combustion

1. Velocity Profiles 1. Temperature Profiles 1. Concentration Profiles 1. Detailed Fuel (Coal) Analysis (particle size distribution, etc.) 1. Wall Temperatures	1. Wall Heat Flux 2. Effluent Temperature 2. Effluent Species Concentration 2. Particle Properties Profile 2. Effluent Particle Properties 3. Ash Analysis 3. Slag Deposition Rates, Composition of Slag, Temp. through Deposit

Section 4

Summary, Conclusions, and Recommendations

Several conclusions have resulted from this study. This section presents the conclusions grouped by the five data book tasks. Recommendations are given at the end of the section.

4.1 Summary and Conclusions

The three-dimensional combustion data book fulfills the main objective of providing a data source for model evaluation within the current state of availability and quality of three-dimensional combustion data. The data included in the data book are intended to be the most complete and highest quality of the three-dimensional data that could be located and obtained.

Some data were identified but not obtained because of availability. For example, a set of relevant data was located at one facility that, technically, was available for distribution to the public domain. However, the company could not provide the necessary manpower to retrieve the data from files for distribution. The cost for data retrieval was estimated to be over five thousand dollars. Since the quality and suitability of the data were unknown, it was not deemed feasible to obtain the data.

All classes of data are not represented in the data book. All sets that are included in the data book are incomplete in some way for model evaluation. Parametric test data are included, but more cases are needed. However, given the scarce nature of available three-dimensional data, the data book is a necessary first step towards providing an acceptable source of such data. The establishment of criteria for selecting data as well as for specifying the most useful measurements for including in test matrices can help guide future work in collecting combustion data.

Task 1. Identify Needs and Selection Criteria

The data selection criteria presented in chapter two were sufficiently stringent to screen out unusable data, yet flexible enough to permit engineering discretion to evaluate data that are of acceptable quality. Because of the current state of three-dimensional combustion data, a fine line was required to select between data that were too incomplete or of low quality to be useful and not having any data to use for even a coarse evaluation.

Task 2. Document Three-Dimensional Combustion Data

As seen from the results of a survey and several literature searches, the quantity of three-dimensional data in any form or quality is limited. Appendix F contains a bibliography of references to three-dimensional data that were found during this study. Several excellent sources of two-dimensional data were also included in the bibliography for the sake of documentation. For reasons mentioned below, existing data were difficult to identify. A thorough search was performed of the literature and a survey of test facilities was made seeking three-dimensional combustion data of the five types listed in Table 2.1 in Section 2. Some unobtained data were identified and requested by letter or through other reasonable means without response.

Task 3. Obtain and Evaluate Data

All identified, available data suitable for three-dimensional combustion model evaluation were obtained and evaluated using the data selection criteria explained in Section 2. The data that were judged to be the best possible data for model evaluation were included in the appendices.

Task 4. Organize Data

The data book appendices contain the best available combustion data obtained. The format is intended to be concise and logically arranged. Compared to the reports that much of the data were extracted from, the data book is intended to be easy to use.

Task 5. Evaluate and Interpret the Data Base

The current state of available three-dimensional combustion data is somewhat limited. Data quality is also questionable. Measurement is typically with probes and therefore limited to the accuracy of the method, with estimated error often as high as ± 30 percent. The spatial resolution within furnaces leaves many parts of the furnace with little or no data to characterize the test plane sufficiently. The access to the inside of the furnace through ports is often quite limited.

The number of facilities with the capability to obtain reliable three-dimensional data appears to be limited. Three-dimensional facilities are often owned by companies such as Combustion Engineering Co., Babcock and Wilcox Co., and Consolidation Coal Co. Sometimes the data are proprietary or available with restrictions on distribution. Three-dimensional combustion data in large-scale furnaces are typically obtained without achieving steady-state conditions. Data collection is slow and arduous near furnace walls. The data collection period is often extended over days or even weeks. The data over the whole collection period may not have been collected at one near-constant set of operating conditions.

None of the cases made any mention of statistical design techniques being used for the measurement phase of the experiments. The test programs typically have no provisions for repeating measurements to provide an estimate of data precision or reproducibility. Statistical error analysis of the data is not generally provided to estimate the quality of the data. Pre-test statistical considerations appeared to be adequate for checking the equipment accuracy and precision in most cases, but analysis of the consistency of the data through material and energy balances is generally not done.

More and better data are needed in all categories of data listed in Table 2.1. No data for particle-laden, non-reacting gases and coal gasification were obtained. Only limited data were found for the other categories. Parametric data were limited, but several cases were sufficiently documented to be included in the data book. Types of data of interest were noted in five categories from simple non-reacting gaseous flow to reacting coal gasification. Another category is needed for classifying data: size or scale. In the two-dimensional data book (Smoot and Christensen, 1985), the need for size was not apparent since all reactors were pilot-scale or lab-scale. Three-dimensional combustion furnaces are typically medium or large scale (approximately 20 MW_e and above). Several pilot-scale

furnaces are in operation currently, including furnaces operated by Consolidation Coal Co., Combustion Engineering Co, and Babcock and Wilcox Co. Lab-scale facilities would be the smallest category of combustion facility that would be necessary. By using size as a category for data classification, greater attention can be given to obtaining data in a variety of different sized furnaces. Data for various furnaces loads are needed to evaluate the computer model's capability to accurately predict combustion conditions in all sizes of furnaces.

Several factors combined to make locating and obtaining relevant combustion data a difficult task. First, many abstracts do not distinguish between two dimensional and three-dimensional facilities used for data collection. Often, the fact that data were collected is omitted since it may have been a small part of the overall study. In one case, the data portion of a contract report did not show up in abstracts or conference papers mentioning the data. After extensive searching, a second volume was identified and obtained which contained all the necessary data. It was fortuitous that the data were obtained.

Another problem with obtaining data results from insufficient resources to extract data from computer tapes or paper archives. Costs and lack of available, qualified personnel can restrict data extraction from old reports, especially if the data are of uncertain quality or completeness. Also, most data are proprietary, owned by either the consulting engineering firm that took the data or the industrial company who provided the furnace. For economic reasons, it is not usually feasible to release expensive data to competitors. Alliances of industry, government, and academia are needed so that available resources can be used as effectively as possible.

Even with the limitations noted above, the 3-D data included herein will be useful in model evaluation. Additional forthcoming data such as those from the Goudey furnace (Cannon, 1989) will add to this data base. And, evaluation of combustion models with 2-D data (Smoot and Christensen, 1985) add substantially to confidence placed in the use of these models.

4.2 Recommendations

Based on the conclusions and experiences gained during this project, several recommendations are provided below to improve the state of three-dimensional combustion data.

Work in the data book should continue in order to add new data, and to replace lesser

quality data with higher quality data as it becomes available. Data without restrictions are preferred. Given the shortage of readily available data and the high cost of taking new data, it is recommended that an additional effort be made to obtain data that were identified but for some reason were unobtainable. For a fraction of the cost of taking new data, it may be possible to obtain available, archived, data if the necessary resources can be provided. In other cases, initial objections to releasing data may have been resolved or are no longer applicable. Companies or facilities that deal in combustion-related work that were not included during this study should also be surveyed. For example, the study being conducted by EPRI to evaluate the Coal Quality Impact Model may become a valuable source of three-dimensional combustion data.

Better cooperation among government and industry is needed to sponsor programs which include internal furnace measurements. Strong leadership must be implemented to give the data collection direction and focus in order to effectively utilize whatever funds become available. The Advanced Combustion Engineering Research Center (ACERC) has initiated the discussion and direction through its Working Group 6, which is in charge of model evaluation data issues, and is currently participating in full-scale utility boiler tests. A long term master plan is needed among combustion organizations who wish to participate. Better use of existing facilities should be implemented. Available optical experimental techniques should be applied to larger scale systems. New or innovative experimental designs in small-scale facilities may be capable of providing useful data for model evaluation by using scaled-down models of full-scale furnaces and fluids of different densities. Advanced methods of taking measurements in furnaces are under development at ACERC. For example, laser-based measurements were used in the recently completed tests at the Goudey facility in New York (Cannon, 1989).

Careful planning is recommended before experimental work for model evaluation is initiated. The facility where data are to be measured should be examined months before any test matrices are completed to look for unexpected difficulties, access ports, and other possible problems that should be addressed before testing begins. Statistical considerations should be addressed adequately to increase the probability of taking useful data. If possible, sufficient information about the furnace should be collected so that the furnace conditions to be tested can be modeled before testing begins. Preliminary computer results may be

beneficial for planning the test location matrix. Comprehensive information must be gathered about all operating conditions and how they vary during test periods. To aid in test planning, as much information as possible should be obtained about the furnace long before data collection starts.

Finally, a detailed specification is needed outlining the proper method for organizing and presenting experimental data to prevent its loss through insufficient documentation. ACERC should provide the leadership for setting requirements towards obtaining quality data for code evaluation. ACERC should continue adding data to the data book as it becomes available.

It is believed that, with correct guidance and cooperation among industry, government, and academia, much valuable data suitable for model evaluation can be made available.

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Appendix A

Non-Reacting Gaseous Flow

Introduction to Case A1

Combustion Engineering, Inc. Cold Flow Facility (Koucky, 1988)

Case A1 is a non-reacting gas flow taken in a tangentially-fired furnace model constructed of plexiglass. The model is owned by Combustion Engineering, Inc. of Windsor, Conn. The data were taken as part of a sorbent injection study conducted for the Environmental Protection Agency (Koucky, 1988).

The first pages of the section describe the furnace in detail using perspective and dimensioned drawings. As much information as was available in the reports was included in the drawings. Dimensions used in Case A1 figures are in meters unless otherwise indicated.

General information about the furnace is given after the illustrations. The general information consists mainly of the operating conditions used during furnace testing such as gas temperature and flow rates.

The experimental data are listed following the general information. Velocities in meter per second are the only measurements provided. The data are organized with a normalized X-Y-Z coordinate in the first column, and the three (X, Y, and Z, respectively) components of the velocity measurements in the next three columns. The X-Y-Z coordinate system used for Case A1, shown in Figure A.1, is used to identify the test locations in the furnace. The coordinate system is normalized using the furnace's width, depth, and height for the X, Y, and Z axes, respectively. The data are grouped by test plane in the furnace. Level 1 was taken at a normalized elevation of 0.174 which is approximately 17% of the distance from the bottom to the top of the furnace. The first test level corresponds to an elevation of 0.938 meters. Levels two and above are at increasingly higher elevations in the furnace.

The main assumption used in this data set are the inlet flow rates from each inlet. Only a total flow rate is given for the data set. Proportionally-distributed flow through each level of each corner-positioned burner is assumed.

Figure A.1

Case A1 - Three-Dimensional Drawing of Furnace.

Details of the furnace dimensions are given in Figures A.2 through A.4. X+, Y+, and Z+ refer to the coordinate system used to locate measurements and geometrical features. Approximate test planes are indicated by labels at different locations along the side and top of the illustration. Information taken from Koucky (1988).

Figure A.2

Case A1 - Dimensioned Drawing of Furnace.

The firing pattern is illustrated in Figure A.3, and burner details are given in Figure A.4. All lengths have units of meters. X+, Y+, and Z+ refer to the coordinate axes described in Figure A.1. Information for figure taken from Koucky (1988).

Figure A.3

Case A1 - Burner Orientation in Furnace.

Large arrows indicate the orientation of the corner burners relative to the furnace. All lengths are given in units of meters. $X+$ and $Y+$ are the coordinate axes pointing in the positive direction. See Figure A.1 for furnace orientation relative to X - Y - Z axes. Burner dimensions are given in Figure A.4. Information for figure from Koucky (1988).

Figure A.4

Case A1 - Dimensions of Burners Used in Furnace.

For cold flow operation, air is permitted to exit the fuel inlet and the two small inlets above and below the fuel exit. All dimensions are given in meters. The over-fired fuel inlets (OFA) are one opening into the furnace interior. Burner dimensions taken from Koucky (1988).

Table A.1

Data Set for Case A1 (Koucky, 1987).

Combustion Engineering, Inc.

Large Scale Furnace Aerodynamics Test Facility (LSFATF)

General Information

Dimensions (w X d X h, meters) 1.549 X 1.321 X 5.391

Number of burners 12 (3 burners in each corner)

Burner Locations (see Figure A.2)

Primary Stream

Solids Feed Rate (kg/s)	0	0	0	0
Gas Flow (m/s @ STP)	7.50	7.50	7.50	7.50
Gas Temperature (K)	294	294	294	294
Burner Dimensions (see Figure A.4)				
Burner Velocity (m/s)	25.0	25.0	25.0	25.0
Theoretical Swirl No.	0	0	0	0

Secondary Stream - Does not apply to this data case.

Fuel Compositions (mole fraction)

Gas - Primary

N2	0.79	0.79	0.79	0.79
O2	0.21	0.21	0.21	0.21

Velocity Data (m/s)

Measurement level 1

(X, Y, Z)	V _x	V _y	V _z
(0.933, 0.923, 0.174)	-3.09E+00	2.04E+00	-1.47E+00
(0.067, 0.846, 0.174)	-1.60E+00	1.39E+00	-4.33E+00
(0.133, 0.846, 0.174)	-2.04E+00	-4.28E+00	-3.72E+00
(0.200, 0.846, 0.174)	-6.19E+00	1.79E+00	-1.54E+00
(0.267, 0.846, 0.174)	-6.87E+00	1.02E+00	-7.22E-01
(0.333, 0.846, 0.174)	-8.02E+00	1.55E-01	5.06E-01
(0.400, 0.846, 0.174)	-9.23E+00	2.35E-01	-2.10E-01
(0.467, 0.846, 0.174)	-9.15E+00	1.71E-01	1.20E-01
(0.533, 0.846, 0.174)	-1.02E+01	8.23E-02	4.79E-01
(0.600, 0.846, 0.174)	-9.29E+00	1.05E+00	9.60E-01
(0.667, 0.846, 0.174)	-8.71E+00	1.98E+00	3.17E-01
(0.733, 0.846, 0.174)	-7.19E+00	2.71E+00	1.71E-01
(0.800, 0.846, 0.174)	-5.92E+00	3.54E+00	2.13E-02

1-Each column is for one of four corner burners. All four burners are considered to have the same output parameters.

Table A.1- continued

Velocity Data (m/s)

Measurement level 1

(X, Y, Z)	V _x	V _y	V _z
(0.867, 0.846, 0.174)	-	-	-
(0.933, 0.846, 0.174)	-7.77E-01	1.69E+00	-1.96E+00
(0.067, 0.769, 0.174)	-4.75E-01	-6.42E+00	-3.14E+00
(0.133, 0.769, 0.174)	-3.01E+00	-4.61E+00	-2.45E+00
(0.200, 0.769, 0.174)	-2.51E+00	-4.65E+00	-2.01E+00
(0.267, 0.769, 0.174)	-2.48E+00	-3.21E+00	-1.06E+00
(0.333, 0.769, 0.174)	-7.58E+00	9.39E-01	9.97E-01
(0.400, 0.769, 0.174)	-8.18E+00	1.07E+00	1.40E+00
(0.467, 0.769, 0.174)	-8.25E+00	1.09E+00	1.98E+00
(0.533, 0.769, 0.174)	-8.31E+00	2.02E+00	2.64E+00
(0.600, 0.769, 0.174)	-8.08E+00	1.64E+00	2.29E+00
(0.667, 0.769, 0.174)	-7.57E+00	2.85E+00	2.83E+00
(0.733, 0.769, 0.174)	-6.60E+00	3.04E+00	1.99E+00
(0.800, 0.769, 0.174)	-5.65E+00	3.71E+00	1.73E+00
(0.867, 0.769, 0.174)	-4.59E+00	-3.36E+00	1.71E-01
(0.933, 0.769, 0.174)	-3.11E-01	4.38E+00	-2.19E+00
(0.067, 0.692, 0.174)	-6.61E-01	-7.42E+00	3.89E+00
(0.133, 0.692, 0.174)	-1.05E+00	-6.14E+00	4.06E+00
(0.200, 0.692, 0.174)	-1.48E+00	-4.62E+00	3.19E+00
(0.267, 0.692, 0.174)	-9.94E-01	-3.95E+00	2.49E+00
(0.333, 0.692, 0.174)	-6.77E+00	4.30E-01	3.20E+00
(0.400, 0.692, 0.174)	-6.21E+00	1.01E+00	4.16E+00
(0.467, 0.692, 0.174)	-6.26E+00	5.18E-01	3.91E+00
(0.533, 0.692, 0.174)	-6.56E+00	2.43E+00	3.15E+00
(0.600, 0.692, 0.174)	-6.72E+00	3.69E-01	3.59E+00
(0.667, 0.692, 0.174)	-6.04E+00	3.09E+00	1.94E+00
(0.733, 0.692, 0.174)	-4.82E+00	4.54E+00	2.25E+00
(0.800, 0.692, 0.174)	-4.60E+00	4.55E+00	1.78E+00
(0.867, 0.692, 0.174)	-1.34E+00	4.32E+00	-4.30E+00
(0.933, 0.692, 0.174)	-4.63E-01	2.66E+00	-6.13E+00
(0.067, 0.615, 0.174)	-4.57E-01	-7.75E+00	5.35E+00
(0.133, 0.615, 0.174)	-8.32E-01	-6.13E+00	4.37E+00
(0.200, 0.615, 0.174)	-1.32E+00	-4.62E+00	3.30E+00
(0.267, 0.615, 0.174)	-1.44E+00	-9.60E-01	3.98E+00
(0.333, 0.615, 0.174)	-4.91E+00	1.66E+00	2.62E+00
(0.400, 0.615, 0.174)	-4.41E+00	1.71E+00	3.47E+00
(0.467, 0.615, 0.174)	-4.00E+00	2.53E-01	5.51E+00
(0.533, 0.615, 0.174)	-2.87E+00	-1.28E+00	4.86E+00
(0.600, 0.615, 0.174)	-3.11E+00	2.43E+00	3.74E+00
(0.667, 0.615, 0.174)	-3.15E+00	3.80E+00	3.38E+00
(0.733, 0.615, 0.174)	-3.52E+00	2.00E+00	3.62E+00
(0.800, 0.615, 0.174)	-2.61E+00	3.59E+00	3.88E+00
(0.867, 0.615, 0.174)	-2.10E-01	5.20E+00	-3.96E+00
(0.933, 0.615, 0.174)	-3.08E-01	3.81E+00	-6.86E+00
(0.067, 0.538, 0.174)	-4.75E-01	-7.48E+00	5.33E+00
(0.133, 0.538, 0.174)	-1.40E+00	-5.82E+00	4.67E+00
(0.200, 0.538, 0.174)	-1.94E+00	-2.38E+00	4.04E+00
(0.267, 0.538, 0.174)	-2.40E+00	2.90E-01	3.01E+00

Table A.1- continued

Velocity Data (m/s)

Measurement level 1

(X, Y, Z)	V _x	V _y	V _z
(0.333, 0.538, 0.174)	-2.07E+00	2.26E-01	3.87E+00
(0.400, 0.538, 0.174)	-3.91E+00	9.48E-01	4.49E+00
(0.467, 0.538, 0.174)	-2.28E+00	4.54E+00	5.05E+00
(0.533, 0.538, 0.174)	-1.06E+00	1.07E+00	7.62E+00
(0.600, 0.538, 0.174)	-2.19E-01	5.89E+00	6.83E-01
(0.667, 0.538, 0.174)	8.08E-01	4.09E+00	4.01E+00
(0.733, 0.538, 0.174)	-1.91E+00	2.28E+00	3.99E+00
(0.800, 0.538, 0.174)	-6.74E-01	5.99E+00	-3.04E+00
(0.867, 0.538, 0.174)	-8.66E-01	5.59E+00	-4.48E+00
(0.933, 0.538, 0.174)	-1.45E+00	3.63E+00	-7.47E+00
(0.067, 0.462, 0.174)	-6.68E-01	9.88E-01	4.63E+00
(0.133, 0.462, 0.174)	-1.53E+00	-5.98E+00	5.20E+00
(0.200, 0.462, 0.174)	-2.43E+00	-3.55E+00	3.19E+00
(0.267, 0.462, 0.174)	-1.48E+00	-3.35E-02	3.24E+00
(0.333, 0.462, 0.174)	-1.36E+00	1.52E-02	4.41E+00
(0.400, 0.462, 0.174)	-3.72E-01	-3.96E-02	5.92E+00
(0.467, 0.462, 0.174)	-2.21E+00	5.76E-01	5.31E+00
(0.533, 0.462, 0.174)	1.01E+00	1.65E-01	6.66E+00
(0.600, 0.462, 0.174)	-1.12E+00	2.23E+00	5.86E+00
(0.667, 0.462, 0.174)	2.46E+00	3.51E+00	3.65E+00
(0.733, 0.462, 0.174)	-9.36E-01	5.61E+00	-1.87E+00
(0.800, 0.462, 0.174)	-1.69E+00	5.74E+00	-2.62E+00
(0.867, 0.462, 0.174)	-1.98E+00	5.81E+00	-3.84E+00
(0.933, 0.462, 0.174)	-1.26E+00	8.17E+00	-7.01E-01
(0.067, 0.385, 0.174)	-1.03E+00	-8.04E+00	-3.04E+00
(0.133, 0.385, 0.174)	-2.11E+00	-6.33E+00	-1.91E+00
(0.200, 0.385, 0.174)	-2.58E+00	-4.86E+00	-1.19E-01
(0.267, 0.385, 0.174)	1.46E+00	1.84E+00	2.43E+00
(0.333, 0.385, 0.174)	-6.10E-03	1.18E+00	3.81E+00
(0.400, 0.385, 0.174)	-1.83E-01	2.69E+00	4.20E+00
(0.467, 0.385, 0.174)	-1.95E+00	1.92E-01	4.30E+00
(0.533, 0.385, 0.174)	-7.32E-01	1.52E-02	6.14E+00
(0.600, 0.385, 0.174)	2.78E+00	2.00E+00	6.04E+00
(0.667, 0.385, 0.174)	3.17E+00	3.96E+00	3.53E+00
(0.733, 0.385, 0.174)	2.63E+00	3.10E+00	4.01E+00
(0.800, 0.385, 0.174)	-2.40E+00	5.39E+00	2.77E+00
(0.867, 0.385, 0.174)	-2.03E+00	6.92E+00	1.84E+00
(0.933, 0.385, 0.174)	-1.16E+00	6.75E+00	-5.09E-01
(0.067, 0.308, 0.174)	-1.20E+00	-5.95E+00	-3.11E+00
(0.133, 0.308, 0.174)	-2.94E+00	-5.35E+00	-1.31E+00
(0.200, 0.308, 0.174)	3.84E+00	2.33E+00	-7.59E-01
(0.267, 0.308, 0.174)	4.32E+00	7.28E-01	-2.71E-01
(0.333, 0.308, 0.174)	3.87E+00	1.89E+00	3.26E-01
(0.400, 0.308, 0.174)	4.33E+00	1.17E+00	1.85E+00
(0.467, 0.308, 0.174)	3.87E+00	4.57E-01	2.39E+00
(0.533, 0.308, 0.174)	4.82E+00	2.54E+00	3.22E+00
(0.600, 0.308, 0.174)	3.76E+00	2.69E+00	4.24E+00

Table A.1- continued

Velocity Data (m/s)

Measurement level 1

(X, Y, Z)

 V_x V_y V_z

(0.667,0.308,0.174)	5.51E+00	3.20E+00	2.59E+00
(0.733,0.308,0.174)	4.19E+00	3.69E+00	1.87E+00
(0.800,0.308,0.174)	-3.24E+00	4.42E+00	1.96E+00
(0.867,0.308,0.174)	-2.97E+00	5.66E+00	5.94E-01
(0.933,0.308,0.174)	-1.55E+00	7.18E+00	-7.80E-01
(0.067,0.231,0.174)	-1.79E+00	-4.70E+00	-3.26E+00
(0.133,0.231,0.174)	3.83E+00	1.53E+00	-3.69E+00
(0.200,0.231,0.174)	5.25E+00	2.94E+00	-2.12E+00
(0.267,0.231,0.174)	6.14E+00	2.50E+00	-1.09E+00
(0.333,0.231,0.174)	6.68E+00	2.57E+00	-1.29E+00
(0.400,0.231,0.174)	6.92E+00	1.47E+00	-2.29E-01
(0.467,0.231,0.174)	6.63E+00	2.43E+00	-1.49E-01
(0.533,0.231,0.174)	6.42E+00	1.53E+00	-2.35E-01
(0.600,0.231,0.174)	6.41E+00	1.29E+00	-1.34E-01
(0.667,0.231,0.174)	6.06E+00	3.91E+00	6.80E-01
(0.733,0.231,0.174)	4.55E+00	3.32E+00	3.99E-01
(0.800,0.231,0.174)	4.05E+00	2.92E+00	-2.26E-01
(0.867,0.231,0.174)	3.13E+00	-2.70E+00	-6.95E-01
(0.933,0.231,0.174)	-1.98E+00	5.07E+00	-6.22E-01
(0.067,0.154,0.174)	1.16E+00	-5.27E-01	-5.94E+00
(0.133,0.154,0.174)	4.75E+00	2.34E+00	-4.30E+00
(0.200,0.154,0.174)	6.03E+00	3.38E+00	-2.70E+00
(0.267,0.154,0.174)	7.67E+00	3.87E-01	-2.82E+00
(0.333,0.154,0.174)	8.48E+00	-5.49E-02	-2.61E+00
(0.400,0.154,0.174)	9.01E+00	1.19E-01	-1.85E+00
(0.467,0.154,0.174)	9.11E+00	-5.18E-02	-1.48E+00
(0.533,0.154,0.174)	8.66E+00	1.65E+00	-1.34E+00
(0.600,0.154,0.174)	7.88E+00	2.66E+00	-1.80E+00
(0.667,0.154,0.174)	6.76E+00	2.18E+00	-1.08E+00
(0.733,0.154,0.174)	7.01E+00	3.36E+00	-1.18E+00
(0.800,0.154,0.174)	5.93E+00	4.27E+00	-1.48E+00
(0.867,0.154,0.174)	-3.93E+00	4.76E+00	-1.56E+00
(0.933,0.154,0.174)	2.45E+00	2.03E+00	-2.40E+00
(0.067,0.077,0.174)	-9.75E-01	8.02E-01	-2.59E+00
(0.133,0.077,0.174)	2.54E+00	8.53E-02	-4.94E+00
(0.200,0.077,0.174)	6.15E+00	-2.07E-01	-4.08E+00
(0.267,0.077,0.174)	7.55E+00	1.22E-01	-3.78E+00
(0.333,0.077,0.174)	9.38E+00	1.83E-01	-3.87E+00
(0.400,0.077,0.174)	9.97E+00	4.72E-01	-4.72E+00
(0.467,0.077,0.174)	9.24E+00	4.91E-01	-4.08E+00
(0.533,0.077,0.174)	1.07E+01	6.10E-01	-3.54E+00
(0.600,0.077,0.174)	9.95E+00	-2.68E-01	-3.72E+00
(0.667,0.077,0.174)	8.74E+00	1.44E+00	-3.26E+00
(0.733,0.077,0.174)	8.02E+00	1.68E+00	-3.17E+00
(0.800,0.077,0.174)	5.96E+00	2.49E+00	-2.54E+00
(0.867,0.077,0.174)	1.87E+00	2.30E+00	-3.75E+00
(0.933,0.077,0.174)	2.43E+00	2.10E-01	-7.13E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 2

(X, Y, Z)

	V _x	V _y	V _z
(0.067,0.923,0.403)	-6.98E-01	-1.16E-01	1.77E-01
(0.133,0.923,0.403)	-7.83E-01	7.92E-02	5.88E-01
(0.200,0.923,0.403)	-6.58E-01	5.18E-02	4.91E-01
(0.267,0.923,0.403)	-6.74E-01	7.62E-02	3.96E-01
(0.333,0.923,0.403)	-7.74E-01	1.22E-01	2.26E-01
(0.400,0.923,0.403)	-7.59E-01	2.44E-02	2.44E-01
(0.467,0.923,0.403)	-8.87E-01	2.44E-01	1.68E-01
(0.533,0.923,0.403)	-9.45E-01	1.65E-01	2.10E-01
(0.600,0.923,0.403)	-8.47E-01	3.35E-01	2.68E-01
(0.667,0.923,0.403)	-8.60E-01	2.74E-01	3.35E-01
(0.733,0.923,0.403)	-6.92E-01	4.27E-01	2.68E-01
(0.800,0.923,0.403)	-6.07E-01	4.15E-01	2.65E-01
(0.867,0.923,0.403)	-4.57E-02	1.68E-01	8.78E-01
(0.933,0.923,0.403)	-2.26E-01	2.71E-01	2.71E-01
(0.067,0.846,0.403)	-2.99E-01	-6.80E-01	7.71E-01
(0.133,0.846,0.403)	-2.41E-01	-6.16E-01	6.00E-01
(0.200,0.846,0.403)	-1.74E-01	-6.00E-01	5.52E-01
(0.267,0.846,0.403)	-5.85E-01	2.77E-01	2.93E-01
(0.333,0.846,0.403)	-6.00E-01	3.35E-01	2.93E-01
(0.400,0.846,0.403)	-7.92E-01	1.52E-01	2.93E-01
(0.467,0.846,0.403)	-7.74E-01	2.93E-01	3.75E-01
(0.533,0.846,0.403)	-8.90E-01	1.19E-01	3.57E-01
(0.600,0.846,0.403)	-7.65E-01	3.38E-01	4.63E-01
(0.667,0.846,0.403)	-7.83E-01	2.77E-01	4.66E-01
(0.733,0.846,0.403)	-7.25E-01	3.44E-01	2.96E-01
(0.800,0.846,0.403)	-3.72E-01	5.61E-01	4.42E-01
(0.867,0.846,0.403)	-	-	-
(0.933,0.846,0.403)	-	-	-
(0.067,0.769,0.403)	-9.14E-02	-5.88E-01	6.49E-01
(0.133,0.769,0.403)	-2.71E-01	-6.43E-01	4.54E-01
(0.200,0.769,0.403)	-5.18E-01	-5.43E-01	3.84E-01
(0.267,0.769,0.403)	-2.32E-01	-5.61E-01	2.87E-01
(0.333,0.769,0.403)	-3.20E-01	-3.11E-01	3.47E-01
(0.400,0.769,0.403)	-6.77E-01	8.84E-02	3.02E-01
(0.467,0.769,0.403)	-7.56E-01	1.34E-01	2.53E-01
(0.533,0.769,0.403)	-6.77E-01	2.13E-01	2.62E-01
(0.600,0.769,0.403)	-6.40E-01	1.89E-01	2.29E-01
(0.667,0.769,0.403)	-5.39E-01	2.16E-01	1.80E-01
(0.733,0.769,0.403)	0.00E+00	0.00E+00	0.00E+00
(0.800,0.769,0.403)	-2.10E-01	5.18E-01	3.08E-01
(0.867,0.769,0.403)	-	-	-
(0.933,0.769,0.403)	-4.18E-01	5.46E-01	2.87E-01
(0.067,0.692,0.403)	-2.04E-01	-7.41E-01	5.73E-01
(0.133,0.692,0.403)	-2.59E-01	-7.01E-01	3.26E-01
(0.200,0.692,0.403)	-2.38E-01	-7.77E-01	3.11E-01
(0.267,0.692,0.403)	-1.86E-01	-7.47E-01	3.66E-01
(0.333,0.692,0.403)	-2.53E-01	-4.02E-01	2.68E-01
(0.400,0.692,0.403)	-1.71E-01	-2.53E-01	2.50E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 2

(X,Y,Z)	V _x	V _y	V _z
(0.467,0.692,0.403)	-5.09E-01	1.49E-01	2.19E-01
(0.533,0.692,0.403)	-6.00E-01	9.45E-02	1.65E-01
(0.600,0.692,0.403)	-3.26E-01	2.41E-01	-9.14E-03
(0.667,0.692,0.403)	-3.90E-01	1.95E-01	8.23E-02
(0.733,0.692,0.403)	-1.37E-01	4.63E-01	1.68E-01
(0.800,0.692,0.403)	-3.17E-01	2.41E-01	7.01E-02
(0.867,0.692,0.403)	-3.57E-01	8.44E-01	3.63E-01
(0.933,0.692,0.403)	-2.10E-01	8.78E-01	1.92E-01
(0.067,0.615,0.403)	-4.27E-02	-6.92E-01	5.58E-01
(0.133,0.615,0.403)	-2.19E-01	-7.13E-01	3.75E-01
(0.200,0.615,0.403)	-5.79E-02	-7.74E-01	3.81E-01
(0.267,0.615,0.403)	-1.37E-01	-6.19E-01	3.26E-01
(0.333,0.615,0.403)	-3.35E-02	-3.90E-01	4.21E-01
(0.400,0.615,0.403)	-3.47E-01	6.10E-02	1.65E-01
(0.467,0.615,0.403)	-1.77E-01	1.77E-01	3.05E-01
(0.533,0.615,0.403)	-1.62E-01	7.62E-02	2.19E-01
(0.600,0.615,0.403)	-2.10E-01	1.07E-01	1.52E-01
(0.667,0.615,0.403)	-2.29E-01	2.41E-01	7.92E-02
(0.733,0.615,0.403)	-3.35E-02	5.09E-01	6.71E-02
(0.800,0.615,0.403)	-3.57E-01	5.27E-01	2.44E-01
(0.867,0.615,0.403)	-2.44E-01	7.96E-01	2.68E-01
(0.933,0.615,0.403)	-8.53E-02	8.63E-01	2.53E-01
(0.067,0.538,0.403)	-5.49E-02	2.32E-01	5.49E-01
(0.133,0.538,0.403)	-1.92E-01	-8.69E-01	4.45E-01
(0.200,0.538,0.403)	-4.27E-02	-8.69E-01	4.69E-01
(0.267,0.538,0.403)	-7.32E-02	-3.72E-01	2.68E-01
(0.333,0.538,0.403)	-1.89E-01	-3.66E-01	2.65E-01
(0.400,0.538,0.403)	-1.49E-01	1.22E-01	2.99E-01
(0.467,0.538,0.403)	-4.57E-02	8.84E-02	3.66E-01
(0.533,0.538,0.403)	-9.14E-03	4.27E-02	2.56E-01
(0.600,0.538,0.403)	-3.35E-02	4.88E-02	2.68E-01
(0.667,0.538,0.403)	-5.79E-02	3.23E-01	7.62E-02
(0.733,0.538,0.403)	-1.49E-01	4.18E-01	2.44E-01
(0.800,0.538,0.403)	-7.92E-02	6.61E-01	2.50E-01
(0.867,0.538,0.403)	-5.79E-02	9.11E-01	2.74E-01
(0.933,0.538,0.403)	-3.05E-02	1.05E+00	3.05E-01
(0.067,0.462,0.403)	-2.23E-01	-7.28E-01	7.01E-02
(0.133,0.462,0.403)	-2.41E-01	-6.92E-01	4.79E-01
(0.200,0.462,0.403)	-2.04E-01	-8.20E-01	5.61E-01
(0.267,0.462,0.403)	-2.44E-02	2.90E-01	3.75E-01
(0.333,0.462,0.403)	2.74E-02	1.31E-01	3.14E-01
(0.400,0.462,0.403)	8.84E-02	7.92E-02	2.96E-01
(0.467,0.462,0.403)	3.35E-02	7.32E-02	2.93E-01
(0.533,0.462,0.403)	7.92E-02	1.19E-01	3.29E-01
(0.600,0.462,0.403)	1.28E-01	8.53E-02	2.26E-01
(0.667,0.462,0.403)	-9.45E-02	3.14E-01	1.46E-01
(0.733,0.462,0.403)	-2.44E-01	4.08E-01	-1.16E-01
(0.800,0.462,0.403)	-1.04E-01	5.88E-01	7.32E-02

Table A.1- continued

Velocity Data (m/s)

Measurement level 2

(X, Y, Z)	V _x	V _y	V _z
(0.867, 0.462, 0.403)	6.10E-03	8.69E-01	2.50E-01
(0.933, 0.462, 0.403)	-9.14E-03	1.07E+00	2.71E-01
(0.067, 0.385, 0.403)	3.35E-02	2.93E-01	6.80E-01
(0.133, 0.385, 0.403)	-3.99E-01	-7.10E-01	5.55E-01
(0.200, 0.385, 0.403)	-3.20E-01	-6.80E-01	4.72E-01
(0.267, 0.385, 0.403)	2.41E-01	3.44E-01	3.11E-01
(0.333, 0.385, 0.403)	1.46E-01	-6.10E-03	4.05E-01
(0.400, 0.385, 0.403)	-	-	-
(0.467, 0.385, 0.403)	1.13E-01	9.14E-03	3.05E-01
(0.533, 0.385, 0.403)	1.16E-01	2.19E-01	2.71E-01
(0.600, 0.385, 0.403)	-2.16E-01	1.49E-01	2.41E-01
(0.667, 0.385, 0.403)	-2.47E-01	1.68E-01	1.86E-01
(0.733, 0.385, 0.403)	2.41E-01	2.41E-01	6.71E-02
(0.800, 0.385, 0.403)	-2.87E-01	6.16E-01	2.13E-01
(0.867, 0.385, 0.403)	-1.65E-01	9.02E-01	3.35E-01
(0.933, 0.385, 0.403)	-6.10E-02	1.02E+00	2.29E-01
(0.067, 0.308, 0.403)	-4.02E-01	-5.39E-01	-1.04E-01
(0.133, 0.308, 0.403)	-4.85E-01	-7.22E-01	5.70E-01
(0.200, 0.308, 0.403)	-3.08E-01	-6.71E-01	6.19E-01
(0.267, 0.308, 0.403)	3.90E-01	2.77E-01	3.17E-01
(0.333, 0.308, 0.403)	3.81E-01	1.19E-01	2.90E-01
(0.400, 0.308, 0.403)	3.51E-01	7.62E-02	2.59E-01
(0.467, 0.308, 0.403)	3.20E-01	7.01E-02	2.68E-01
(0.533, 0.308, 0.403)	4.11E-01	1.52E-02	7.01E-02
(0.600, 0.308, 0.403)	3.66E-01	2.41E-01	1.55E-01
(0.667, 0.308, 0.403)	3.78E-01	2.53E-01	2.19E-01
(0.733, 0.308, 0.403)	4.94E-01	3.69E-01	2.59E-01
(0.800, 0.308, 0.403)	-3.44E-01	6.83E-01	2.56E-01
(0.867, 0.308, 0.403)	-1.77E-01	7.44E-01	2.29E-01
(0.933, 0.308, 0.403)	-1.31E-01	9.20E-01	3.54E-01
(0.067, 0.231, 0.403)	1.58E-01	2.35E-01	7.04E-01
(0.133, 0.231, 0.403)	-5.39E-01	-5.58E-01	6.89E-01
(0.200, 0.231, 0.403)	4.24E-01	1.28E-01	4.36E-01
(0.267, 0.231, 0.403)	4.69E-01	3.81E-01	3.84E-01
(0.333, 0.231, 0.403)	5.73E-01	2.44E-02	3.05E-01
(0.400, 0.231, 0.403)	5.52E-01	3.54E-01	2.47E-01
(0.467, 0.231, 0.403)	5.79E-01	-3.05E-03	1.37E-01
(0.533, 0.231, 0.403)	6.55E-01	2.32E-01	2.68E-01
(0.600, 0.231, 0.403)	5.64E-01	2.68E-01	1.74E-01
(0.667, 0.231, 0.403)	5.67E-01	2.38E-01	1.77E-01
(0.733, 0.231, 0.403)	6.25E-01	4.75E-01	1.98E-01
(0.800, 0.231, 0.403)	5.27E-01	4.72E-01	1.77E-01
(0.867, 0.231, 0.403)	5.70E-01	4.42E-01	2.96E-01
(0.933, 0.231, 0.403)	-1.58E-01	7.80E-01	3.51E-01
(0.067, 0.154, 0.403)	-	-	-
(0.133, 0.154, 0.403)	-5.79E-01	-2.90E-01	7.28E-01
(0.200, 0.154, 0.403)	4.36E-01	2.07E-01	6.28E-01
(0.267, 0.154, 0.403)	6.98E-01	-3.66E-02	4.51E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 2

(X,Y,Z)	V _x	V _y	V _z
(0.333,0.154,0.403)	7.68E-01	4.27E-02	3.87E-01
(0.400,0.154,0.403)	7.41E-01	1.95E-01	1.46E-01
(0.467,0.154,0.403)	8.44E-01	2.01E-01	2.65E-01
(0.533,0.154,0.403)	8.26E-01	2.68E-01	2.93E-01
(0.600,0.154,0.403)	8.81E-01	2.62E-01	3.26E-01
(0.667,0.154,0.403)	7.62E-01	2.19E-01	2.38E-01
(0.733,0.154,0.403)	7.41E-01	2.50E-01	2.16E-01
(0.800,0.154,0.403)	6.37E-01	4.08E-01	2.13E-01
(0.867,0.154,0.403)	6.71E-01	3.35E-01	2.53E-01
(0.933,0.154,0.403)	-2.26E-01	6.19E-01	4.39E-01
(0.067,0.077,0.403)	-2.68E-01	9.45E-02	5.73E-01
(0.133,0.077,0.403)	4.48E-01	3.02E-01	3.23E-01
(0.200,0.077,0.403)	5.12E-01	1.13E-01	1.31E-01
(0.267,0.077,0.403)	7.71E-01	2.44E-02	3.47E-01
(0.333,0.077,0.403)	8.60E-01	2.74E-02	2.68E-01
(0.400,0.077,0.403)	9.60E-01	2.74E-02	2.68E-01
(0.467,0.077,0.403)	9.94E-01	5.49E-02	2.87E-01
(0.533,0.077,0.403)	9.78E-01	6.71E-02	2.53E-01
(0.600,0.077,0.403)	9.45E-01	2.62E-01	3.29E-01
(0.667,0.077,0.403)	9.08E-01	2.68E-01	2.74E-01
(0.733,0.077,0.403)	8.05E-01	1.95E-01	2.35E-01
(0.800,0.077,0.403)	7.25E-01	2.13E-01	4.08E-01
(0.867,0.077,0.403)	6.19E-01	2.87E-01	4.39E-01
(0.933,0.077,0.403)	6.52E-01	1.49E-01	6.10E-02

Measurement level 3

(0.067,0.923,0.563)	-2.35E-01	1.28E-01	8.56E-01
(0.133,0.923,0.563)	-6.10E-02	-9.14E-02	8.47E-01
(0.200,0.923,0.563)	-2.99E-01	-1.43E-01	7.83E-01
(0.267,0.923,0.563)	-7.99E-01	1.58E-01	4.60E-01
(0.333,0.923,0.563)	-8.78E-01	4.57E-02	5.33E-01
(0.400,0.923,0.563)	-1.01E+00	6.10E-02	4.45E-01
(0.467,0.923,0.563)	-1.10E+00	8.53E-02	4.33E-01
(0.533,0.923,0.563)	-1.04E+00	2.44E-02	3.99E-01
(0.600,0.923,0.563)	-1.07E+00	1.25E-01	4.91E-01
(0.667,0.923,0.563)	-9.88E-01	-1.83E-02	4.48E-01
(0.733,0.923,0.563)	-8.72E-01	1.13E-01	5.52E-01
(0.800,0.923,0.563)	-7.32E-01	2.07E-01	5.49E-01
(0.867,0.923,0.563)	-2.04E-01	2.10E-01	7.35E-01
(0.933,0.923,0.563)	-3.51E-01	-4.57E-02	6.71E-01
(0.067,0.846,0.563)	-2.32E-01	-3.08E-01	6.25E-01
(0.133,0.846,0.563)	-4.57E-01	-4.88E-01	5.03E-01
(0.200,0.846,0.563)	-6.40E-02	-5.88E-01	5.58E-01
(0.267,0.846,0.563)	-	-	-
(0.333,0.846,0.563)	-8.11E-01	1.22E-01	3.90E-01
(0.400,0.846,0.563)	-8.38E-01	1.92E-01	2.65E-01
(0.467,0.846,0.563)	-8.99E-01	8.84E-02	2.77E-01
(0.533,0.846,0.563)	-8.23E-01	3.66E-02	3.14E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 3

(X, Y, Z)	V _x	V _y	V _z
(0.600, 0.846, 0.563)	-8.53E-02	-3.54E-01	-3.72E-01
(0.667, 0.846, 0.563)	-8.63E-01	1.71E-01	3.32E-01
(0.733, 0.846, 0.563)	-8.14E-01	2.29E-01	4.05E-01
(0.800, 0.846, 0.563)	-6.16E-01	4.57E-01	3.99E-01
(0.867, 0.846, 0.563)	-5.49E-01	4.79E-01	5.67E-01
(0.933, 0.846, 0.563)	-3.20E-01	2.44E-01	5.55E-01
(0.067, 0.769, 0.563)	-2.01E-01	-6.58E-01	5.85E-01
(0.133, 0.769, 0.563)	-4.79E-01	-6.13E-01	4.27E-01
(0.200, 0.769, 0.563)	-3.54E-01	-6.31E-01	4.11E-01
(0.267, 0.769, 0.563)	-2.38E-01	-5.97E-01	2.41E-01
(0.333, 0.769, 0.563)	-2.07E-01	-5.55E-01	2.38E-01
(0.400, 0.769, 0.563)	-7.04E-01	1.13E-01	1.71E-01
(0.467, 0.769, 0.563)	-7.77E-01	1.65E-01	2.35E-01
(0.533, 0.769, 0.563)	-6.61E-01	8.53E-02	2.04E-01
(0.600, 0.769, 0.563)	-6.83E-01	-1.22E-02	2.68E-01
(0.667, 0.769, 0.563)	-6.31E-01	2.16E-01	3.14E-01
(0.733, 0.769, 0.563)	-6.22E-01	1.58E-01	1.40E-01
(0.800, 0.769, 0.563)	-3.14E-01	5.79E-01	4.60E-01
(0.867, 0.769, 0.563)	-4.54E-01	5.85E-01	4.60E-01
(0.933, 0.769, 0.563)	-5.18E-02	5.52E-01	7.10E-01
(0.067, 0.692, 0.563)	-7.62E-02	-8.72E-01	5.73E-01
(0.133, 0.692, 0.563)	-5.43E-01	-6.71E-01	2.90E-01
(0.200, 0.692, 0.563)	-4.18E-01	-7.07E-01	2.90E-01
(0.267, 0.692, 0.563)	-2.87E-01	-6.92E-01	2.68E-01
(0.333, 0.692, 0.563)	-	-	-
(0.400, 0.692, 0.563)	-	-	-
(0.467, 0.692, 0.563)	-5.21E-01	2.04E-01	2.74E-02
(0.533, 0.692, 0.563)	-3.81E-01	9.45E-02	4.54E-01
(0.600, 0.692, 0.563)	-3.57E-01	2.13E-02	2.90E-01
(0.667, 0.692, 0.563)	-3.17E-01	2.53E-01	2.38E-01
(0.733, 0.692, 0.563)	-2.65E-01	4.36E-01	4.51E-01
(0.800, 0.692, 0.563)	-3.29E-01	6.89E-01	3.84E-01
(0.867, 0.692, 0.563)	-4.97E-01	6.83E-01	4.02E-01
(0.933, 0.692, 0.563)	-1.01E-01	8.05E-01	4.54E-01
(0.067, 0.615, 0.563)	-2.44E-01	-1.02E+00	5.52E-01
(0.133, 0.615, 0.563)	2.13E-02	-9.91E-01	3.44E-01
(0.200, 0.615, 0.563)	-5.09E-01	-7.13E-01	3.35E-02
(0.267, 0.615, 0.563)	-5.15E-01	-6.46E-01	1.04E-01
(0.333, 0.615, 0.563)	-4.79E-01	-4.66E-01	-4.57E-02
(0.400, 0.615, 0.563)	-	-	-
(0.467, 0.615, 0.563)	3.35E-02	2.68E-01	3.51E-01
(0.533, 0.615, 0.563)	-2.74E-02	5.49E-02	5.61E-01
(0.600, 0.615, 0.563)	-5.49E-02	-9.14E-03	4.42E-01
(0.667, 0.615, 0.563)	-8.23E-02	0.00E+00	3.69E-01
(0.733, 0.615, 0.563)	-3.60E-01	4.82E-01	3.51E-01
(0.800, 0.615, 0.563)	-3.41E-01	6.22E-01	2.87E-01
(0.867, 0.615, 0.563)	-1.55E-01	9.54E-01	4.18E-01
(0.933, 0.615, 0.563)	-1.55E-01	9.60E-01	4.85E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 3

(X, Y, Z)	V _x	V _y	V _z
(0.067, 0.538, 0.563)	-3.66E-02	-1.13E+00	4.97E-01
(0.133, 0.538, 0.563)	-9.75E-02	-9.27E-01	3.29E-01
(0.200, 0.538, 0.563)	-7.32E-02	-8.96E-01	1.16E-01
(0.267, 0.538, 0.563)	-5.09E-01	-6.77E-01	9.14E-03
(0.333, 0.538, 0.563)	-5.30E-01	-5.52E-01	-1.52E-02
(0.400, 0.538, 0.563)	2.56E-01	2.07E-01	3.47E-01
(0.467, 0.538, 0.563)	1.28E-01	2.56E-01	3.54E-01
(0.533, 0.538, 0.563)	-1.43E-01	-1.13E-01	4.97E-01
(0.600, 0.538, 0.563)	-2.16E-01	-7.62E-02	4.27E-01
(0.667, 0.538, 0.563)	-1.55E-01	2.44E-01	5.15E-01
(0.733, 0.538, 0.563)	-1.58E-01	4.85E-01	3.84E-01
(0.800, 0.538, 0.563)	-1.98E-01	7.07E-01	3.02E-01
(0.867, 0.538, 0.563)	-1.49E-01	9.11E-01	3.08E-01
(0.933, 0.538, 0.563)	-1.40E-01	1.07E+00	5.00E-01
(0.067, 0.462, 0.563)	-8.84E-02	-1.07E+00	5.61E-01
(0.133, 0.462, 0.563)	-8.23E-02	-3.17E-01	3.23E-01
(0.200, 0.462, 0.563)	-1.34E-01	-8.44E-01	7.92E-02
(0.267, 0.462, 0.563)	-1.52E-01	-8.05E-01	-6.10E-03
(0.333, 0.462, 0.563)	-8.53E-02	-6.37E-01	8.53E-02
(0.400, 0.462, 0.563)	-2.83E-01	-2.74E-01	3.02E-01
(0.467, 0.462, 0.563)	-1.16E-01	-2.50E-01	4.82E-01
(0.533, 0.462, 0.563)	4.11E-01	2.19E-01	2.93E-01
(0.600, 0.462, 0.563)	4.63E-01	8.53E-02	3.17E-01
(0.667, 0.462, 0.563)	3.38E-01	1.25E-01	3.20E-01
(0.733, 0.462, 0.563)	3.63E-01	3.63E-01	2.59E-01
(0.800, 0.462, 0.563)	-3.96E-02	7.44E-01	2.83E-01
(0.867, 0.462, 0.563)	-8.84E-02	8.81E-01	3.29E-01
(0.933, 0.462, 0.563)	-1.55E-01	1.06E+00	5.21E-01
(0.067, 0.385, 0.563)	-1.34E-01	-1.02E+00	5.88E-01
(0.133, 0.385, 0.563)	-2.07E-01	-8.63E-01	3.02E-01
(0.200, 0.385, 0.563)	-2.99E-01	-8.08E-01	1.68E-01
(0.267, 0.385, 0.563)	-2.47E-01	-7.56E-01	7.62E-02
(0.333, 0.385, 0.563)	-2.35E-01	-6.10E-01	4.57E-02
(0.400, 0.385, 0.563)	6.40E-01	1.58E-01	1.13E-01
(0.467, 0.385, 0.563)	7.32E-01	1.04E-01	1.28E-01
(0.533, 0.385, 0.563)	6.34E-01	1.13E-01	1.31E-01
(0.600, 0.385, 0.563)	6.00E-01	3.35E-02	1.16E-01
(0.667, 0.385, 0.563)	5.55E-01	1.49E-01	2.68E-01
(0.733, 0.385, 0.563)	5.18E-01	3.87E-01	2.62E-01
(0.800, 0.385, 0.563)	4.85E-01	5.00E-01	2.19E-01
(0.867, 0.385, 0.563)	-2.77E-01	8.32E-01	2.65E-01
(0.933, 0.385, 0.563)	-1.34E-01	1.02E+00	4.85E-01
(0.067, 0.308, 0.563)	-1.22E-01	-6.68E-01	6.77E-01
(0.133, 0.308, 0.563)	-3.02E-01	-8.20E-01	4.27E-01
(0.200, 0.308, 0.563)	-4.02E-01	-6.98E-01	1.92E-01
(0.267, 0.308, 0.563)	-3.84E-01	-5.82E-01	1.34E-01
(0.333, 0.308, 0.563)	-4.63E-01	-5.46E-01	1.34E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 3

(X, Y, Z)	V _x	V _y	V _z
(0.400,0.308,0.563)	8.20E-01	7.62E-02	4.27E-02
(0.467,0.308,0.563)	6.31E-01	5.64E-01	3.96E-02
(0.533,0.308,0.563)	8.41E-01	2.74E-02	1.80E-01
(0.600,0.308,0.563)	-1.65E-01	-9.75E-02	3.47E-01
(0.667,0.308,0.563)	6.68E-01	2.47E-01	1.37E-01
(0.733,0.308,0.563)	6.64E-01	3.29E-01	1.55E-01
(0.800,0.308,0.563)	5.43E-01	4.63E-01	2.65E-01
(0.867,0.308,0.563)	-3.60E-01	7.22E-01	3.35E-01
(0.933,0.308,0.563)	-2.59E-01	9.08E-01	5.43E-01
(0.067,0.231,0.563)	-2.59E-01	-4.75E-01	6.49E-01
(0.133,0.231,0.563)	-4.72E-01	-6.16E-01	3.90E-01
(0.200,0.231,0.563)	-6.49E-01	-6.22E-01	3.29E-01
(0.267,0.231,0.563)	6.25E-01	4.91E-01	2.01E-01
(0.333,0.231,0.563)	8.14E-01	1.58E-01	2.47E-01
(0.400,0.231,0.563)	8.66E-01	2.29E-01	2.04E-01
(0.467,0.231,0.563)	8.72E-01	1.80E-01	6.10E-02
(0.533,0.231,0.563)	9.24E-01	4.88E-02	2.10E-01
(0.600,0.231,0.563)	9.48E-01	1.43E-01	2.41E-01
(0.667,0.231,0.563)	8.53E-01	2.77E-01	2.32E-01
(0.733,0.231,0.563)	6.55E-01	3.23E-01	3.11E-01
(0.800,0.231,0.563)	5.79E-01	3.99E-01	3.66E-01
(0.867,0.231,0.563)	4.97E-01	5.61E-01	3.78E-01
(0.933,0.231,0.563)	-2.99E-01	8.35E-01	4.42E-01
(0.067,0.154,0.563)	-3.96E-02	4.36E-01	-6.68E-01
(0.133,0.154,0.563)	-4.91E-01	5.33E-01	-3.23E-01
(0.200,0.154,0.563)	5.64E-01	5.52E-01	3.20E-01
(0.267,0.154,0.563)	7.65E-01	1.25E-01	4.33E-01
(0.333,0.154,0.563)	8.84E-01	-4.57E-02	3.14E-01
(0.400,0.154,0.563)	9.51E-01	1.49E-01	3.87E-01
(0.467,0.154,0.563)	9.81E-01	5.18E-02	3.63E-01
(0.533,0.154,0.563)	1.03E+00	1.62E-01	2.13E-01
(0.600,0.154,0.563)	9.88E-01	1.58E-01	3.20E-01
(0.667,0.154,0.563)	8.60E-01	2.44E-01	3.66E-01
(0.733,0.154,0.563)	7.25E-01	2.13E-01	3.41E-01
(0.800,0.154,0.563)	6.64E-01	2.77E-01	4.42E-01
(0.867,0.154,0.563)	-5.24E-01	-4.05E-01	-5.97E-01
(0.933,0.154,0.563)	-3.63E-01	-2.74E-02	-5.00E-01
(0.067,0.077,0.563)	-1.13E-01	3.08E-01	-9.36E-01
(0.133,0.077,0.563)	-1.77E-01	3.69E-01	-7.89E-01
(0.200,0.077,0.563)	-1.74E-01	2.23E-01	-4.72E-01
(0.267,0.077,0.563)	6.46E-01	2.62E-01	6.13E-01
(0.333,0.077,0.563)	7.71E-01	2.41E-01	7.16E-01
(0.400,0.077,0.563)	8.84E-01	2.80E-01	7.32E-01
(0.467,0.077,0.563)	1.00E+00	3.05E-02	4.54E-01
(0.533,0.077,0.563)	1.07E+00	1.92E-01	4.60E-01
(0.600,0.077,0.563)	9.48E-01	1.40E-01	4.97E-01
(0.667,0.077,0.563)	9.45E-01	2.01E-01	5.82E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 3

(X,Y,Z)	V _x	V _y	V _z
(0.733,0.077,0.563)	7.38E-01	3.14E-01	5.85E-01
(0.800,0.077,0.563)	5.52E-01	1.89E-01	4.54E-01
(0.867,0.077,0.563)	-5.15E-01	5.79E-02	-8.17E-01
(0.933,0.077,0.563)	-1.37E-01	1.46E-01	5.64E-01

Measurement level 4

(0.067,0.615,0.718)	2.13E-02	7.01E-02	8.32E-01
(0.133,0.615,0.718)	-1.89E-01	4.02E-01	6.83E-01
(0.200,0.615,0.718)	-4.85E-01	2.01E-01	4.30E-01
(0.267,0.615,0.718)	-5.76E-01	2.19E-01	9.14E-02
(0.333,0.615,0.718)	-5.12E-01	2.74E-01	1.95E-01
(0.400,0.615,0.718)	-6.28E-01	3.66E-02	2.16E-01
(0.467,0.615,0.718)	-5.97E-01	2.74E-02	1.07E-01
(0.533,0.615,0.718)	-4.15E-01	2.74E-02	1.98E-01
(0.600,0.615,0.718)	-4.48E-01	8.84E-02	2.56E-01
(0.667,0.615,0.718)	-4.72E-01	1.37E-01	3.54E-01
(0.733,0.615,0.718)	-4.69E-01	4.57E-02	1.89E-01
(0.800,0.615,0.718)	-2.07E-01	1.89E-01	4.42E-01
(0.867,0.615,0.718)	-1.49E-01	1.89E-01	5.06E-01
(0.933,0.615,0.718)	-1.13E-01	1.83E-01	6.55E-01
(0.067,0.538,0.718)	-1.98E-01	-1.49E-01	5.88E-01
(0.133,0.538,0.718)	-4.05E-01	-3.90E-01	3.17E-01
(0.200,0.538,0.718)	-3.99E-01	-3.47E-01	2.10E-01
(0.267,0.538,0.718)	-5.18E-01	1.55E-01	1.22E-02
(0.333,0.538,0.718)	-4.30E-01	4.57E-02	1.07E-01
(0.400,0.538,0.718)	-3.84E-01	8.23E-02	4.88E-02
(0.467,0.538,0.718)	-2.99E-01	1.28E-01	7.32E-02
(0.533,0.538,0.718)	-1.16E-01	1.46E-01	9.14E-02
(0.600,0.538,0.718)	-2.23E-01	8.84E-02	1.95E-01
(0.667,0.538,0.718)	-1.34E-01	1.31E-01	1.77E-01
(0.733,0.538,0.718)	-2.23E-01	1.19E-01	1.65E-01
(0.800,0.538,0.718)	-1.07E-01	2.90E-01	2.93E-01
(0.867,0.538,0.718)	-8.53E-02	3.72E-01	4.36E-01
(0.933,0.538,0.718)	-4.27E-02	3.87E-01	5.27E-01
(0.067,0.462,0.718)	-1.62E-01	-3.57E-01	4.45E-01
(0.133,0.462,0.718)	-2.59E-01	-3.51E-01	2.80E-01
(0.200,0.462,0.718)	-2.68E-01	-3.20E-01	2.19E-01
(0.267,0.462,0.718)	-2.38E-01	-1.58E-01	1.34E-01
(0.333,0.462,0.718)	-1.71E-01	-1.68E-01	3.96E-02
(0.400,0.462,0.718)	-1.62E-01	1.19E-01	7.32E-02
(0.467,0.462,0.718)	-1.80E-01	1.07E-01	3.96E-02
(0.533,0.462,0.718)	2.74E-02	1.52E-02	1.52E-01
(0.600,0.462,0.718)	-4.27E-02	3.35E-02	2.26E-01
(0.667,0.462,0.718)	-9.75E-02	1.13E-01	1.98E-01
(0.733,0.462,0.718)	-7.32E-02	2.50E-01	1.95E-01
(0.800,0.462,0.718)	1.52E-02	2.50E-01	2.68E-01
(0.867,0.462,0.718)	-6.71E-02	4.27E-01	4.42E-01
(0.933,0.462,0.718)	0.00E+00	3.66E-01	4.79E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 4

(X, Y, Z)	V _x	V _y	V _z
(0.067, 0.385, 0.718)	-1.40E-01	-4.91E-01	3.72E-01
(0.133, 0.385, 0.718)	-1.71E-01	-4.57E-01	3.20E-01
(0.200, 0.385, 0.718)	-2.56E-01	-2.87E-01	1.86E-01
(0.267, 0.385, 0.718)	-2.23E-01	1.34E-01	1.34E-01
(0.333, 0.385, 0.718)	-3.05E-02	-1.37E-01	1.58E-01
(0.400, 0.385, 0.718)	-1.62E-01	-1.01E-01	1.49E-01
(0.467, 0.385, 0.718)	-2.44E-02	9.14E-03	2.16E-01
(0.533, 0.385, 0.718)	-5.49E-02	1.52E-02	1.37E-01
(0.600, 0.385, 0.718)	-4.88E-02	3.05E-03	2.41E-01
(0.667, 0.385, 0.718)	-6.10E-03	2.44E-02	1.98E-01
(0.733, 0.385, 0.718)	-1.52E-01	2.59E-01	8.84E-02
(0.800, 0.385, 0.718)	-1.25E-01	2.99E-01	3.23E-01
(0.867, 0.385, 0.718)	1.55E-01	3.66E-01	3.84E-01
(0.933, 0.385, 0.718)	6.71E-02	3.93E-01	4.11E-01
(0.067, 0.308, 0.718)	-2.44E-02	-4.54E-01	3.96E-01
(0.133, 0.308, 0.718)	-4.88E-02	-3.81E-01	3.47E-01
(0.200, 0.308, 0.718)	-3.66E-02	-2.93E-01	3.41E-01
(0.267, 0.308, 0.718)	-2.13E-02	-1.80E-01	2.59E-01
(0.333, 0.308, 0.718)	-7.32E-02	-1.19E-01	2.04E-01
(0.400, 0.308, 0.718)	-5.18E-02	-5.79E-02	2.26E-01
(0.467, 0.308, 0.718)	3.96E-02	1.01E-01	1.92E-01
(0.533, 0.308, 0.718)	2.10E-01	1.22E-01	2.10E-01
(0.600, 0.308, 0.718)	1.22E-01	1.28E-01	2.59E-01
(0.667, 0.308, 0.718)	1.68E-01	2.16E-01	1.68E-01
(0.733, 0.308, 0.718)	-	-	-
(0.800, 0.308, 0.718)	2.99E-01	3.08E-01	2.50E-01
(0.867, 0.308, 0.718)	1.80E-01	3.75E-01	3.87E-01
(0.933, 0.308, 0.718)	3.96E-02	3.41E-01	5.03E-01
(0.067, 0.231, 0.718)	-1.28E-01	-3.75E-01	4.08E-01
(0.133, 0.231, 0.718)	-7.62E-02	-3.23E-01	4.27E-01
(0.200, 0.231, 0.718)	-7.62E-02	-2.56E-01	3.75E-01
(0.267, 0.231, 0.718)	2.83E-01	6.40E-02	2.80E-01
(0.333, 0.231, 0.718)	3.08E-01	6.10E-03	3.69E-01
(0.400, 0.231, 0.718)	2.35E-01	5.49E-02	3.14E-01
(0.467, 0.231, 0.718)	1.95E-01	2.19E-01	1.71E-01
(0.533, 0.231, 0.718)	3.72E-01	1.07E-01	2.59E-01
(0.600, 0.231, 0.718)	3.66E-01	1.74E-01	2.47E-01
(0.667, 0.231, 0.718)	2.80E-01	2.29E-01	2.10E-01
(0.733, 0.231, 0.718)	3.69E-01	3.26E-01	5.18E-02
(0.800, 0.231, 0.718)	3.38E-01	2.99E-01	3.11E-01
(0.867, 0.231, 0.718)	2.80E-01	3.29E-01	3.75E-01
(0.933, 0.231, 0.718)	1.46E-01	2.04E-01	5.09E-01
(0.067, 0.154, 0.718)	-1.19E-01	-2.19E-01	4.36E-01
(0.133, 0.154, 0.718)	-2.71E-01	-1.98E-01	4.08E-01
(0.200, 0.154, 0.718)	3.05E-01	5.18E-02	4.54E-01
(0.267, 0.154, 0.718)	4.79E-01	6.40E-02	2.59E-01
(0.333, 0.154, 0.718)	4.82E-01	3.66E-02	4.39E-01
(0.400, 0.154, 0.718)	4.63E-01	8.23E-02	4.30E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 4

(X, Y, Z)	V _x	V _y	V _z
(0.467, 0.154, 0.718)	3.81E-01	1.74E-01	2.90E-01
(0.533, 0.154, 0.718)	5.91E-01	2.01E-01	2.41E-01
(0.600, 0.154, 0.718)	5.24E-01	1.92E-01	2.90E-01
(0.667, 0.154, 0.718)	4.39E-01	1.95E-01	2.93E-01
(0.733, 0.154, 0.718)	4.85E-01	2.13E-01	1.19E-01
(0.800, 0.154, 0.718)	4.57E-01	2.32E-01	3.23E-01
(0.867, 0.154, 0.718)	3.08E-01	2.26E-01	4.60E-01
(0.933, 0.154, 0.718)	1.58E-01	2.74E-02	5.85E-01
(0.067, 0.077, 0.718)	-7.32E-02	5.18E-02	5.94E-01
(0.133, 0.077, 0.718)	1.34E-01	5.18E-02	5.18E-01
(0.200, 0.077, 0.718)	2.68E-01	1.31E-01	4.42E-01
(0.267, 0.077, 0.718)	4.66E-01	6.40E-02	3.11E-01
(0.333, 0.077, 0.718)	5.18E-01	7.32E-02	4.54E-01
(0.400, 0.077, 0.718)	4.94E-01	1.22E-01	4.21E-01
(0.467, 0.077, 0.718)	4.63E-01	8.23E-02	3.14E-01
(0.533, 0.077, 0.718)	6.22E-01	1.52E-01	3.23E-01
(0.600, 0.077, 0.718)	5.70E-01	9.75E-02	3.23E-01
(0.667, 0.077, 0.718)	4.51E-01	5.79E-02	3.38E-01
(0.733, 0.077, 0.718)	5.27E-01	8.23E-02	1.40E-01
(0.800, 0.077, 0.718)	4.18E-01	1.25E-01	3.96E-01
(0.867, 0.077, 0.718)	8.53E-02	1.95E-01	5.76E-01
(0.933, 0.077, 0.718)	-6.10E-03	7.62E-02	6.28E-01

Measurement level 5

(0.067, 0.615, 0.981)	1.74E-01	2.59E-01	3.66E-02
(0.133, 0.615, 0.981)	2.35E-01	3.51E-01	2.07E-01
(0.200, 0.615, 0.981)	1.46E-01	2.62E-01	-3.05E-03
(0.267, 0.615, 0.981)	3.17E-01	4.30E-01	-5.79E-02
(0.333, 0.615, 0.981)	6.71E-02	3.17E-01	7.01E-02
(0.400, 0.615, 0.981)	7.92E-02	3.51E-01	8.53E-02
(0.467, 0.615, 0.981)	9.45E-02	3.63E-01	1.07E-01
(0.533, 0.615, 0.981)	1.19E-01	5.70E-01	-3.35E-02
(0.600, 0.615, 0.981)	1.77E-01	5.49E-01	6.71E-02
(0.667, 0.615, 0.981)	1.80E-01	5.43E-01	-3.66E-02
(0.733, 0.615, 0.981)	1.52E-01	5.21E-01	-1.13E-01
(0.800, 0.615, 0.981)	9.45E-02	6.31E-01	1.71E-01
(0.867, 0.615, 0.981)	2.13E-01	6.68E-01	-9.14E-03
(0.933, 0.615, 0.981)	1.55E-01	7.01E-01	-9.45E-02
(0.067, 0.615, 0.962)	2.26E-01	2.32E-01	2.80E-01
(0.133, 0.615, 0.962)	-1.34E-01	2.77E-01	2.56E-01
(0.200, 0.615, 0.962)	-	-	-
(0.267, 0.615, 0.962)	2.68E-01	3.96E-01	-1.92E-01
(0.333, 0.615, 0.962)	2.26E-01	3.08E-01	6.40E-02
(0.400, 0.615, 0.962)	2.07E-01	3.29E-01	1.43E-01
(0.467, 0.615, 0.962)	1.31E-01	3.90E-01	1.19E-01
(0.533, 0.615, 0.962)	1.46E-01	4.18E-01	1.52E-01
(0.600, 0.615, 0.962)	1.37E-01	3.47E-01	9.75E-02
(0.667, 0.615, 0.962)	7.92E-02	4.02E-01	-9.45E-02

Table A.1- continued

Velocity Data (m/s)

Measurement level 5

(X, Y, Z)	V _x	V _y	V _z
(0.733, 0.615, 0.962)	1.58E-01	4.69E-01	1.22E-02
(0.800, 0.615, 0.962)	1.68E-01	5.49E-01	1.83E-01
(0.867, 0.615, 0.962)	1.40E-01	6.61E-01	6.71E-02
(0.933, 0.615, 0.962)	1.68E-01	6.10E-01	-1.49E-01
(0.067, 0.615, 0.943)	7.92E-02	1.46E-01	3.02E-01
(0.133, 0.615, 0.943)	2.71E-01	2.13E-01	2.47E-01
(0.200, 0.615, 0.943)	1.80E-01	1.95E-01	-6.10E-02
(0.267, 0.615, 0.943)	2.47E-01	3.87E-01	-2.99E-01
(0.333, 0.615, 0.943)	1.83E-01	3.26E-01	1.19E-01
(0.400, 0.615, 0.943)	1.83E-01	2.93E-01	7.92E-02
(0.467, 0.615, 0.943)	1.49E-01	3.51E-01	-9.14E-03
(0.533, 0.615, 0.943)	9.14E-02	2.93E-01	2.93E-01
(0.600, 0.615, 0.943)	1.22E-01	2.96E-01	1.13E-01
(0.667, 0.615, 0.943)	6.40E-02	3.23E-01	-1.34E-01
(0.733, 0.615, 0.943)	4.02E-01	4.21E-01	3.96E-02
(0.800, 0.615, 0.943)	8.53E-02	5.64E-01	1.74E-01
(0.867, 0.615, 0.943)	4.27E-02	5.09E-01	1.58E-01
(0.933, 0.615, 0.943)	8.53E-02	5.61E-01	-1.80E-01
(0.067, 0.615, 0.925)	1.80E-01	2.41E-01	5.09E-01
(0.133, 0.615, 0.925)	2.04E-01	1.77E-01	3.32E-01
(0.200, 0.615, 0.925)	6.10E-02	2.47E-01	-1.52E-01
(0.267, 0.615, 0.925)	1.77E-01	3.14E-01	-3.23E-01
(0.333, 0.615, 0.925)	1.80E-01	1.98E-01	2.71E-01
(0.400, 0.615, 0.925)	4.88E-02	2.44E-01	9.14E-02
(0.467, 0.615, 0.925)	7.62E-02	3.02E-01	-1.01E-01
(0.533, 0.615, 0.925)	4.27E-02	2.65E-01	2.99E-01
(0.600, 0.615, 0.925)	1.62E-01	2.47E-01	2.23E-01
(0.667, 0.615, 0.925)	2.10E-01	2.10E-01	-2.32E-01
(0.733, 0.615, 0.925)	-	-	-
(0.800, 0.615, 0.925)	1.92E-01	4.69E-01	1.62E-01
(0.867, 0.615, 0.925)	3.32E-01	3.93E-01	2.16E-01
(0.933, 0.615, 0.925)	3.96E-02	4.91E-01	7.32E-02
(0.067, 0.615, 0.906)	8.84E-02	3.69E-01	5.94E-01
(0.133, 0.615, 0.906)	2.32E-01	1.31E-01	2.56E-01
(0.200, 0.615, 0.906)	1.28E-01	1.43E-01	-1.86E-01
(0.267, 0.615, 0.906)	1.95E-01	2.23E-01	-2.13E-01
(0.333, 0.615, 0.906)	1.28E-01	1.46E-01	1.65E-01
(0.400, 0.615, 0.906)	4.57E-02	2.23E-01	1.83E-02
(0.467, 0.615, 0.906)	7.62E-02	2.83E-01	-1.25E-01
(0.533, 0.615, 0.906)	1.16E-01	2.93E-01	3.20E-01
(0.600, 0.615, 0.906)	1.10E-01	7.01E-02	2.44E-01
(0.667, 0.615, 0.906)	1.28E-01	2.19E-01	-3.20E-01
(0.733, 0.615, 0.906)	4.05E-01	4.33E-01	1.13E-01
(0.800, 0.615, 0.906)	9.14E-03	5.46E-01	1.16E-01
(0.867, 0.615, 0.906)	6.10E-02	3.93E-01	2.83E-01
(0.933, 0.615, 0.906)	3.05E-02	3.57E-01	4.51E-01
(0.067, 0.615, 0.887)	1.31E-01	2.93E-01	6.77E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 5

(X, Y, Z)	V _x	V _y	V _z
(0.133, 0.615, 0.887)	1.43E-01	1.62E-01	3.57E-01
(0.200, 0.615, 0.887)	6.40E-02	3.26E-01	-1.83E-01
(0.267, 0.615, 0.887)	1.74E-01	1.52E-01	-2.41E-01
(0.333, 0.615, 0.887)	1.65E-01	1.10E-01	2.50E-01
(0.400, 0.615, 0.887)	8.53E-02	1.95E-01	2.74E-02
(0.467, 0.615, 0.887)	3.05E-02	2.71E-01	-1.80E-01
(0.533, 0.615, 0.887)	8.53E-02	3.35E-01	2.68E-01
(0.600, 0.615, 0.887)	1.49E-01	1.34E-01	1.83E-01
(0.667, 0.615, 0.887)	2.32E-01	1.04E-01	-2.16E-01
(0.733, 0.615, 0.887)	1.49E-01	5.70E-01	1.68E-01
(0.800, 0.615, 0.887)	1.83E-02	4.48E-01	1.89E-01
(0.867, 0.615, 0.887)	-6.10E-03	3.35E-01	2.99E-01
(0.933, 0.615, 0.887)	3.05E-02	3.57E-01	3.84E-01
(0.067, 0.615, 0.868)	8.84E-02	3.63E-01	7.22E-01
(0.133, 0.615, 0.868)	1.62E-01	2.68E-01	2.87E-01
(0.200, 0.615, 0.868)	6.40E-02	1.01E-01	-2.53E-01
(0.267, 0.615, 0.868)	1.92E-01	2.16E-01	-2.07E-01
(0.333, 0.615, 0.868)	1.40E-01	2.62E-01	2.23E-01
(0.400, 0.615, 0.868)	8.23E-02	2.50E-01	-4.88E-02
(0.467, 0.615, 0.868)	4.57E-02	2.29E-01	-1.19E-01
(0.533, 0.615, 0.868)	1.16E-01	3.90E-01	2.71E-01
(0.600, 0.615, 0.868)	1.58E-01	1.07E-01	1.43E-01
(0.667, 0.615, 0.868)	2.10E-01	1.19E-01	-2.83E-01
(0.733, 0.615, 0.868)	1.13E-01	4.42E-01	-6.10E-03
(0.800, 0.615, 0.868)	1.58E-01	3.02E-01	2.47E-01
(0.867, 0.615, 0.868)	6.10E-03	2.68E-01	3.96E-01
(0.933, 0.615, 0.868)	5.49E-02	2.26E-01	5.76E-01
(0.067, 0.615, 0.849)	1.16E-01	5.21E-01	6.13E-01
(0.133, 0.615, 0.849)	1.46E-01	1.65E-01	4.15E-01
(0.200, 0.615, 0.849)	1.34E-01	2.38E-01	2.99E-01
(0.267, 0.615, 0.849)	4.27E-02	2.93E-01	2.80E-01
(0.333, 0.615, 0.849)	2.77E-01	2.04E-01	1.92E-01
(0.400, 0.615, 0.849)	1.16E-01	7.01E-02	-1.07E-01
(0.467, 0.615, 0.849)	-	-	-
(0.533, 0.615, 0.849)	8.53E-02	2.29E-01	1.40E-01
(0.600, 0.615, 0.849)	-	-	-
(0.667, 0.615, 0.849)	1.13E-01	4.57E-02	-2.44E-01
(0.733, 0.615, 0.849)	3.05E-02	3.17E-01	1.52E-02
(0.800, 0.615, 0.849)	8.84E-02	2.93E-01	1.22E-01
(0.867, 0.615, 0.849)	5.79E-02	5.49E-02	4.63E-01
(0.933, 0.615, 0.849)	1.28E-01	8.53E-02	5.55E-01
(0.067, 0.615, 0.830)	1.31E-01	5.52E-01	6.40E-01
(0.133, 0.615, 0.830)	9.45E-02	5.15E-01	5.00E-01
(0.200, 0.615, 0.830)	1.43E-01	3.38E-01	3.02E-01
(0.267, 0.615, 0.830)	1.55E-01	2.65E-01	3.69E-01
(0.333, 0.615, 0.830)	-3.96E-02	2.19E-01	1.22E-01
(0.400, 0.615, 0.830)	5.79E-02	-5.18E-02	-1.34E-01
(0.467, 0.615, 0.830)	2.74E-02	7.32E-02	1.74E-01

Table A.1- continued

Velocity Data (m/s)

Measurement level 5

(X,Y,Z)	V _x	V _y	V _z
(0.533,0.615,0.830)	2.26E-01	2.41E-01	1.01E-01
(0.600,0.615,0.830)	-	-	-
(0.667,0.615,0.830)	3.35E-02	6.10E-03	-1.86E-01
(0.733,0.615,0.830)	1.16E-01	1.52E-01	-3.96E-02
(0.800,0.615,0.830)	4.88E-02	1.52E-01	3.17E-01
(0.867,0.615,0.830)	3.35E-02	7.62E-02	4.48E-01
(0.933,0.615,0.830)	1.40E-01	1.68E-01	6.77E-01
(0.067,0.615,0.812)	7.01E-02	6.00E-01	5.76E-01
(0.133,0.615,0.812)	6.71E-02	5.85E-01	5.97E-01
(0.200,0.615,0.812)	1.04E-01	3.44E-01	3.78E-01
(0.267,0.615,0.812)	1.86E-01	2.93E-01	4.69E-01
(0.333,0.615,0.812)	1.86E-01	1.95E-01	7.62E-02
(0.400,0.615,0.812)	5.18E-02	1.74E-01	1.77E-01
(0.467,0.615,0.812)	7.92E-02	6.10E-02	1.98E-01
(0.533,0.615,0.812)	-	-	-
(0.600,0.615,0.812)	-	-	-
(0.667,0.615,0.812)	-	-	-
(0.733,0.615,0.812)	-	-	-
(0.800,0.615,0.812)	-	-	-
(0.867,0.615,0.812)	1.22E-01	1.55E-01	3.99E-01
(0.933,0.615,0.812)	1.95E-01	1.95E-01	6.07E-01
(0.067,0.615,0.792)	1.77E-01	0.00E+00	6.25E-01
(0.133,0.615,0.792)	1.22E-01	5.43E-01	5.24E-01
(0.200,0.615,0.792)	1.37E-01	6.13E-01	4.63E-01
(0.267,0.615,0.792)	2.04E-01	4.79E-01	5.64E-01
(0.333,0.615,0.792)	5.49E-02	3.78E-01	1.07E-01
(0.400,0.615,0.792)	1.43E-01	2.65E-01	1.19E-01
(0.467,0.615,0.792)	1.83E-01	1.98E-01	2.13E-01
(0.533,0.615,0.792)	0.00E+00	1.46E-01	0.00E+00
(0.600,0.615,0.792)	-	-	-
(0.667,0.615,0.792)	8.84E-02	0.00E+00	1.04E-01
(0.733,0.615,0.792)	0.00E+00	-5.49E-02	0.00E+00
(0.800,0.615,0.792)	-	-	-
(0.867,0.615,0.792)	1.43E-01	1.95E-01	4.75E-01
(0.933,0.615,0.792)	1.16E-01	2.38E-01	5.64E-01
(0.067,0.615,0.774)	5.79E-02	6.92E-01	-7.13E-01
(0.133,0.615,0.774)	1.95E-01	6.92E-01	-7.50E-01
(0.200,0.615,0.774)	2.13E-01	6.34E-01	-6.31E-01
(0.267,0.615,0.774)	2.13E-01	5.18E-01	-4.15E-01
(0.333,0.615,0.774)	2.10E-01	9.45E-02	-2.62E-01
(0.400,0.615,0.774)	1.92E-01	2.13E-01	-2.16E-01
(0.467,0.615,0.774)	-	-	-
(0.533,0.615,0.774)	-	-	-
(0.600,0.615,0.774)	-	-	-
(0.667,0.615,0.774)	6.71E-02	1.74E-01	-4.27E-02
(0.733,0.615,0.774)	1.52E-01	1.10E-01	-1.19E-01
(0.800,0.615,0.774)	1.31E-01	-9.45E-02	1.10E-01
(0.867,0.615,0.774)	-	-	-

Table A.1- continued

Velocity Data (m/s)

Measurement level 5

(X, Y, Z)	V _x	V _y	V _z
(0.933, 0.615, 0.774)	8.84E-02	2.13E-01	-2.68E-01

Measurement level 6

(0.067, 1.173, 0.981)	-	-	-
(0.133, 1.173, 0.981)	1.31E-01	2.32E-01	7.62E-02
(0.200, 1.173, 0.981)	2.13E-01	2.50E-01	3.66E-02
(0.267, 1.173, 0.981)	1.68E-01	3.81E-01	-2.13E-02
(0.333, 1.173, 0.981)	1.68E-01	2.44E-01	-1.52E-02
(0.400, 1.173, 0.981)	5.79E-02	3.20E-01	-1.83E-02
(0.467, 1.173, 0.981)	7.32E-02	3.32E-01	-9.14E-03
(0.533, 1.173, 0.981)	3.35E-02	3.99E-01	-3.35E-02
(0.600, 1.173, 0.981)	3.35E-02	3.60E-01	3.05E-03
(0.667, 1.173, 0.981)	2.13E-02	3.69E-01	-3.35E-02
(0.733, 1.173, 0.981)	1.13E-01	4.57E-01	-6.40E-02
(0.800, 1.173, 0.981)	4.27E-02	4.21E-01	1.52E-02
(0.867, 1.173, 0.981)	3.66E-02	4.36E-01	-3.96E-02
(0.933, 1.173, 0.981)	3.35E-02	3.90E-01	-1.01E-01
(0.067, 1.173, 0.962)	-	-	-
(0.133, 1.173, 0.962)	1.89E-01	1.92E-01	1.52E-01
(0.200, 1.173, 0.962)	2.35E-01	2.35E-01	4.88E-02
(0.267, 1.173, 0.962)	1.40E-01	3.54E-01	-7.32E-02
(0.333, 1.173, 0.962)	5.49E-02	2.50E-01	-2.13E-02
(0.400, 1.173, 0.962)	7.01E-02	2.93E-01	-3.05E-02
(0.467, 1.173, 0.962)	4.57E-02	3.23E-01	-2.74E-02
(0.533, 1.173, 0.962)	5.79E-02	3.08E-01	-4.57E-02
(0.600, 1.173, 0.962)	4.27E-02	3.14E-01	9.14E-03
(0.667, 1.173, 0.962)	1.83E-02	3.51E-01	-4.88E-02
(0.733, 1.173, 0.962)	1.22E-01	3.78E-01	0.00E+00
(0.800, 1.173, 0.962)	1.52E-02	4.63E-01	1.52E-02
(0.867, 1.173, 0.962)	3.96E-02	4.02E-01	-4.88E-02
(0.933, 1.173, 0.962)	3.96E-02	3.84E-01	-1.43E-01
(0.067, 1.173, 0.943)	1.68E-01	1.25E-01	2.07E-01
(0.133, 1.173, 0.943)	1.92E-01	2.16E-01	1.77E-01
(0.200, 1.173, 0.943)	2.35E-01	2.71E-01	1.01E-01
(0.267, 1.173, 0.943)	1.40E-01	3.11E-01	-1.19E-01
(0.333, 1.173, 0.943)	8.53E-02	2.41E-01	-1.22E-02
(0.400, 1.173, 0.943)	5.79E-02	2.87E-01	-1.52E-02
(0.467, 1.173, 0.943)	6.40E-02	3.14E-01	-3.96E-02
(0.533, 1.173, 0.943)	6.71E-02	2.74E-01	-1.22E-02
(0.600, 1.173, 0.943)	4.57E-02	2.74E-01	1.52E-02
(0.667, 1.173, 0.943)	5.18E-02	3.17E-01	-5.79E-02
(0.733, 1.173, 0.943)	6.71E-02	3.84E-01	-3.05E-03
(0.800, 1.173, 0.943)	9.45E-02	3.93E-01	4.57E-02
(0.867, 1.173, 0.943)	9.75E-02	4.15E-01	-1.83E-02
(0.933, 1.173, 0.943)	9.75E-02	4.45E-01	-1.68E-01
(0.067, 1.173, 0.925)	1.25E-01	2.56E-01	3.11E-01
(0.133, 1.173, 0.925)	1.31E-01	2.16E-01	2.04E-01
(0.200, 1.173, 0.925)	1.71E-01	2.50E-01	9.75E-02

Table A.1- continued

Velocity Data (m/s)

Measurement level 6

(X, Y, Z)

	V _x	V _y	V _z
(0.267, 1.173, 0.925)	1.04E-01	3.23E-01	-1.25E-01
(0.333, 1.173, 0.925)	7.32E-02	2.38E-01	-3.35E-02
(0.400, 1.173, 0.925)	6.40E-02	2.44E-01	1.83E-02
(0.467, 1.173, 0.925)	5.18E-02	2.83E-01	-4.57E-02
(0.533, 1.173, 0.925)	3.35E-02	2.56E-01	5.79E-02
(0.600, 1.173, 0.925)	6.10E-02	3.17E-01	-1.83E-02
(0.667, 1.173, 0.925)	7.62E-02	3.29E-01	-7.62E-02
(0.733, 1.173, 0.925)	1.10E-01	3.66E-01	3.05E-03
(0.800, 1.173, 0.925)	1.07E-01	3.84E-01	9.75E-02
(0.867, 1.173, 0.925)	9.14E-02	3.96E-01	-1.83E-02
(0.933, 1.173, 0.925)	1.10E-01	4.08E-01	-1.92E-01
(0.067, 1.173, 0.906)	1.10E-01	2.59E-01	3.51E-01
(0.133, 1.173, 0.906)	1.28E-01	2.53E-01	2.38E-01
(0.200, 1.173, 0.906)	1.28E-01	2.74E-01	4.88E-02
(0.267, 1.173, 0.906)	8.84E-02	2.93E-01	-1.55E-01
(0.333, 1.173, 0.906)	8.84E-02	2.32E-01	6.10E-03
(0.400, 1.173, 0.906)	6.71E-02	2.10E-01	4.27E-02
(0.467, 1.173, 0.906)	2.44E-02	2.77E-01	-7.01E-02
(0.533, 1.173, 0.906)	7.01E-02	2.29E-01	3.66E-02
(0.600, 1.173, 0.906)	5.49E-02	2.83E-01	-2.74E-02
(0.667, 1.173, 0.906)	4.27E-02	2.93E-01	-5.49E-02
(0.733, 1.173, 0.906)	1.01E-01	3.81E-01	0.00E+00
(0.800, 1.173, 0.906)	1.22E-01	3.57E-01	0.00E+00
(0.867, 1.173, 0.906)	6.40E-02	3.63E-01	-6.10E-02
(0.933, 1.173, 0.906)	1.25E-01	3.57E-01	-1.68E-01
(0.067, 1.173, 0.887)	1.04E-01	2.53E-01	3.81E-01
(0.133, 1.173, 0.887)	1.01E-01	3.05E-01	2.90E-01
(0.200, 1.173, 0.887)	4.57E-02	2.96E-01	2.01E-01
(0.267, 1.173, 0.887)	5.18E-02	2.87E-01	-1.13E-01
(0.333, 1.173, 0.887)	1.04E-01	2.16E-01	4.88E-02
(0.400, 1.173, 0.887)	2.13E-02	2.65E-01	6.71E-02
(0.467, 1.173, 0.887)	5.49E-02	2.74E-01	6.40E-02
(0.533, 1.173, 0.887)	6.10E-03	2.59E-01	4.57E-02
(0.600, 1.173, 0.887)	5.49E-02	2.62E-01	9.14E-03
(0.667, 1.173, 0.887)	5.49E-02	2.77E-01	-6.71E-02
(0.733, 1.173, 0.887)	9.75E-02	3.57E-01	-3.05E-03
(0.800, 1.173, 0.887)	5.79E-02	3.63E-01	2.44E-02
(0.867, 1.173, 0.887)	5.49E-02	3.20E-01	-3.35E-02
(0.933, 1.173, 0.887)	5.18E-02	2.87E-01	-1.28E-01
(0.067, 1.173, 0.868)	1.22E-01	3.32E-01	3.38E-01
(0.133, 1.173, 0.868)	3.66E-02	3.54E-01	2.50E-01
(0.200, 1.173, 0.868)	3.05E-02	3.23E-01	1.86E-01
(0.267, 1.173, 0.868)	1.58E-01	2.93E-01	9.75E-02
(0.333, 1.173, 0.868)	1.52E-01	2.29E-01	7.01E-02
(0.400, 1.173, 0.868)	2.74E-02	2.74E-01	1.22E-02
(0.467, 1.173, 0.868)	2.44E-02	2.80E-01	3.35E-02
(0.533, 1.173, 0.868)	2.44E-02	2.59E-01	6.40E-02

Table A.1- continued

Velocity Data (m/s)

Measurement level 6

(X, Y, Z)	V _x	V _y	V _z
(0.600,1.173,0.868)	2.13E-02	2.83E-01	1.22E-02
(0.667,1.173,0.868)	4.27E-02	2.50E-01	3.96E-02
(0.733,1.173,0.868)	4.27E-02	3.17E-01	-2.13E-02
(0.800,1.173,0.868)	5.18E-02	3.14E-01	-3.05E-03
(0.867,1.173,0.868)	1.34E-01	2.35E-01	-3.35E-02
(0.933,1.173,0.868)	1.52E-01	2.68E-01	-1.07E-01
(0.067,1.173,0.849)	7.32E-02	3.63E-01	3.17E-01
(0.133,1.173,0.849)	9.14E-02	4.08E-01	2.68E-01
(0.200,1.173,0.849)	7.62E-02	3.90E-01	2.32E-01
(0.267,1.173,0.849)	1.55E-01	4.15E-01	3.02E-01
(0.333,1.173,0.849)	9.45E-02	2.87E-01	1.43E-01
(0.400,1.173,0.849)	5.18E-02	2.93E-01	5.10E-02
(0.467,1.173,0.849)	2.13E-02	2.90E-01	7.32E-02
(0.533,1.173,0.849)	2.74E-02	2.29E-01	6.10E-02
(0.600,1.173,0.849)	4.57E-02	2.44E-01	3.96E-02
(0.667,1.173,0.849)	1.83E-02	2.35E-01	3.05E-02
(0.733,1.173,0.849)	8.53E-02	3.02E-01	6.10E-03
(0.800,1.173,0.849)	2.44E-02	2.50E-01	0.00E+00
(0.867,1.173,0.849)	4.57E-02	2.62E-01	-2.13E-02
(0.933,1.173,0.849)	6.40E-02	1.86E-01	-4.57E-02
(0.067,1.173,0.830)	6.10E-02	4.08E-01	4.05E-01
(0.133,1.173,0.830)	8.84E-02	4.39E-01	3.41E-01
(0.200,1.173,0.830)	1.07E-01	4.24E-01	3.02E-01
(0.267,1.173,0.830)	1.40E-01	4.36E-01	3.66E-01
(0.333,1.173,0.830)	5.18E-02	2.90E-01	1.34E-01
(0.400,1.173,0.830)	8.23E-02	2.93E-01	8.53E-02
(0.467,1.173,0.830)	4.27E-02	2.93E-01	1.43E-01
(0.533,1.173,0.830)	4.57E-02	2.53E-01	6.71E-02
(0.600,1.173,0.830)	1.07E-01	2.32E-01	8.84E-02
(0.667,1.173,0.830)	1.22E-02	2.53E-01	1.10E-01
(0.733,1.173,0.830)	1.22E-01	2.96E-01	3.05E-03
(0.800,1.173,0.830)	2.44E-02	3.02E-01	3.96E-02
(0.867,1.173,0.830)	5.18E-02	2.04E-01	6.40E-02
(0.933,1.173,0.830)	7.32E-02	1.07E-01	8.23E-02

Measurement level 7

(0.240,1.452,0.986)	0.00E+00	2.01E-01	9.14E-03
(0.292,1.452,0.986)	-9.75E-02	3.08E-01	9.14E-03
(0.344,1.452,0.986)	-1.28E-01	2.80E-01	0.00E+00
(0.396,1.452,0.986)	-1.07E-01	2.77E-01	-1.22E-02
(0.448,1.452,0.986)	-1.04E-01	2.68E-01	-2.44E-02
(0.500,1.452,0.986)	-8.53E-02	2.80E-01	-1.83E-02
(0.552,1.452,0.986)	-6.40E-02	2.83E-01	-1.52E-02
(0.604,1.452,0.986)	-4.88E-02	3.02E-01	-1.22E-02
(0.656,1.452,0.986)	-4.27E-02	2.96E-01	-1.52E-02
(0.708,1.452,0.986)	-4.27E-02	3.38E-01	-1.52E-02
(0.760,1.452,0.986)	-3.35E-02	3.47E-01	-2.44E-02
(0.240,1.452,0.972)	-3.05E-02	2.71E-01	6.10E-02

Table A.1- continued

Velocity Data (m/s)

Measurement level 7

(X, Y, Z)	V _x	V _y	V _z
(0.292, 1.452, 0.972)	-1.07E-01	3.11E-01	4.57E-02
(0.344, 1.452, 0.972)	-1.49E-01	2.80E-01	9.14E-03
(0.396, 1.452, 0.972)	-1.01E-01	2.80E-01	-2.13E-02
(0.448, 1.452, 0.972)	-7.62E-02	2.80E-01	-3.96E-02
(0.500, 1.452, 0.972)	-5.18E-02	2.83E-01	-3.96E-02
(0.552, 1.452, 0.972)	-4.88E-02	2.93E-01	-3.35E-02
(0.604, 1.452, 0.972)	-2.74E-02	2.96E-01	-1.83E-02
(0.656, 1.452, 0.972)	-3.66E-02	3.11E-01	-2.13E-02
(0.708, 1.452, 0.972)	-3.35E-02	3.35E-01	-1.22E-02
(0.760, 1.452, 0.972)	-3.35E-02	3.35E-01	-4.27E-02
(0.240, 1.452, 0.958)	-2.13E-02	3.02E-01	1.01E-01
(0.292, 1.452, 0.958)	-8.23E-02	3.14E-01	5.18E-02
(0.344, 1.452, 0.958)	-6.71E-02	3.11E-01	-3.35E-02
(0.396, 1.452, 0.958)	-6.40E-02	2.96E-01	-5.79E-02
(0.448, 1.452, 0.958)	-3.66E-02	2.96E-01	-6.10E-02
(0.500, 1.452, 0.958)	-3.35E-02	3.02E-01	-4.57E-02
(0.552, 1.452, 0.958)	-3.05E-02	3.02E-01	-3.35E-02
(0.604, 1.452, 0.958)	-2.44E-02	2.87E-01	-1.83E-02
(0.656, 1.452, 0.958)	-2.13E-02	2.99E-01	-2.44E-02
(0.708, 1.452, 0.958)	-3.96E-02	3.26E-01	-1.83E-02
(0.760, 1.452, 0.958)	-4.57E-02	3.38E-01	-5.49E-02
(0.240, 1.452, 0.944)	-1.22E-02	3.38E-01	1.04E-01
(0.292, 1.452, 0.944)	-3.35E-02	3.26E-01	4.88E-02
(0.344, 1.452, 0.944)	-2.13E-02	3.26E-01	-2.44E-02
(0.396, 1.452, 0.944)	-6.10E-03	3.11E-01	-4.88E-02
(0.448, 1.452, 0.944)	-2.44E-02	2.99E-01	-6.40E-02
(0.500, 1.452, 0.944)	-3.05E-02	2.99E-01	-4.88E-02
(0.552, 1.452, 0.944)	-1.22E-02	3.05E-01	-2.44E-02
(0.604, 1.452, 0.944)	-2.44E-02	2.83E-01	-2.44E-02
(0.656, 1.452, 0.944)	-2.13E-02	3.05E-01	-2.74E-02
(0.708, 1.452, 0.944)	-3.05E-02	3.17E-01	-2.13E-02
(0.760, 1.452, 0.944)	-2.13E-02	3.44E-01	-7.01E-02
(0.240, 1.452, 0.930)	-1.22E-02	3.47E-01	8.23E-02
(0.292, 1.452, 0.930)	-6.10E-03	3.26E-01	3.35E-02
(0.344, 1.452, 0.930)	-6.10E-03	3.23E-01	-1.83E-02
(0.396, 1.452, 0.930)	-9.14E-03	3.05E-01	-4.27E-02
(0.448, 1.452, 0.930)	-1.83E-02	2.99E-01	-3.96E-02
(0.500, 1.452, 0.930)	-2.44E-02	2.83E-01	-3.96E-02
(0.552, 1.452, 0.930)	-2.74E-02	2.77E-01	-2.13E-02
(0.604, 1.452, 0.930)	-1.52E-02	2.74E-01	-2.44E-02
(0.656, 1.452, 0.930)	-1.83E-02	3.08E-01	-1.83E-02
(0.708, 1.452, 0.930)	-1.52E-02	3.17E-01	-3.35E-02
(0.760, 1.452, 0.930)	-3.96E-02	3.32E-01	-8.53E-02
(0.240, 1.452, 0.916)	-1.22E-02	3.66E-01	5.79E-02
(0.292, 1.452, 0.916)	-1.22E-02	3.41E-01	1.52E-02
(0.344, 1.452, 0.916)	-6.10E-03	3.35E-01	-9.14E-03
(0.396, 1.452, 0.916)	-2.74E-02	2.93E-01	-3.05E-02
(0.448, 1.452, 0.916)	-2.13E-02	2.87E-01	-2.74E-02

Table A.1- continued

Velocity Data (m/s)

Measurement level 7

(X, Y, Z)	V _x	V _y	V _z
(0.500, 1.452, 0.916)	-2.74E-02	2.83E-01	-1.22E-02
(0.552, 1.452, 0.916)	-1.52E-02	2.83E-01	-2.74E-02
(0.604, 1.452, 0.916)	-6.10E-03	2.96E-01	-3.05E-02
(0.656, 1.452, 0.916)	-1.22E-02	3.02E-01	-2.13E-02
(0.708, 1.452, 0.916)	-1.22E-02	3.26E-01	-3.35E-02
(0.760, 1.452, 0.916)	-3.35E-02	3.38E-01	-7.32E-02
(0.240, 1.452, 0.902)	-1.52E-02	3.66E-01	3.66E-02
(0.292, 1.452, 0.902)	-1.83E-02	3.44E-01	2.13E-02
(0.344, 1.452, 0.902)	-6.10E-03	3.14E-01	-3.05E-03
(0.396, 1.452, 0.902)	-6.10E-03	3.08E-01	-9.14E-03
(0.448, 1.452, 0.902)	-9.14E-03	3.02E-01	-3.35E-02
(0.500, 1.452, 0.902)	-1.52E-02	2.83E-01	-1.83E-02
(0.552, 1.452, 0.902)	-9.14E-03	2.90E-01	-1.83E-02
(0.604, 1.452, 0.902)	-1.22E-02	2.83E-01	-1.83E-02
(0.656, 1.452, 0.902)	-6.10E-03	3.17E-01	-1.22E-02
(0.708, 1.452, 0.902)	-1.83E-02	3.20E-01	-3.66E-02
(0.760, 1.452, 0.902)	-7.32E-02	3.44E-01	-7.01E-02
(0.240, 1.452, 0.888)	-2.44E-02	3.35E-01	-9.14E-03
(0.292, 1.452, 0.888)	-3.35E-02	3.11E-01	3.05E-03
(0.344, 1.452, 0.888)	-6.40E-02	3.02E-01	-6.10E-03
(0.396, 1.452, 0.888)	-1.83E-02	3.08E-01	-6.10E-03
(0.448, 1.452, 0.888)	-2.13E-02	2.96E-01	-1.22E-02
(0.500, 1.452, 0.888)	-9.14E-03	2.83E-01	-6.10E-03
(0.552, 1.452, 0.888)	-2.13E-02	2.83E-01	-6.10E-03
(0.604, 1.452, 0.888)	-2.44E-02	2.87E-01	-6.10E-03
(0.656, 1.452, 0.888)	-2.74E-02	2.90E-01	-3.05E-02
(0.708, 1.452, 0.888)	-1.22E-02	3.23E-01	-3.35E-02
(0.760, 1.452, 0.888)	-3.66E-02	3.20E-01	-6.71E-02
(0.240, 1.452, 0.874)	-6.10E-03	3.08E-01	-3.96E-02
(0.292, 1.452, 0.874)	-4.57E-02	3.08E-01	1.52E-02
(0.344, 1.452, 0.874)	-3.96E-02	2.80E-01	3.05E-03
(0.396, 1.452, 0.874)	-1.52E-02	3.02E-01	-1.52E-02
(0.448, 1.452, 0.874)	-1.52E-02	2.93E-01	-2.13E-02
(0.500, 1.452, 0.874)	-6.10E-02	2.71E-01	-1.52E-02
(0.552, 1.452, 0.874)	-6.10E-02	2.74E-01	-1.83E-02
(0.604, 1.452, 0.874)	-4.57E-02	2.80E-01	-2.13E-02
(0.656, 1.452, 0.874)	-2.74E-02	2.93E-01	-1.22E-02
(0.708, 1.452, 0.874)	-5.18E-02	3.05E-01	-1.83E-02
(0.760, 1.452, 0.874)	-3.96E-02	3.05E-01	-4.27E-02

Introduction to Case A2

Consolidation Coal Company Cold Flow (Havekotte, 1988)

Case A2 a non-reacting gaseous flow data set. The data were taken in a pilot-scale furnace owned by Consolidation Coal Company located in Library, Penn. The cold-flow data were taken by Consolidation Coal Company to assist Brigham Young University evaluate the cold flow portions of the three-dimensional code before other gaseous, non-reacting flow data were located. The confidential report (Havekotte, 1988) was provided to Brigham Young University with a restriction that furnace dimensions can only be released in non-dimensional format. The data were included in the data book because it was one of only two cold-flow data sets located of acceptable quality. By fully documenting the data set, potential users can determine if the set merits pursuing from the owners.

The first section of the data set gives as much detail as possible about the geometry of the furnace within the limitations of the non-disclosure agreement. A three-dimensional perspective illustration shows the basic design of the furnace and the coordinate system used to identify measurement locations and some geometrical features. Figure A.6 shows the furnace dimensions. The dimensions are all normalized by using the width, depth, and height for transforming the X, Y, and Z axes, respectively.

Table A.2 contains the data set. The first page of the data set provides general information about the furnace operating conditions. A tracer gas was injected through three of the four burners to evaluate mixing characteristics. The composition of the gas entering the furnace is specified.

The data measurements are presented in a five-column format. The first column has the normalized X, Y, and Z coordinates of the measurement. The second column is the carbon monoxide concentration in parts per million. A carbon monoxide/carbon dioxide mixture of gases was used as the tracer. The last three columns are the three components of the velocity vector in meters per second. The X-component of the velocity was not reported since it was experimentally determined to be undetectable at all measurement locations. A "-" sign was used for missing values to document that a velocity parallel to the X-axis was checked for but not measured.

Figure A.5

Case A2 and D1 - Three-Dimensional Drawing of Furnace.

X+, Y+, and Z+ are the coordinate axes used to locate measurements and geometrical features of the furnace. Dimensions of the furnace are not permitted to be used in this document by agreement with Consolidation Coal Company, Library, Penn. Information used for this figure was taken from Havekotte (1987), provided by Consolidation Coal Company.

Figure A.6

Cases A2 and D1 - Dimensioned Drawing of Furnace.

Publication of furnace dimensions is restricted through agreement with Consolidation Coal Company, Library, Penn. Dimensions shown above are normalized by the furnace width, depth, and height. $X+$, $Y+$, and $Z+$ refer to the coordinate axes. See Figure A.5 for furnace orientation relative to the X - Y - Z coordinates. Information for this figure is from Havekotte (1987), provided by Consolidation Coal Company.

Figure A.7

Case A2 and D1 - Schematic of Burner

Furnace dimensions are restricted from publication through agreement with Consolidation Coal Company. The dimensions used above have units of meters. Information about the burners was provided by Consolidation Coal Company and was not included in any publicly available reports.

Data are used by permission of Consolidation Coal Company, Library, Penn.

Table A.2
Data Set for Case A2

Case A2.
Consolidation Coal Company
Cold Flow (Havekotte, 1988)

General Information

Furnace Specifications

Dimensions (w X d X h, meters)   restricted
No. of Burners: 4

Burner Locations (see Figure A.6)

Primary Stream

Solids Feed Rate (kg/s)	0.0	0.0	0.0	0.0
Gas Flow (kg/s)	0.00753	0.00742	0.00769	0.00745
Gas Temperature (K)	347	353	344	346
Tube Dimensions i.d. (m)	0.017	0.017	0.017	0.017
o.d. (m)	0.038	0.038	0.038	0.038
Burner Velocity (m/s)	35	35	35	34
Theoretical Swirl No.	6.0	5.6	6.0	5.9

Secondary Stream

Gas Flow (kg/s)	0.04896	0.04621	0.04797	0.04852
Gas Temperature (K)	374	374	373	373
Tube Dimension i.d. (m)	0.0665	0.0665	0.0665	0.0665
Theoretical Swirl No.	6.0	5.6	6.0	5.9
Furnace Pressure ²	-	-	-	-

Fuel Compositions

Gas - Primary

N ₂	0.79	0.78	0.78	0.78
O ₂	0.21	0.21	0.21	0.21
CO	0	0.00500	0.00500	0.00500
CO ₂	0	0.00300	0.00300	0.00300

Gas - Secondary

N ₂	0.79	0.79	0.79	0.79
O ₂	0.21	0.21	0.21	0.21

CO Concentration and Velocity Measurements

(X, Y, Z)	[CO] (ppm)	V _x (m/s)	V _y (m/s)	V _z (m/s)
(0.97, 0.54, FireBox)	102	-	0.00E+00	1.19E-01
(0.83, 0.54, FireBox)	110	-	1.82E-01	1.42E-01

1- Furnace dimensions are restricted to non-dimensional form by request of Consolidation Coal Company.

2- No information given about furnace pressure. -0.4 inches of water reported in Case D1 which is in the same furnace using pulverized coal as the fuel.

Table A.2 - continued

CO Concentration and Velocity Measurements				
(X, Y, Z)	[CO] (ppm)	Vx (m/s)	Vy (m/s)	Vz (m/s)
(0.50, 0.54, FireBox)	106	-	-7.11E-02	-4.45E-02
(0.17, 0.54, FireBox)	98	-	-1.42E-01	-3.02E-02
(0.03, 0.54, FireBox)	102	-	0.00E+00	4.57E-02
(0.97, 0.14, 0.44)	111	-	0.00E+00	5.11E-02
(0.97, 0.49, 0.44)	110	-	0.00E+00	2.54E-02
(0.97, 0.83, 0.44)	105	-	0.00E+00	1.78E-02
(0.83, 0.14, 0.44)	109	-	5.08E-02	1.17E-01
(0.83, 0.49, 0.44)	113	-	-8.13E-02	6.60E-02
(0.83, 0.83, 0.44)	110	-	5.08E-02	6.35E-02
(0.50, 0.14, 0.44)	104	-	-2.54E-02	3.56E-02
(0.50, 0.49, 0.44)	109	-	-3.56E-02	-5.84E-02
(0.50, 0.83, 0.44)	112	-	1.78E-02	0.00E+00
(0.17, 0.14, 0.44)	105	-	-2.54E-02	0.00E+00
(0.17, 0.49, 0.44)	108	-	-8.13E-02	5.33E-02
(0.17, 0.83, 0.44)	110	-	-4.32E-02	0.00E+00
(0.03, 0.14, 0.44)	104	-	0.00E+00	0.00E+00
(0.03, 0.49, 0.44)	106	-	0.00E+00	6.86E-02
(0.03, 0.83, 0.44)	104	-	0.00E+00	1.78E-02
(0.97, 0.14, 0.58)	104	-	0.00E+00	3.30E-02
(0.97, 0.49, 0.58)	109	-	0.00E+00	1.27E-02
(0.97, 0.83, 0.58)	106	-	0.00E+00	1.78E-02
(0.83, 0.14, 0.58)	110	-	0.00E+00	4.32E-02
(0.83, 0.49, 0.58)	113	-	3.56E-02	0.00E+00
(0.83, 0.83, 0.58)	110	-	2.03E-02	2.03E-02
(0.50, 0.14, 0.58)	109	-	0.00E+00	4.57E-02
(0.50, 0.49, 0.58)	109	-	2.79E-02	2.79E-02
(0.50, 0.83, 0.58)	111	-	0.00E+00	2.29E-02
(0.17, 0.14, 0.58)	109	-	-2.54E-02	6.60E-02
(0.17, 0.49, 0.58)	108	-	2.54E-02	4.83E-02
(0.17, 0.83, 0.58)	111	-	-2.29E-02	0.00E+00
(0.03, 0.14, 0.58)	109	-	0.00E+00	0.00E+00
(0.03, 0.49, 0.58)	109	-	0.00E+00	4.32E-02
(0.03, 0.83, 0.58)	111	-	0.00E+00	3.05E-02
(0.97, 0.14, 0.72)	66	-	0.00E+00	0.00E+00
(0.97, 0.49, 0.72)	102	-	0.00E+00	1.27E-02
(0.97, 0.83, 0.72)	100	-	0.00E+00	1.27E-02
(0.83, 0.14, 0.72)	109	-	0.00E+00	2.79E-02
(0.83, 0.49, 0.72)	105	-	-2.29E-02	2.54E-02
(0.83, 0.83, 0.72)	109	-	0.00E+00	3.56E-02
(0.50, 0.14, 0.72)	110	-	-1.27E-02	4.83E-02
(0.50, 0.49, 0.72)	105	-	-1.78E-02	3.05E-02
(0.50, 0.83, 0.72)	106	-	0.00E+00	1.78E-02
(0.17, 0.14, 0.72)	108	-	2.29E-02	7.11E-02
(0.17, 0.49, 0.72)	106	-	2.54E-02	3.56E-02
(0.17, 0.83, 0.72)	106	-	0.00E+00	2.54E-02
(0.03, 0.14, 0.72)	-	-	0.00E+00	0.00E+00
(0.03, 0.49, 0.72)	107	-	0.00E+00	3.56E-02
(0.03, 0.83, 0.72)	106	-	0.00E+00	4.57E-02

Appendix B

Particle Ladened Cold Flow

(This section is intentionally left empty. It has been added to keep the logical ordering of appendices for a future time in which this class of data becomes available.)

Appendix C

Reacting Gases

Combustion

Introduction to Case C1

Institute of Gas Technology Furnace (Abbasi, 1983)

Case C1 is a parametric data set with six different sets of operating conditions. The operating conditions are similar except for two or three inlet conditions that are changed for each set. The data were taken in a pilot-scale furnace that was modified to simulate an industrial glass melting furnace with soda-lime glass and heat exchangers used as a heat sink. The furnace is owned and operated by the Institute of Gas Technology located in Chicago, Ill. The data were taken as part of a study sponsored by the Gas Research Institute and tabulated in the final contract report (Abbasi, 1983).

The first several pages of the data set contain figures showing the furnace orientation relative to an arbitrarily assigned coordinate system. The coordinate system is used to locate various furnace geometries and measurement locations. All dimensions in the figures are given in meters unless otherwise indicated.

The Case C1 furnace is horizontally oriented. The burner is inserted through a port in the end of the rectangular section of the furnace where the glass is melted. The combustion air is pre-heated by burning natural gas in a pre-heater section upstream from the burner (not shown in figures) and adding make-up oxygen to the combustion gases leaving the pre-heater. The natural-gas fuel is injected through an orifice located on both side walls of the burner. The fuel inlet is either directed perpendicular (90°) to the burner walls or at a 45° angle with the wall pointing towards the burner outlet. Fuel injection velocity at a constant firing rate is the major parameter investigated in the data sets included in this appendix. The effect of the injection velocity on NO_x emissions is the result of interest in the original study.

Following the Figures of the furnace details are the operating conditions and experimental measurements. The case identifications all start with C1 to indicate that the data are all part of a parametric data set. A numerical extension is added to the case identification number to identify the individual operating condition within the case, such as C1.2 for the second set of data in Case C1. Most of the operating conditions are assumed to be the same for each of the data sets except for the parametric variables of interest. Case C1.1 is considered to be the base case. Parameters in the other sets in Case C1 that are different from the base case are underlined.

No specifications were given concerning the natural gas composition. Natural gas composition changes from location to location and from time to time. Since

no composition was specified, estimations were made using information provided in Perry (1973). No physical parameters such as heat capacity were given for the glass. The glass composition is listed in Table C.1.

Table C.1

Case C1 - Composition of Soda-Lime Glass.

The glass covering the furnace floor has the composition listed below. Information taken from Abbasi (1983).

	Weight Percent
SiO ₂	72.20
Al ₂ O ₃	1.64
Fe ₂ O ₃	0.05
CaO	10.98
MgO	0.49
Na ₂ O	14.03
K ₂ O	0.30
SO ₃	0.24
MnO	0.03

The Case C1 furnace is interesting because of its unusual design compared to power-generating facilities. The roof and side walls, insulated with thick refractory lining, are probably close to being adiabatic. The furnace floor is covered with 0.05 meters (2 inches) of glass on top of water-cooled heat exchangers. At steady-state conditions, the furnace floor is approximately isothermal. The two types of surfaces provide two types of boundary conditions within the same furnace. Most of the furnaces used in power generation have only isothermal boundary conditions since the walls are typically water cooled.

Figure C.1

Case C1 - Three-dimensional Drawing of Furnace.

The various layers on the bottom of the furnace are detailed in Figure C.3. The X-Y-Z system superimposed on the furnace drawing is used to located furnace geometries and measurement locations. Information for the drawing taken from Abbassi (1983).

Figure C.2

Case C1 - Dimensioned Drawing of Furnace.

The layers on the floor are water-cooled heat exchangers covered with a layer of refractory brick followed by a layer of glass. The information for this drawing was taken from Abbasi (1983). See Figure C.1 for the X-Y-Z orientation. See Figure C.3 for the end view of the furnace. All dimensions are given in meters.

Figure C.3

Case C1 - Dimensioned End View of Furnace.

X, Y, Z axes are shown for furnace in Figure C.1. Information taken from Abbasi (1983). Glass composition is given in Table C.1. All dimension are in meters.

Figure C.4

Case C1 - Dimensions of Burners.

Information for burners taken from original report (Abbasi, 1983). All dimensions are in meters. Fuel injector angles are 45° for the front two injectors and 90° for the injectors nearest to the rear of the burner. The burner inserts into a port on the main furnace section.

Table C.2

Data Set for Case C1.1 (Abbasi, 1983)

Reacting Gas Combustion
Institute of Gas Technology

Fuel Type: Natural Gas

Furnace Specifications

Dimensions (w X d X h, meters) 1.37 x 3.35 x 0.914

Combustion Air Stream

Gas Flow (kg/s)	0.198
Gas Temperature (K)	1439
Air Velocity (m/s)	4.42
Excess Air, %	11

Fuel Gas Stream

Gas Flow (kg/s)	0.0106
Gas Temperature (K)	289
Gas Velocity (m/s)	155
Firing Rate (J/s)	590000
Furnace Pressure (kPa)	0.009

Fuel Compositions

Fuel Air, mol. frct.

N ₂	0.697
O ₂	0.210
CO ₂	0.031
H ₂ O	0.062
NO _x (ppm)	170
CO (ppm)	≤10

Fuel Gas¹

CH ₄	0.8901
C ₂ H ₆	0.0519
C ₃ H ₈	0.0189
Butanes	0.0066
Pentanes	0.0044
Hexanes plus	0.0002
N ₂	0.0273
He	0.0006

Heating Value, Dry (MJ/kg) 55.6

-
- 1- Exact composition not given in report.
  - 2- Details about fuel are not given. Values for fuel are estimated using the given firing rate of 2 million Btu/h and a heating value of 1051 Btu/cubic foot (Perry, 1973).
  - 3- Fuel composition and heating value estimation from Chemical Engineers' Handbook (Perry, 1973). Natural gas compositions vary from location to location and over time.

Table C.2 - continued

Temperature (X, Y, Z)		Temperature (K)		
(0.50, 0.091, 1.0)		1747		
(0.50, 0.36, 1.0)		1783		
(0.50, 0.64, 1.0)		1754		
(0.50, 0.91, 1.0)		1783		
(1.0, 0.12, 0.50)		1779		
(1.0, 0.66, 0.50)		1811		
(0.50, 0.36, 0.045) ¹		1674		
(0.50, 1.2, 0.50)		1856		

Flue Gas Analyses				
O ₂ (mol %)	CO (ppm)	CO ₂ (mol %)	NO (ppm)	NO _x (ppm)
2.4	50	14.8	2400	2500

Table C.3

Data Set for Case C1.2² (Abbasi, 1983)

Reacting Gas Combustion
Institute of Gas Technology

Fuel Type: Natural Gas³

Furnace Specifications
Dimensions (w X d X h, meters)   1.37 x 3.35 x 0.914

Combustion Air Stream
Gas Flow (kg/s)   0.198
Gas Temperature (K)   1436
Air Velocity (m/s)   4.42
Excess Air, %   11

Fuel Gas Stream⁴
Gas Flow (kg/s)   0.0106
Gas Temperature (K)   289
Gas Velocity (m/s)   76.2
Firing Rate (J/s)   590000
Furnace Pressure (kPa)   0.009

-
- 1- Thermocouple tip was covered with ceramic and located on furnace wall.
  - 2- The ".2" extension on the case number refers to a second data set similar to the first case given in Table C.1 but with the underlined inlet conditions changed.
  - 3- Composition not given in original report.
  - 4- Details about fuel are not given. Values for fuel are estimated using the given firing rate of 2 million Btu/h and a heating value of 1051 Btu/cubic foot (Perry, 1973).

Table C.3 - continued

Fuel Compositions

Fuel Air, mol. frac.

N ₂	0.697
O ₂	0.210
CO ₂	0.031
H ₂ O	0.062
NO _x (ppm)	170
CO (ppm)	≤10

Fuel Gas¹

CH ₄	0.8901
C ₂ H ₆	0.0519
C ₃ H ₈	0.0189
Butanes	0.0066
Pentanes	0.0044
Hexanes plus	0.0002
N ₂	0.0273
He	0.0006

Heating Value, Dry (MJ/kg) 55.6

Temperature

(X, Y, Z)	Temp (K)
(0.50, 0.091, 1.0)	1738
(0.50, 0.36, 1.0)	1774
(0.50, 0.64, 1.0)	1746
(0.50, 0.91, 1.0)	1778
(1.0, 0.12, 0.50)	1766
(1.0, 0.66, 0.50)	1779
(0.50, 0.36, 0.045) ²	1683
(0.50, 1.2, 0.50)	1869

Heat Flux Through Glass on Furnace Floor

(X, Y, Z)	Heat Flux (J/s-m ²)
(0.50, 0.091, 0.0)	16.9
(0.50, 0.27, 0.0)	16.2
(0.50, 0.43, 0.0)	15.1
(0.50, 0.59, 0.0)	14.7
(0.50, 0.74, 0.0)	14.2
(0.50, 0.89, 0.0)	14.8

1- Details about fuel are not given. Values for fuel are estimated using the given firing rate of 2 million Btu/h and a heating value of 1051 Btu/cubic foot (Perry, 1973).

2- Thermocouple tip was covered with ceramic and located on furnace wall.

Table C.3 - continued

Flue Gas Analyses

O ₂ (mol %)	CO (ppm)	CO ₂ (mol %)	NO (ppm)	NO _x (ppm)
2.4	100	14.8	1930	2070

Table C.4

Data Set for Case C1.3 (Abbasi, 1983)

Reacting Gas Combustion
Institute of Gas Technology

Fuel Type: Natural Gas

Furnace Specifications

Dimensions (w X d X h, meters)   1.37 x 3.35 x 0.914

Combustion Air Stream

Gas Flow (kg/s)	0.198
Gas Temperature (K)	<u>1433</u>
Air Velocity (m/s)	4.42
Excess Air, %	11

Fuel Gas Stream

Gas Flow (kg/s)	0.0106
Gas Temperature (K)	289
Gas Velocity (m/s)	<u>36.6</u>
Firing Rate (J/s)	590000
Furnace Pressure (kPa)	0.014

Fuel Compositions

Fuel Air, mol. fr.

N ₂	0.697
O ₂	0.210
CO ₂	0.031
H ₂ O	0.062
NO _x (ppm)	170
CO (ppm)	≤10

Fuel Gas

CH ₄	0.8901
C ₂ H ₆	0.0519
C ₃ H ₈	0.0189
Butanes	0.0066
Pentanes	0.0044
Hexanes plus	0.0002
N ₂	0.0273
He	0.0006

1- Footnotes for cases C1.1 and C1.2 apply to all cases in the C1 data set. See Tables C.1, C.2, and C.3 for comments about the data set.

Table C.4 - continued

(0.50, 0.091,1.0)	1745
(0.50, 0.36 ,1.0)	1777
(0.50, 0.64 ,1.0)	1750
(0.50, 0.91 ,1.0)	1775
(1.0 , 0.12 ,0.50)	1779
(1.0 , 0.66 ,0.50)	1783
(0.50, 0.36 ,0.045)	1689
(0.50, 1.2 ,0.50)	1859

Heat Flux Through Glass on Furnace Floor

(X,Y,Z)	Heat Flux (J/s-m ²)
(0.50, 0.091,0.0)	17.1
(0.50, 0.27 ,0.0)	16.3
(0.50, 0.43 ,0.0)	14.9
(0.50, 0.59 ,0.0)	14.7
(0.50, 0.74 ,0.0)	14.0
(0.50, 0.89 ,0.0)	14.8

Flue Gas Analyses

O ₂ (mol %)	CO (ppm)	CO ₂ (mol %)	NO (ppm)	NO _x (ppm)
2.5	50	14.8	1550	1630

Table C.5

Data Set for Case C1.4 (Abbasi, 1983)

Reacting Gas Combustion
Institute of Gas Technology

Fuel Type: Natural Gas

Furnace Specifications

Dimensions (w X d X h, meters)   1.37 x 3.35 x 0.914

Combustion Air Stream

Gas Flow (kg/s)	0.198
Gas Temperature (K)	<u>1436</u>
Air Velocity (m/s)	4.42
Excess Air, %	11

Fuel Gas Stream

Gas Flow (kg/s)	0.0106
Gas Temperature (K)	289
Gas Velocity (m/s)	<u>24</u>
Firing Rate (J/s)	590000
Furnace Pressure (kPa)	<u>0.014</u>

Table C.5- continued

Fuel Compositions

Fuel Air, mol. frac.

N ₂	0.697
O ₂	0.210
CO ₂	0.031
H ₂ O	0.062
NO _x (ppm)	170
CO (ppm)	≤10

Fuel Gas

CH ₄	0.8901
C ₂ H ₆	0.0519
C ₃ H ₈	0.0189
Butanes	0.0066
Pentanes	0.0044
Hexanes plus	0.0002
N ₂	0.0273
He	0.0006

Heating Value, Dry (MJ/kg) 55.6

Temperature

(X, Y, Z)	Temp (K)
(0.50, 0.091, 1.0)	1744
(0.50, 0.36, 1.0)	1776
(0.50, 0.64, 1.0)	1747
(0.50, 0.91, 1.0)	1773
(1.0, 0.12, 0.50)	1778
(1.0, 0.66, 0.50)	1777
(0.50, 0.36, 0.045)	-
(0.50, 1.2, 0.50)	1831

Heat Flux Through Glass on Furnace Floor

(X, Y, Z)	Heat Flux (J/s-m ²)
(0.50, 0.091, 0.0)	17.4
(0.50, 0.27, 0.0)	17.2
(0.50, 0.43, 0.0)	15.8
(0.50, 0.59, 0.0)	15.2
(0.50, 0.74, 0.0)	14.6
(0.50, 0.89, 0.0)	14.9

Flue Gas Analyses

O ₂ (mol %)	CO (ppm)	CO ₂ (mol %)	NO (ppm)	NO _x (ppm)
2.5	50	14.0	1280	1350

Table C.6

Data Set for Case C1.5 (Abbasi, 1983)

Reacting Gas Combustion
Institute of Gas Technology

Fuel Type: Natural Gas

Furnace Specifications

Dimensions (w X d X h, meters) 1.37 x 3.35 x 0.914

Combustion Air Stream

Gas Flow (kg/s) 0.198

Gas Temperature (K) 1431

Air Velocity (m/s) 4.42

Excess Air, % 11

Fuel Gas Stream

Gas Flow (kg/s) 0.0106

Gas Temperature (K) 289

Gas Velocity (m/s) 23

Firing Rate (J/s) 590000

Furnace Pressure (kPa) 0.014

Fuel Compositions

Fuel Air, mol. frac.

N₂ 0.697

O₂ 0.210

CO₂ 0.031

H₂O 0.062

NO_x (ppm) 170

CO (ppm) ≤10

Fuel Gas

CH₄ 0.8901

C₂H₆ 0.0519

C₃H₈ 0.0189

Butanes 0.0066

Pentanes 0.0044

Hexanes plus 0.0002

N₂ 0.0273

He 0.0006

Heating Value, Dry (MJ/kg) 55.6

Table C.6 - continued

Temperature (X, Y, Z)	Temp (K)
(0.50, 0.091, 1.0)	1743
(0.50, 0.36, 1.0)	1779
(0.50, 0.64, 1.0)	1751
(0.50, 0.91, 1.0)	1772
(0.12, 1.0, 0.50)	1778
(0.66, 1.0, 0.50)	1783
(0.50, 0.36, 0.045)	1692
(0.50, 1.2, 0.50)	1852

Heat Flux Through Glass on Furnace Floor (X, Y, Z)	Heat Flux (J/m ²)
(0.50, 0.091, 0.0)	17.2
(0.50, 0.27, 0.0)	16.6
(0.50, 0.43, 0.0)	15.3
(0.50, 0.59, 0.0)	14.7
(0.50, 0.74, 0.0)	14.1
(0.50, 0.89, 0.0)	14.4

Flue Gas Analyses

Table C.7

Data Set for Case C1.6 (Abbasi, 1983)

Reacting Gas Combustion
Institute of Gas Technology

Fuel Type: Natural Gas

Furnace Specifications
Dimensions (w X d X h, meters)   1.37 x 3.35 x 0.914

Combustion Air Stream
Gas Flow (kg/s)   0.198
Gas Temperature (K)   1432
Air Velocity (m/s)   4.42
Excess Air, %   11

Fuel Gas Stream
Gas Flow (kg/s)   0.0106
Gas Temperature (K)   289
Gas Velocity (m/s)   17
Firing Rate (J/s)   590000
Furnace Pressure (kPa)   0.014

Table C.7 - continued

Fuel Compositions

Fuel Air, mol. frs.

N ₂	0.697
O ₂	0.210
CO ₂	0.031
H ₂ O	0.062
NO _x (ppm)	170
CO (ppm)	≤10

Fuel Gas

CH ₄	0.8901
C ₂ H ₆	0.0519
C ₃ H ₈	0.0189
Butanes	0.0066
Pentanes	0.0044
Hexanes plus	0.0002
N ₂	0.0273
He	0.0006

Heating Value, Dry (MJ/kg) 55.6

Temperature

(X, Y, Z)	Temp (K)
(0.50, 0.091, 1.0)	1743
(0.50, 0.36, 1.0)	1779
(0.50, 0.64, 1.0)	1751
(0.50, 0.91, 1.0)	1772
(1.0, 0.12, 0.50)	1778
(1.0, 0.66, 0.50)	1783
(0.50, 0.36, 0.045)	1692
(0.50, 1.2, 0.50)	1852

Heat Flux Through Glass on Furnace Floor

(X, Y, Z)	Heat Flux (J/s-m ²)
(0.50, 0.091, 0.0)	16.8
(0.50, 0.27, 0.0)	16.9
(0.50, 0.43, 0.0)	15.5
(0.50, 0.59, 0.0)	15.1
(0.50, 0.74, 0.0)	14.7
(0.50, 0.89, 0.0)	14.9

Flue Gas Analyses

O ₂ (mol %)	CO (ppm)	CO ₂ (mol %)	NO (ppm)	NO _x (ppm)
2.6	40	15.1	900	950

Appendix D

Pulverized Coal Combustion

Introduction to Case D1

Consolidation Coal Company pilot scale furnace (Havekotte, 1987)

Case D1 is a pulverized-coal combustion data set taken in a pilot-scale furnace. The furnace is owned by Consolidation Coal Company located in Library, Penn. The data were taken and provided to Brigham Young University in a proprietary report (Havekotte, 1987). The data were taken for use in three-dimensional combustion model evaluation. The data were provided with a restriction on usage. The dimensions of the furnace cannot be published. The data were included in the data book because of their relatively high quality and comprehensiveness. Modelers desiring to use the data should contact Consolidation Coal Company for the furnace dimensions.

Drawings of the furnace are provide in Appendix A, Figures A.5 through A.8. The dimensions used in the drawing are normalized by the furnace height. The diagram of the burner has units of meters.

General information about the furnace operating conditions, chemical analysis of the coal, and other information needed for computer code input are provided in Appendix D.

The experimental data are listed in Table D.1. Each measurement is identified by a X, Y, and Z coordinate. The coordinate system for the Consolidation Coal Company furnace is shown in Figure 2.2 and Figure A.5. The coordinates have been normalized in the X, Y, and Z directions by the furnace width, depth, and height, respectively. Measurements were made on three levels in the furnace radiant section. The three levels correspond to elevations of 0.44, 0.58 and 0.72 (normalized).

Table D.1
Data Set for Case D1 (Havekotte, 1987)

Consolidation Coal Company
Pulverized Coal Combustion

Solids Type: Northern West Virginia Coal

Furnace Specifications

Dimensions (w X d X h, meters)   restricted¹

No. of Burners

4

Burner Locations (see Figures A.5 to A.7)

Primary Stream

Burner ID	A	B	C	D
Solids Feed Rate (kg/s)	0.00265	0.00253	0.00261	0.00262
Gas Flow (kg/s)	0.00565	0.00561	0.00573	0.00576
Gas Temperature (K)	347	354	340	344
Tube Dimensions i.d. (m)	0.0165	0.0165	0.0165	0.0165
o.d. (m)	0.0381	0.0381	0.0381	0.0381
Burner Velocity (m/s)	21.9	21.8	21.8	21.9

Secondary Stream

Gas Flow (kg/s)	0.03351	0.03381	0.03358	0.03353
Gas Temperature (K)	615	622	618	614
Tube Dimension i.d. (m)	0.0665	0.0665	0.0665	0.0665
Theoretical Swirl No. ²	6.0	5.6	6.0	5.9
Stoichiometric Ratio	1.41	1.41	1.41	1.41
Nominal Heat Rel. (J/s-m)	25.6	24.6	25.4	25.5
Heat Release per Plan Area (J/s-m)	1065.0	1024.3	1054.7	1059.9
Furnace Pressure (kPa)	-0.1	-0.1	-0.1	-0.1

Fuel Compositions

Gas - Primary

N ₂	0.79	0.79	0.79	0.79
O ₂	0.21	0.21	0.21	0.21

Gas - Secondary

N ₂	0.79	0.79	0.79	0.79
O ₂	0.21	0.21	0.21	0.21

Solids Analysis

Proximate, (wt%)

Moisture	1.08	1.26	1.2	1.24
Volatile Matter	36.93	36.95	36.53	36.83
Ash	6.09	6.02	6.14	6.15
Fixed Carbon	56.98	57.03	57.33	57.02

1- Dimensions of the furnace are restricted from publication by agreement with Consolidation Coal Company.

2- These swirl numbers appear to be abnormally high, but have been verified by Consolidation Coal Company

Table D.1 - continued

Ultimate, Dry (wt%)				
Carbon	79.72	79.75	79.93	80.29
Hydrogen	5.18	4.88	4.95	4.90
Nitrogen	1.54	1.48	1.55	1.55
Oxygen	6.17	6.62	6.13	5.80
Sulfur, Total	1.18	1.13	1.18	1.17
Ash	6.21	6.14	6.26	6.29
Heating Value, Dry (MJ/kg)				
	32.849	33.067	33.044	33.060
Elemental (wt% of ash)				
Na ₂ O	0.45	0.46	0.48	0.53
K ₂ O	1.66	1.62	1.72	1.71
CaO	2.9	2.90	3.1	3.15
MgO	0.84	0.80	0.84	0.85
Fe ₂ O ₃	12.62	11.92	12.79	12.71
TiO ₂	1.04	0.99	1.08	1.09
P ₂ O ₅	0.55	0.54	0.55	0.61
SiO ₂	49.88	49.57	49.37	50.12
Al ₂ O ₃	25.8	27.09	27.38	26.1
SO ₃	2.08	2.54	1.8	2.46
unspecified	2.18	1.57	0.89	0.67
Size (microns) Distribution (wt%)				
149+	3	1.4	2	1.3
74	36.7	26	34.1	30.1
44	24.98	24.24	27.22	23.39
40.3	2.26	5.03	2.09	2.46
32	6.11	8.52	6.88	6.7
25.4	6.1	8.07	5.94	7.69
20.2	4.87	7.26	5.42	7.25
16	3.91	5.55	4.46	5.71
12.7	3.33	4.43	3.54	4.65
10.1	2.5	3.45	2.63	3.36
8	1.95	2.72	2.04	2.71
6.4	1.5	2.01	1.56	1.98
5	1.09	1.45	1.14	1.43
4	0.89	1.1	0.89	1.11
3.2	0.62	0.75	0.64	0.77
2.5	0.43	0.55	0.46	0.55
2	0.05	0.05	0.05	0.05
Ash Fusion Temperature (K)				
Reducing				
Initial	1622	1628	1626	1623
Softening	1649	1656	1639	1646
Hemispheric	1669	1677	1662	1669
Fluid	1687	1701	1690	1694

Table D.1 - continued

Oxidizing				
Initial	1673	1681	1680	1676
Softening	1716	1724	1714	1714
Hemispheric	1734	1742	1732	1732
Fluid	1750	1772	1757	1769

Temperature, Velocity, and Mass Flux

(X, Y, Z)	Temp (K)	V _x (m/s)	V _y (m/s)	V _z (m/s)	Mass Flux (kg/s-m ²)
(0.14, 0.17, 0.44)	1526	-	7.28E-01	6.56E+00	1.22E-03
(0.50, 0.17, 0.44)	1530	-	8.84E-01	0.00E+00	4.22E-04
(0.86, 0.17, 0.44)	1558	-	-1.61E+00	-1.13E+01	3.13E-03
(0.14, 0.50, 0.44)	1524	-	0.00E+00	6.02E+00	1.01E-03
(0.50, 0.50, 0.44)	1534	-	0.00E+00	-2.45E+00	4.09E-04
(0.86, 0.50, 0.44)	1498	-	-1.00E+00	-1.23E+01	3.56E-03
(0.14, 0.83, 0.44)	1516	-	-6.58E-01	3.74E+00	6.40E-04
(0.50, 0.83, 0.44)	1539	-	-8.14E-01	-2.24E+00	6.05E-04
(0.86, 0.83, 0.44)	1551	-	9.33E-01	-8.40E+00	1.81E-03
(0.14, 0.17, 0.58)	1480	-	0.00E+00	5.17E+00	8.12E-04
(0.50, 0.17, 0.58)	1483	-	0.00E+00	3.12E+00	5.48E-04
(0.86, 0.17, 0.58)	1508	-	0.00E+00	-1.11E+01	2.58E-03
(0.14, 0.50, 0.58)	1483	-	-4.91E-01	3.46E+00	7.19E-04
(0.50, 0.50, 0.58)	1488	-	0.00E+00	-4.28E+00	8.37E-04
(0.86, 0.50, 0.58)	1507	-	-6.16E-01	-1.15E+01	2.53E-03
(0.14, 0.83, 0.58)	1444	-	-5.06E-01	4.57E+00	8.14E-04
(0.50, 0.83, 0.58)	1476	-	0.00E+00	2.20E+00	3.72E-04
(0.86, 0.83, 0.58)	1512	-	0.00E+00	-8.90E+00	1.69E-03
(0.14, 0.17, 0.72)	1377	-	0.00E+00	4.26E+00	7.95E-04
(0.50, 0.17, 0.72)	1434	-	5.73E-01	0.00E+00	3.05E-04
(0.86, 0.17, 0.72)	1454	-	8.60E-01	-7.75E+00	1.80E-03
(0.14, 0.50, 0.72)	1408	-	0.00E+00	4.30E+00	8.19E-04
(0.50, 0.50, 0.72)	1439	-	9.24E-01	-5.24E+00	1.12E-03
(0.86, 0.50, 0.72)	1447	-	0.00E+00	-7.48E+00	1.58E-03
(0.14, 0.83, 0.72)	1411	-	-3.87E-01	3.15E+00	6.40E-04
(0.50, 0.83, 0.72)	1441	-	8.17E-01	1.88E+00	4.28E-04
(0.86, 0.83, 0.72)	1460	-	0.00E+00	-4.90E+00	1.06E-03

Gas Analyses

(X, Y, Z)	O ₂ (mol %)	CO ₂ (mol %)	CO (ppm)	NO _x (ppm)	SO ₂ (ppm)
(0.14, 0.17, 0.44)	6.65	12.34	15.5	557	805
(0.50, 0.17, 0.44)	7.77	11.34	32	535	720
(0.86, 0.17, 0.44)	5.37	13.52	51.5	655	895
(0.14, 0.50, 0.44)	5.6	13.32	48	638	890
(0.50, 0.50, 0.44)	6.92	12.2	14	563	795
(0.86, 0.50, 0.44)	5.6	13.32	48	638	890
(0.14, 0.83, 0.44)	7.47	11.76	14	550	760
(0.50, 0.83, 0.44)	7.08	12.04	20	570	775
(0.86, 0.83, 0.44)	7.81	11.25	34	527	750
(0.14, 0.17, 0.58)	7.71	11.48	13.6	533	760
(0.50, 0.17, 0.58)	7.18	12	19.5	536	785

Table D1 - continued

(X, Y, Z)	O ₂ (mol %)	CO ₂ (mol %)	CO (ppm)	NO _x (ppm)	SO ₂ (ppm)
(0.86, 0.17, 0.58)	6.71	12.5	32	572	825
(0.14, 0.50, 0.58)	6.84	12.22	14.5	557	810
(0.50, 0.50, 0.58)	7.15	12.2	17.5	559	800
(0.86, 0.50, 0.58)	6.3	12.8	30	591	850
(0.14, 0.83, 0.58)	6.91	12.24	14.5	548	810
(0.50, 0.83, 0.58)	7.26	11.9	19	538	785
(0.86, 0.83, 0.58)	6.6	12.5	27	499	850
(0.14, 0.17, 0.72)	8.3	11	7.4	532	750
(0.50, 0.17, 0.72)	7.15	11.84	18	517	875
(0.86, 0.17, 0.72)	6.58	13	23	575	855
(0.14, 0.50, 0.72)	6.85	12.2	9	559	850
(0.50, 0.50, 0.72)	6.83	12.5	12	520	875
(0.86, 0.50, 0.72)	6.65	13	20	570	810
(0.14, 0.83, 0.72)	6.68	12.5	9.6	545	850
(0.50, 0.83, 0.72)	6.4	13.2	24.4	545	850
(0.86, 0.83, 0.72)	6.65	12.55	20	570	815

Particulate Analyses

	Location of Measurement					
X coordinate	0.14	0.50	0.86	0.14	0.50	0.86
Y coordinate	0.17	0.17	0.17	0.50	0.50	0.50
Z coordinate	0.44	0.44	0.44	0.44	0.44	0.44

Proximate (wt%)

Moisture	0.50	0.27	0.70	0.57	0.32	0.71
Ash	99.59	98.61	65.84	99.72	92.49	65.54
Fixed Carbon	0.0	1.12	33.46	0.0	7.19	33.75

Ultimate, dry (wt %)

Carbon	0.38	1.36	33.58	0.17	7.16	34.88
Hydrogen	0	0	0	0	0	0
Nitrogen	0.12	0.1	0.55	0.11	0.27	0.59
Oxygen	0	0	0	0	0	0
Sulfur	0.39	0.23	0.35	0.24	0.23	0.37
Ash	99.11	98.31	65.52	99.48	92.34	64.16

Elemental (wt% of ash)

Na ₂ O	0.6	0.64	0.52	0.68	0.61	0.5
K ₂ O	1.88	1.89	1.8	1.96	1.86	1.7
CaO	3.97	3.53	3.14	3.71	3.37	3.34
MgO	1.1	0.99	0.89	1.05	0.96	0.88
Fe ₂ O ₃	9.26	9.58	10.83	9.06	9.74	12.64
TiO ₂	1.24	1.32	1.12	1.32	1.29	1.07
P ₂ O ₅	0.66	0.61	0.49	0.66	0.61	0.67
SiO ₂	51.38	51.96	51.99	52.08	51.73	52.55
Al ₂ O ₃	27.23	27.69	26.58	28.4	27.43	26.11
SO ₃	1.1	0.58	1.08	0	0.6	0
unspecified	1.58	1.21	1.56	1.08	1.80	0.54

Table D.1 - continued

Size (microns)	Distribution (wt%)					
64	0.6	0.2	0.2	-	1.5	0.2
50.8	1.78	0.8	0.37	-	0.15	0.4
40.3	3.16	0.58	1.85	-	0.58	1.76
32	3.36	1.2	3.97	0.88	1.75	6.7
25.4	5.19	2.91	6.09	1.05	4.33	7.6
20.2	8.5	6.56	9.14	2.16	6.69	10.21
16	9.41	8.72	14.46	3.06	10.82	13.7
12.7	9.63	10.59	13.78	5.12	13.2	12.52
10.1	9.81	12.02	11.94	7.81	12.72	10.69
8	10.51	13.05	10.14	11.45	12.3	9.33
6.4	10.16	12.4	8.59	12.6	10.87	8.3
5	8.78	10.34	6.97	12.6	8.67	6.62
4	8.18	9.02	5.64	12.05	7.36	5.39
3.2	6.17	6.61	3.9	10.64	5.16	3.76
2.5	4.67	4.91	2.87	8.13	3.81	2.71
2	0.08	0.1	0.1	6.33	0.1	0.1
1.6	-	-	-	3.77	-	-
1.3	-	-	-	2.26	-	-
1	-	-	-	0.1	-	-
Location of Measurement						
X coordinate	0.14	0.50	0.86	0.14	0.50	0.86
Y coordinate	0.83	0.83	0.83	0.17	0.17	0.17
Z coordinate	0.44	0.44	0.44	0.58	0.58	0.58
Proximate (wt%)						
Moisture	0.29	0.34	0.52	0.33	0.50	0.37
Ash	99.22	92.19	81.33	99.77	98.41	81.39
Fixed Carbon	0.49	7.47	18.15	0.00	1.09	18.24
Ultimate, dry (wt %)						
Carbon	0.88	7.76	18.24	0.11	1.63	18.29
Hydrogen	0.00	0.00	0.00	0.00	0.00	0.08
Nitrogen	0.12	0.27	0.34	0.14	0.22	0.38
Oxygen	0.00	0.00	0.00	0.00	0.00	0.00
Sulfur	0.22	0.26	0.31	0.15	0.22	0.24
Ash	98.78	91.71	81.11	99.60	97.93	81.01
Elemental (wt% of ash)						
Na ₂ O	0.60	0.62	0.66	0.60	0.67	0.52
K ₂ O	1.89	1.90	1.80	1.81	1.83	1.70
CaO	3.35	3.40	3.52	3.56	3.44	3.21
MgO	0.97	0.97	0.92	0.99	0.98	0.89
Fe ₂ O ₃	9.35	9.63	11.23	10.39	11.04	12.25
TiO ₂	1.29	1.29	1.13	1.27	1.26	1.16
P ₂ O ₅	0.60	0.80	0.59	0.69	0.67	0.66
SiO ₂	52.13	51.57	52.54	53.08	52.91	52.30
Al ₂ O ₃	28.35	27.64	26.35	27.01	26.82	26.46
SO ₃	0.40	0.65	0.00	0.00	0.70	0.78
unspecified	1.07	1.53	1.26	0.06	-0.30	0.07

Table D.1 - continued

Size (microns)	Distribution (wt%)					
64	1.20	0.25	-	0.20	0.17	-
50.8	1.81	0.72	-	0.60	0.15	-
40.3	2.11	0.20	-	0.60	0.87	-
32	3.16	1.36	2.65	1.07	1.67	3.45
25.4	4.39	3.08	3.95	3.84	3.65	2.82
20.2	8.90	5.86	5.90	9.08	7.80	6.94
16	10.33	10.27	7.67	11.17	10.42	11.24
12.7	10.58	11.71	9.29	11.25	12.10	11.99
10.1	10.01	12.16	12.14	11.05	12.35	12.99
8	10.61	13.00	11.24	12.12	12.70	10.77
6.4	10.28	12.06	10.27	10.67	11.35	9.39
5	8.73	9.88	8.74	8.98	9.10	7.89
4	7.80	8.54	7.74	8.18	7.80	6.60
3.2	5.69	6.20	6.45	6.23	5.60	5.17
2.5	4.29	4.64	5.10	4.86	4.22	3.95
2	0.10	0.07	4.05	0.10	0.02	3.10
1.6	-	-	2.75	-	-	2.10
1.3	-	-	1.97	-	-	1.50
1	-	-	0.10	-	-	0.10
Location of Measurement						
X coordinate	0.14	0.50	0.86	0.14	0.50	0.86
Y coordinate	0.50	0.50	0.50	0.83	0.83	0.83
Z coordinate	0.58	0.58	0.58	0.58	0.58	0.58
Proximate (wt%)						
Moisture	0.00	0.22	0.37	0.00	0.36	0.57
Ash	99.79	95.14	86.04	99.95	99.13	88.08
Fixed Carbon						
Ultimate, dry (wt %)						
Carbon	0.00	4.75	13.72	0.44	0.79	11.55
Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00
Nitrogen	0.17	0.18	0.22	0.14	0.24	0.25
Oxygen	0.00	0.00	0.00	0.00	0.00	0.00
Sulfur	0.21	0.15	0.19	0.18	0.24	0.22
Ash	99.62	94.92	85.87	99.24	98.73	87.98
Elemental (wt% of ash)						
Na ₂ O	0.70	0.55	0.50	0.66	0.66	0.52
K ₂ O	1.94	1.74	1.66	1.87	1.83	1.70
CaO	3.83	3.36	3.10	3.64	3.64	3.96
MgO	1.06	0.93	0.87	1.02	1.00	1.35
Fe ₂ O ₃	9.26	12.71	13.08	9.56	10.13	10.89
TiO ₂	1.33	1.18	1.13	1.36	1.29	1.19
P ₂ O ₅	0.74	0.62	0.61	0.71	0.72	0.63
SiO ₂	51.93	51.60	51.95	52.47	51.62	51.56
Al ₂ O ₃	27.57	26.04	26.34	27.45	26.44	26.91
SO ₃	0.00	0.75	0.68	0.70	0.65	0.63
unspecified	1.37	0.52	0.08	0.56	2.02	0.66

Table D.1 - continued

Size (microns) Distribution (wt%)						
64	-	-	0.97	1.80	-	0.95
50.8	-	-	0.90	0.75	-	2.46
40.3	-	-	1.87	0.55	-	2.06
32	0.62	2.45	5.52	1.17	1.00	4.57
25.4	1.70	3.10	6.64	2.80	3.43	5.42
20.2	3.95	5.00	10.02	6.50	3.48	9.18
16	4.17	7.35	13.91	9.75	5.66	13.35
12.7	6.10	9.50	13.83	10.87	7.89	14.13
10.1	11.27	11.85	11.52	11.47	11.40	11.74
8	14.39	12.58	9.75	12.27	11.80	10.01
6.4	14.49	11.25	8.01	11.79	11.50	8.23
5	11.89	9.70	6.17	10.02	10.45	6.32
4	9.65	8.10	4.95	8.75	9.05	5.09
3.2	7.05	6.28	3.38	6.55	7.59	3.66
2.5	5.20	4.63	2.46	4.90	5.91	2.71
2	4.35	3.78	0.10	0.07	4.99	0.10
1.6	2.95	2.55	-	-	3.46	-
1.3	2.07	1.80	-	-	2.28	-
1	0.15	1.00	-	-	0.10	-
Location of Measurement						
X coordinate	0.14	0.50	0.86	0.14	0.50	0.86
Y coordinate	0.17	0.17	0.17	0.50	0.50	0.50
Z coordinate	0.72	0.72	0.72	0.72	0.72	0.72
Proximate (wt%)						
Moisture	0.29	0.41	0.34	0.34	1.41	3.29
Ash	99.31	99.06	94.22	99.41	98.54	96.41
Fixed Carbon	0.40	0.53	5.44	0.25	0.05	0.30
Ultimate, dry (wt %)						
Carbon	0.26	0.59	5.65	0.34	1.41	3.29
Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00
Nitrogen	0.06	0.74	0.26	0.22	0.14	0.16
Oxygen	0.18	0.00	0.00	0.00	0.00	0.02
Sulfur	0.20	0.32	0.18	0.24	0.12	0.14
Ash	99.30	98.35	93.91	99.20	98.33	96.39
Elemental (wt% of ash)						
Na ₂ O	0.56	0.73	0.55	0.70	0.59	0.56
K ₂ O	1.74	1.92	1.72	1.92	1.79	1.71
CaO	3.28	4.36	3.36	3.99	3.55	3.24
MgO	0.94	1.09	0.91	1.09	0.97	0.92
Fe ₂ O ₃	11.20	9.25	11.84	9.98	11.14	11.96
TiO ₂	1.18	1.25	1.15	1.31	1.18	1.13
P ₂ O ₅	0.65	0.73	0.62	0.71	0.66	0.63
SiO ₂	53.06	52.11	51.66	52.30	52.65	52.27
Al ₂ O ₃	26.52	26.34	26.44	27.59	26.61	26.94
SO ₃	0.58	0.78	0.53	0.73	0.23	0.00
unspecified	1.66	1.44	2.04	0.98	1.51	0.64

Table D.1 - continued

Size (microns)	Distribution (wt%)					
64	0.49	-	0.15	-	1.25	0.20
50.8	1.12	-	0.89	-	1.04	0.36
40.3	1.53	-	2.75	-	1.25	1.40
32	4.29	1.72	5.45	1.45	4.57	3.71
25.4	6.80	0.86	7.03	1.00	7.06	7.42
20.2	10.30	2.63	10.19	5.41	11.42	10.16
16	12.04	4.33	13.05	7.21	13.40	13.82
12.7	12.58	7.09	12.54	7.39	13.91	13.39
10.1	11.30	11.79	10.60	10.12	11.11	11.66
8	10.58	12.75	9.63	11.30	9.55	10.14
6.4	8.90	12.02	8.31	11.07	8.00	8.54
5	7.00	10.48	6.70	9.97	6.23	6.68
4	5.78	9.16	5.58	8.92	5.09	5.56
3.2	4.17	8.00	4.03	8.07	3.53	3.96
2.5	3.04	6.53	3.01	6.61	2.60	2.92
2	0.08	5.77	0.08	5.66	0.00	0.08
1.6	-	4.00	-	3.58	-	-
1.3	-	2.81	-	2.15	-	-
1	-	0.08	-	0.08	-	-

	Location of Measurement			Duplicate Measurements		
X coordinate	0.14	0.50	0.86	0.50	0.50	0.50
Y coordinate	0.83	0.83	0.83	0.50	0.50	0.50
Z coordinate	0.72	0.72	0.72	0.44	0.58	0.72

Proximate (wt%)						
Moisture	0.34	0.51	0.26	1.99	0.40	0.51
Ash	98.46	98.65	95.80	96.99	95.64	88.09
Fixed Carbon	1.20	0.84	3.94	1.02	3.96	11.40

Ultimate, dry (wt %)						
Carbon	1.33	1.01	3.96	1.43	4.28	11.90
Hydrogen	0.00	0.00	0.02	0.00	0.00	0.00
Nitrogen	0.22	0.14	0.12	0.19	0.12	0.25
Oxygen	0.00	0.00	0.00	0.86	0.00	0.00
Sulfur	0.24	0.25	0.12	0.63	0.10	0.33
Ash	98.21	98.60	95.78	96.89	95.50	87.52

Elemental (wt% of ash)						
Na ₂ O	0.62	0.63	0.53	0.59	0.56	0.56
K ₂ O	1.80	2.09	1.67	1.80	1.84	1.77
CaO	3.53	3.40	3.16	3.45	3.25	3.45
MgO	0.97	1.07	0.89	0.92	0.92	0.90
Fe ₂ O ₃	10.42	10.31	11.64	8.75	9.79	9.08
TiO ₂	1.19	1.24	1.12	1.17	1.15	1.13
P ₂ O ₅	0.70	0.62	0.58	0.66	0.55	0.60
SiO ₂	52.59	53.62	52.22	51.43	52.29	48.87
Al ₂ O ₃	26.96	27.20	27.64	27.31	27.33	26.32
SO ₃	0.00	0.69	0.40	1.20	0.45	0.85
unspecified	1.85	-0.87	0.15	2.72	1.87	6.47

Table D.1 - continued

Size (microns)	Distribution (wt%)					
64	-	0.76	0.15	0.60	0.20	0.27
50.8	-	0.15	0.26	1.35	0.18	1.33
40.3	-	0.66	1.64	2.21	0.76	2.15
32	1.27	1.22	4.55	3.64	1.94	3.11
25.4	4.86	3.14	7.67	5.82	4.99	3.46
20.2	7.51	5.76	13.10	9.83	9.02	5.88
16	7.99	9.13	15.14	13.20	12.95	8.65
12.7	8.55	10.55	13.97	13.42	13.18	10.23
10.1	10.59	11.77	11.05	11.72	12.25	10.75
8	11.40	12.33	9.31	9.93	11.37	12.09
6.4	10.66	12.12	7.24	8.28	9.83	12.06
5	9.14	10.50	5.50	6.82	7.86	10.16
4	7.79	9.33	4.71	5.90	6.65	8.87
3.2	6.31	7.08	3.27	4.21	4.94	6.20
2.5	4.86	5.45	2.35	2.96	3.78	4.62
2	4.10	0.05	0.08	0.10	0.10	0.15
1.6	2.85	-	-	-	-	-
1.3	2.01	-	-	-	-	-
1	0.08	-	-	-	-	-

Effluent Data (inlet to baghouse)

Location	inlet to baghouse	inlet to baghouse
Gas Temperature, K	398	401
Velocity, m/s	6.504	6.517
Flow angle from horizontal, °	0	0
Mass flux, kg/s-m ²	2.12E-04	1.78E-04

Location of Measurement

	inlet to baghouse	inlet to baghouse
Date	5/20/87	5/21/87
Proximate (wt%)		
Moisture	0.70	0.51
Ash	99.05	100.34
Fixed Carbon	0.25	0.0

Ultimate, dry (wt %)

Carbon	0.34	0.24
Hydrogen	0.00	0.00
Nitrogen	0.07	0.18
Oxygen	0.19	0.00
Sulfur	0.39	0.34
Ash	99.01	99.24

Table D.1 - continued

Elemental (wt% of ash)		
Na ₂ O	0.63	0.64
K ₂ O	1.92	1.85
CaO	3.41	3.30
MgO	1.00	0.99
Fe ₂ O ₃	9.61	9.54
TiO ₂	1.26	1.27
P ₂ O ₅	0.73	0.77
SiO ₂	52.46	53.10
Al ₂ O ₃	27.44	27.60
SO ₃	0.85	0.00
unspecified	0.69	0.94

Size (microns)	Distribution (wt%)	
64	1.55	0.23
50.8	0.36	0.38
40.3	1.71	1.40
32	2.32	3.41
25.4	4.18	6.59
20.2	6.81	9.84
16	9.74	11.70
12.7	12.29	12.42
10.1	12.29	11.45
8	11.88	10.47
6.4	10.20	8.82
5	8.39	7.29
4	7.55	6.61
3.2	5.91	5.11
2.5	4.79	4.18
2	0.05	0.10
1.6	-	-
1.3	-	-
1	-	-

Fly Ash Analyses			
date	5/20/87	5/21/87	5/22/87
Proximate (wt%)			
Moisture	0.44	0.40	0.45
Ash	98.68	99.04	99.50
Fixed Carbon	0.88	0.56	0.05
Ultimate, Dry (wt%)			
Carbon	0.49	0.31	0.12
Hydrogen	0.00	0.00	0.00
Nitrogen	0.12	0.11	0.03
Oxygen	0.20	0.16	0.00
Sulfur, Total	0.52	0.38	0.42
Ash	98.67	99.04	99.43

Table D.1 - continued

Elemental, (wt% of ash)			
Na ₂ O	0.51	0.57	0.59
K ₂ O	1.79	1.84	1.87
CaO	3.02	2.98	2.99
MgO	0.87	0.90	0.91
Fe ₂ O ₃	11.08	9.50	9.17
TiO ₂	1.17	1.25	1.28
P ₂ O ₅	0.59	0.65	0.67
SiO ₂	52.54	52.68	52.85
Al ₂ O ₃	25.83	26.73	27.26
SO ₃	1.29	0.94	1.05
unspecified	1.31	1.96	1.36

Size (microns) Distribution (wt%)			
149+	0.00	0.00	0.00
74	1.30	1.70	1.00
44	6.83	6.19	4.98
40.3	1.31	1.24	0.58
32	4.92	3.30	1.92
25.4	7.37	6.80	4.04
20.2	12.11	10.10	7.88
16	14.07	12.30	10.53
12.7	13.34	13.07	11.88
10.1	11.05	11.17	11.51
8	8.61	9.62	11.30
6.4	6.45	7.75	9.71
5	4.65	5.94	8.18
4	3.61	4.93	7.14
3.2	2.51	3.44	5.24
2.5	1.83	2.53	4.04
2	0.07	0.07	0.08
1.6	-	-	-
1.3	-	-	-
1	-	-	-

Ash Fusion Temperature (K)			
Reducing			
Initial	1583	1607	1613
Softening	1637	1644	1648
Hemispheric	1667	1760	1728
Fluid	1726	1783	1762
Oxidizing			
Initial	1675	1696	1678
Softening	1734	1726	1728
Hemispheric	1759	1770	1764
Fluid	1773	1791	1778

Table D.1 - continued

Slag Panel Deposit, Fouling Probe and Bottom Ash Analyses					
	Slag Panel	Slag Panel	Slag Panel	Fouling Probe	Bottom Ash
date	5/20/87	5/21/87	5/22/87	5/20/87	5/20- 22/87
Proximate, (wt%)					
Moisture	-	-	-	-	0.16
Ash	-	-	-	-	99.98
Fixed Carbon	-	-	-	-	0.00
Ultimate, Dry (wt%)					
Carbon	-	-	-	-	0.00
Hydrogen	-	-	-	-	0.00
Nitrogen	-	-	-	-	0.05
Oxygen	-	-	-	-	0.00
Sulfur, Total	0.54	0.85	2.24	0.02	0.01
Ash	99.46	99.15	97.76	99.98	99.94
Elemental, (wt% of ash)					
Na ₂ O	-	-	0.57	0.43	0.33
K ₂ O	-	-	1.80	1.69	1.70
CaO	-	-	3.09	3.71	2.78
MgO	-	-	0.83	0.87	0.76
Fe ₂ O ₃	-	-	18.32	11.86	16.95
TiO ₂	-	-	0.99	1.17	0.95
P ₂ O ₅	-	-	0.70	0.61	0.49
SiO ₂	-	-	45.70	52.08	50.50
Al ₂ O ₃	-	-	23.04	26.11	23.99
SO ₃	-	-	5.60	0.05	0.03
unspecified	-	-	4.96	1.42	1.52
Ash Fusion Temperature (K)					
Reducing					
Initial	1425	1414	-	-	1426
Softening	1461	1423	-	-	1530
Hemispheric	1558	1554	-	-	1591
Fluid	1597	1574	-	-	1633
Oxidizing					
Initial	1613	1620	-	-	1636
Softening	1642	1655	-	-	1652
Hemispheric	1678	1681	-	-	1693
Fluid	1700	1695	-	-	1717

Table D.1 - continued

Wall Temperatures Location	Temperature (K)	Temperature Range (K)	
		Low	High
(0.65, -0.30, 0.74)	847	803	876
(1.2, 1.0, 0.72)	825	759	852
(-0.17, 0.80, 0.72)	1042	931	1095
(1.3, 0.32, 0.68)	791	740	815
(1.2, 0.30, 0.54)	874	839	899
(0.31, 1.3, 0.58)	860	791	886
(0.30, 1.4, 0.44)	914	848	947
(0.81, 1.1, 0.42)	1310	1238	1344
(0.73, 1.0, 0.44)	1482	1458	1517
(0.81, 1.1, 0.46)	1064	939	1106
(0.90, 1.3, 0.44)	1183	1064	1224
(-0.26, 0.30, 0.44)	1100	985	1142
(-0.17, 0.20, 0.46)	1195	1084	1238
(-0.086, 0.20, 0.42)	1328	1262	1365
(0.01, 0.12, 0.44)	1357	1268	1396
(0.21, -0.10, 0.39)	1311	1256	1344
(0.73, -0.30, 0.44)	1093	1024	1133
(0.65, -0.10, 0.46)	1333	1281	1371
(0.82, 0.01, 0.46)	1400	1343	1440
(0.74, 0.20, 0.48)	1206	1116	1246
(1.0, 0.90, 0.48)	1316	1274	1354
(1.3, 0.31, 0.39)	1263	1236	1298
(-0.17, -0.20, 0.30)	975	943	991
(-0.17, 0.01, 0.16)	1291	1257	1318
(0.74, 0.01, 0.31)	1442	1413	1474
(0.75, -0.20, 0.16)	888	847	908
(1.1, -0.29, 0.31)	1190	1165	1205
(1.3, -0.29, 0.16)	608	583	619
(1.0, 0.067, 0.27)	1492	378	1518
(1.3, -0.28, 0.20)	821	809	834
(1.3, 0.95, 0.27)	621	608	628
(1.1, 0.94, 0.20)	1366	1344	1395
(1.2, 0.94, 0.31)	880	855	893
(1.1, 1.3, 0.16)	1019	990	1031
(-0.17, 1.0, 0.31)	1284	1270	1303
(-0.17, 1.2, 0.16)	857	830	869
(0.29, 1.3, 0.29)	842	810	851
(0.38, 1.4, 0.19)	584	563	590
(0.20, 1.4, 0.19)	550	528	558
(0.29, 1.3, 0.18)	784	749	796
(0.75, 1.0, 0.16)	1206	1171	1221
(-0.086, 1.3, 0.31)	1038	999	1074
(-0.17, 1.3, 0.16)	615	600	624
(-0.17, -0.30, 0.31)	847	821	861
(-0.086, -0.30, 0.16)	985	962	1000

Introduction to Case D2 Conesville Furnace (Cetegen, 1987)

Case D2 is taken from an evaluation of the time/temperature characteristics in utility boilers by Energy and Environmental Research Corporation of Irvine, California (Cetegen, 1987). The study included measurements from two full-scale furnaces. Case D2 is from an evaluation of the tangentially-fired unit number five of the Conesville Generating Station near Conesville, Ohio. The furnace owner is American Electric Power Corporation.

Dimensioned drawings of the furnace are provided to show the geometrical details needed for modeling. When geometrical details were not provided in the source material, estimation of the correct size and location were made using available information given from throughout the report. All measurements in the data set are in the International System of Units. The furnace drawings are superimposed on an X, Y, Z coordinate system used to locate parts of the furnace and test measurements. The X, Y, Z system is used in various parts of the data set. The locations of test measurements were normalized by the width, depth, and height of the furnace for each of the X, Y, and Z axes, respectively.

After the figures of the furnace are given, the operating conditions and experimental data measurements (Table D.2) are listed. The data were taken using the same approximate set of operating conditions throughout the period of testing. Since testing was taken over several days, and the load was varied on a daily basis, the conditions may have been slightly different each day of testing.

The burners used in the Conesville furnace were not well described in the Cetegen report. The dimensions of the burners were taken using a ruler and assuming that drawing in the report (Cetegen, 1987) were drawn to scale. The fuel air and coal leaving each burner was assumed to be the same.

The experimental data are presented after the inlet conditions. The data include temperature, velocity in both the Z (vertical) and X directions, and concentrations of several gaseous species. An occasional velocity measurement was given for the Y direction. When no velocity was given, the space was left blank.

Figure D.1

Case D2 - Three-Dimensional Drawing of Furnace.

Details of the furnace dimensions are given in Figures D.2 through D.4. $X+$, $Y+$, and $Z+$ refer to the coordinate system used to locate measurements and geometrical features. Information for figure taken from Cetegen (1987).

High Temperature
Superheater platens,
Reheater, and Finishing
Superheater structures,
and burner details on
following pages.

Figure D.2

Case D2 - Dimensioned Drawing of Furnace.

All dimensions are in meters. One burner is located in each corner of the furnace. Five outlets are located on each burner. Burner dimensions are shown in Figure D.4 Information for figure taken from Cetegen (1987).

Figure D.3
Case D2 - Burner Orientation.

The corner burners in Case D2 were oriented as shown in Figure D.3. A line perpendicular to the face of each burner and extending towards the center area of the furnace is tangent to a circle 1.30 meters in diameter. The furnace dimensions are in meters. The angle the perpendicular line makes with a furnace wall is also shown. Burner information taken from Cetegen (1987).

Figure D.4

Case D2 - Burner Dimensions.

The burners used in Case D2 are positioned vertically in each corner of the furnace. The inlets are square and of the approximate dimensions (in meters) shown in the figure. Information for this drawing was obtained using a ruler and a detailed isometric drawing of the burner found in Cetegen (1987).

Figure D.5

Case D2 - Approximate Sizes and Locations of Heater Platens.

Details about the super-heater and reheater platens are unknown. The above diagram represents the approximate number, size, and location (fro left to right) of the three rows of high-temperature, one row of reheater, and one row of finishing super-heater platens. Information for the drawing was taken from Cetegen (1987)

Table D.2

Data Set for Case D2

Conesville Unit 5 (Conesville Furnace)
Location: Conesville, Ohio
Owner: American Electric Power Service Co.
Installed 1978

General Information
Capacity Rating: 420 MW boiler
Solids Type: High Volatile Bituminous Coal

Furnace Specifications

Dimensions (X,Y,Z), meters: (15.8,13.4,51.2)

Number of Burners: 20

Burner ID and Locations (X,Y,Z):

Burner ID: A1,A2,A3,A4

(0.0,0.0,13.7), (0.0,13.5,13.7), (15.7,13.5,13.7),
(15.7,0.0,13.7)

Burner ID: B1,B2,B3,B4

(0.0,0.0,15.5), (0.0,13.5,15.5), (15.7,13.5,15.5),
(15.7,0.0,15.5)

Burner ID: C1,C2,C3,C4

(0.0,0.0,17.3), (0.0,13.5,17.3), (15.7,13.5,17.3),
(15.7,0.0,17.3)

Burner ID: D1,D2,D3,D4

(0.0,0.0,19.2), (0.0,13.5,19.2), (15.7,13.5,19.2),
(15.7,0.0,19.2)

Burner ID: E1,E2,E3,E4

(0.0,0.0,21.0), (0.0,13.5,21.0), (15.7,13.5,21.0),
(15.7,0.0,21.0)

Overfire Air Ports: O1,O2,O3,O4

(0.0,0.0,21.9), (0.0,13.5,21.9), (15.7,13.5,21.9),
(15.7,0.0,21.9)

1- Four columns, one in each corner of furnace, each with five levels of burners. Details about the burners were not included in the report. Estimates of the dimensions were made by using a ruler and figure included in the report. The vertical location is believed to be fairly correct. The width of the burners is questionable.

2- For identification purposes, each burner level is assigned a letter A - E, and each burner in a column is given a number from 1-4. For example, A1 is the lowest level burner located along the Z axis where X and Y both equal zero.

3- There are two OFA ports located one on top of the other. Because of a lack of detail about the OFA ports, they are treated as a single port equal in size to both ports.

Table D.2 - continued

Primary Stream

Solids Total Feedrate (kg/s) 43.0

	A1	A2	A3	A4
Feed Rate, kg/s	0	0	0	0
	B1	B2	B3	B4
Feed Rate, kg/s	2.48	2.48	2.48	2.48
	C1	C2	C3	C4
Feed Rate, kg/s	2.80	2.80	2.80	2.80
	D1	D2	D3	D4
Feed Rate, kg/s	2.80	2.80	2.80	2.80
	E1	E2	E3	E4
Feed Rate, kg/s	2.68	2.68	2.68	2.68

Gas Flow

Primary gas and coal temp., K 344 (all burners)

Gas Flow, kg/s	A1	A2	A3	A4
	0	0	0	0
	B1	B2	B3	B4
	13.30	13.30	13.30	13.30
	C1	C2	C3	C4
	15.04	15.04	15.04	15.04
	D1	D2	D3	D4
	15.04	15.04	15.04	15.04
	E1	E2	E3	E4
	14.41	14.41	14.41	14.41

Secondary Stream

Secondary gas temp., K 593 (all burners)

Gas Flow, kg/s	A1	A2	A3	A4
	30.20	30.20	30.20	30.20
	B1	B2	B3	B4
	69.30	69.30	69.30	69.30
	C1	C2	C3	C4
	71.99	71.99	71.99	71.99
	D1	D2	D3	D4
	71.99	71.99	71.99	71.99
	E1	E2	E3	E4
	63.68	63.68	63.68	63.68
	O1	O2	O3	O4
	64.17	64.17	64.17	64.17

1- all primary air supplied to burners from a common source.

Table D.2 - continued

Burner Register	A1	A2	A3	A4
Degrees vert. tilt	5	5	5	5
	B1	B2	B3	B4
	5	5	5	5
	C1	C2	C3	C4
	5	5	5	5
	D1	D2	D3	D4
	5	5	5	5
	E1	E2	E3	E4
	5	5	5	5

Stoichiometric Ratio	Overall 1.19			
By burner level	A1	A2	A3	A4
	0	0	0	0
	B1	B2	B3	B4
	0.93	0.93	0.93	0.93
	C1	C2	C3	C4
	0.93	0.93	0.93	0.93
	D1	D2	D3	D4
	0.93	0.93	0.93	0.93
	E1	E2	E3	E4
	0.93	0.93	0.93	0.93

Fuel Compositions, mole basis (all burners)

Gas - Primary

N2	0.79
O2	0.21

Gas - Secondary

N2	0.79
O2	0.21

Solids

Ultimate Analysis Dry (wt%) (same for all burners)

Carbon	65.9
Hydrogen	4.50
Nitrogen	1.25
Oxygen	4.12
Sulfur, Total	12.7
Ash	11.6

Proximate Analysis Dry (wt%) (same for all burners)

Volatile Matter	45.1
Ash	12.7
Fixed Carbon	42.3

Moisture (%)	6.19

Heating Value Dry (J/kg) (same for all burners)	5.801 E06

1- Degrees above horizontal.

Table D.2 - continued

Size				
% through 50 mesh				97.3
% through 100 mesh				92.7
% through 200 mesh				78.9
Temperature and velocity				
(X, Y, Z)	Temp. (K)	V_x (m/s)	V_y (m/s)	V_z (m/s)
(14.6, 1.4, 11.5)	1296	-		-12.8
(13.4, 1.4, 11.5)	1278	-		-14.0
(12.2, 1.4, 11.5)	1305	-		
(14.6, 12.1, 11.5)	1669	-	-9.0	-15.6
(13.4, 12.1, 11.5)	1733	-		-17.5
(12.2, 12.1, 11.5)	1726	-		
(1.2, 12.1, 11.5)	1533	-		
(2.4, 12.1, 11.5)	1513	-		
(3.6, 12.1, 11.5)	1613	-		
(7.9, 0.9, 24.3)	1678	2.5		14.0
(7.9, 3.0, 24.3)	1835	19.4		11.2
(7.9, 4.9, 24.3)	1588	-		11.5
(7.9, 5.6, 24.3)	1693	-		
(7.9, 6.1, 24.3)	1896	-		14.9
(1.2, 1.2, 27.0)	1673	-		
(1.2, 2.4, 27.0)	1783	-		
(1.2, 3.6, 27.0)	1843	-		
(5.1, 1.2, 27.0)	1718	-		
(5.1, 2.4, 27.0)	1813	-		
(5.1, 3.6, 27.0)	1833	-		
(10.6, 1.2, 27.0)	1579	-		
(10.6, 2.4, 27.0)	1753	-		
(10.6, 3.6, 27.0)	1843	-		
(14.5, 1.2, 27.0)	1726	-		
(14.5, 2.4, 27.0)	1723	-		
(14.5, 3.6, 27.0)	1888	-		
(1.2, 12.3, 27.0)	1735	-		
(1.2, 11.1, 27.0)	1731	-		
(1.2, 9.9, 27.0)	1753	-		
(5.1, 12.3, 27.0)	1874	-		
(5.1, 11.1, 27.0)	1858	-		
(5.1, 9.9, 27.0)	1867	-		
(10.6, 12.3, 27.0)	1910	-		
(10.6, 11.1, 27.0)	1899	-		
(10.6, 9.9, 27.0)	1875	-		
(14.5, 12.3, 27.0)	1870	-		
(14.5, 11.1, 27.0)	1895	-		

1- Only an occasional velocity was reported in the "y" direction. It is assumed that these values are zero when values are shown for V_x or V_z . At some locations, only temperature was reported.

Table D.2 - continued

Temperature and velocity (X, Y, Z)	Temp. (K)	V_x (m/s)	V_y (m/s)	V_z (m/s)
(14.5, 9.9, 27.0)	1896	-		
(1.2, 1.2, 32.5)	1773	11.3		11.3
(1.2, 2.4, 32.5)	1766	-		-9.8
(1.2, 3.6, 32.5)	1786	-		
(7.9, 1.2, 32.5)	1743	15.9		
(7.9, 2.4, 32.5)	1753	15.1		19.1
(7.9, 3.6, 32.5)	1757	-		
(14.5, 1.2, 32.5)	1648	-		24.0
(14.5, 2.4, 32.5)	1675	5.0		18.8
(14.5, 3.6, 32.5)	1660	-		
(14.5, 12.3, 32.5)	1798	-		
(14.5, 11.1, 32.5)	1819	-		
(14.5, 9.9, 32.5)	1803	-		
(1.2, 12.3, 32.5)	1870	-		
(1.2, 11.1, 32.5)	1895	-		
(1.2, 9.9, 32.5)	1898	-		
(1.3, 2.4, 41.4)		-		19.4
(1.3, 3.6, 41.4)		17.4		17.4
(3.1, 1.2, 41.4)	1778	-		
(3.1, 2.4, 41.4)	1733	-		
(3.1, 3.6, 41.4)	1858	-		
(5.6, 1.2, 41.4)		18.7		18.7
(5.6, 2.4, 41.4)		18.2		18.2
(5.6, 3.6, 41.4)		16.8		16.8
(7.9, 1.2, 41.4)	1673	-		
(7.9, 2.4, 41.4)	1675	-		
(7.9, 3.6, 41.4)	1689	-		
(10.1, 1.2, 41.4)		17.2		17.2
(10.1, 2.4, 41.4)		17.1		17.1
(10.1, 3.6, 41.4)		16.3		16.3
(12.7, 1.2, 41.4)	1583	-		
(12.7, 2.4, 41.4)	1698	-		
(12.7, 3.6, 41.4)	1683	-		
(14.5, 2.4, 41.4)		17.6		17.6
(14.5, 3.6, 41.4)		16.0		16.0
(1.2, 13.9, 43.1)	1368	-		
(2.4, 13.9, 43.1)	1378	-		
(3.6, 13.9, 43.1)	1363	-		
(1.2, 20.1, 43.7)	1193	-		
(2.4, 20.1, 43.7)	1193	-		
(3.6, 20.1, 43.7)	1183	-		
(4.8, 20.1, 43.7)	1184	-		
(5.4, 20.1, 43.7)	1193	-		
(1.2, 23.1, 43.7)	1073	-		
(2.4, 23.1, 43.7)	1076	-		
(3.6, 23.1, 43.7)	1053	-		
(4.8, 23.1, 43.7)	1014	-		
(5.4, 23.1, 43.7)	1011	-		
(1.2, 27.4, 43.7)	929	-		

Table D.2 - continued

Temperature and velocity

(X, Y, Z)	Temp. (K)	V _x (m/s)	V _y (m/s)	V _z (m/s)
(2.4, 27.4, 43.7)	943	-	-	-
(3.6, 27.4, 43.7)	927	-	-	-
(4.8, 27.4, 43.7)	924	-	-	-
(5.4, 27.4, 43.7)	899	-	-	-
(1.2, 13.9, 43.1)	1138	-	-	-
(2.4, 13.9, 43.1)	1211	-	-	-
(1.2, 20.1, 43.7)	1129	-	-	-
(2.4, 20.1, 43.7)	1135	-	-	-
(3.6, 20.1, 43.7)	1124	-	-	-
(4.9, 20.1, 43.7)	1105	-	-	-
(5.8, 20.1, 43.7)	930	-	-	-
(1.2, 23.1, 43.7)	1067	-	-	-
(2.4, 23.1, 43.7)	1032	-	-	-
(4.6, 23.1, 43.7)	1041	-	-	-
(5.8, 23.1, 43.7)	1008	-	-	-
(1.2, 27.4, 43.7)	1057	-	-	-
(3.6, 27.4, 43.7)	970	-	-	-
(4.9, 27.4, 43.7)	914	-	-	-
(5.8, 27.4, 43.7)	905	-	-	-
(14.6, 16.0, 49.1)	1120	-	-	-
(13.4, 16.0, 49.1)	1122	-	-	-
(12.2, 16.0, 49.1)	1125	-	-	-
(14.6, 19.1, 49.1)	1043	-	-	-
(13.4, 19.1, 49.1)	1031	-	-	-
(12.2, 19.1, 49.1)	1059	-	-	-

Species Composition (dry)

(X, Y, Z)	O ₂ (%)	CO (ppm)	CO ₂ (%)	NO _x (ppm)	SO ₂ (ppm)
(14.6, 1.4, 11.5)	6.07	44	13.2	252	1460
(13.4, 1.4, 11.5)	5.21	43	13.7	267	1620
(12.2, 1.4, 11.5)	5.56	31	12.7	246	2280
(14.6, 12.1, 11.5)	2.44	4140	15.0	300	1850
(13.4, 12.1, 11.5)	2.89	3332	14.7	310	1990
(12.2, 12.1, 11.5)	2.54	3145	15.8	308	2240
(1.2, 12.1, 11.5)	3.04	182	15.9	280	2100
(2.4, 12.1, 11.5)	2.53	1016	16.6	283	2920
(3.6, 12.1, 11.5)	3.54	326	14.7	288	2340
(1.2, 1.2, 27.0)	6.69	705	11.2	246	1560
(1.2, 2.4, 27.0)	4.51	1530	13.2	295	1670
(1.2, 3.6, 27.0)	3.40	3740	14.1	316	1730
(5.1, 1.2, 27.0)	6.61	140	10.9	311	1390
(10.6, 1.2, 27.0)	8.88	99	9.6	289	1070
(10.6, 2.4, 27.0)	7.41	1220	10.7	293	1100
(10.6, 3.6, 27.0)	7.29	1060	11.2	311	1400
(14.5, 1.2, 27.0)	7.62	1440	10.1	326	1490
(14.5, 2.4, 27.0)	8.43	3300	9.5	268	1210
(14.5, 3.6, 27.0)	3.00	5010	14.9	407	1720

Table D.2 - continued

Species Composition (dry) (X, Y, Z)	O ₂ (%)	CO (ppm)	CO ₂ (%)	NO _x (ppm)	SO ₂ (ppm)
(1.2, 12.3, 27.0)	8.00	336	10.8	266	2040
(1.2, 11.1, 27.0)	10.56	870	8.3	208	1960
(1.2, 9.9, 27.0)	9.71	1740	8.9	220	2060
(5.1, 12.3, 27.0)	2.00	4760	15.4	286	2630
(5.1, 11.1, 27.0)	6.11	1468	12.6	273	2310
(5.1, 9.9, 27.0)	4.65	1998	15.0	292	2620
(10.6, 11.1, 27.0)	0.44	76250	14.8	260	2340
(10.6, 9.9, 27.0)	0.20	76250	15.4	263	2330
(14.5, 12.3, 27.0)	10.29	5761	13.4	303	2520
(14.5, 11.1, 27.0)	4.56	6052	14.0	320	2300
(14.5, 9.9, 27.0)	4.93	3844	14.0	320	2300
(1.2, 13.9, 43.1)	5.76	38	12.5	352	2210
(2.4, 13.9, 43.1)	5.64	36	12.5	347	2270
(3.6, 13.9, 43.1)	5.52	37	12.3	342	2260
(1.2, 20.1, 43.7)	3.61	46	16.5	312	2760
(2.4, 20.1, 43.7)	3.61	46	16.5	312	2760
(3.6, 20.1, 43.7)	3.17	68	16.7	308	2740
(4.8, 20.1, 43.7)	3.17	68	16.7	308	2740
(5.4, 20.1, 43.7)	3.17	68	16.7	308	2740
(1.2, 23.1, 43.7)	7.38	36	11.4	312	2290
(2.4, 23.1, 43.7)	4.68	43	14.7	308	2456
(3.6, 23.1, 43.7)	4.51	34	14.6	308	1560
(4.8, 23.1, 43.7)	3.89	39	14.2	307	2640
(5.4, 23.1, 43.7)	3.79	28	14.3	310	2440
(1.2, 27.4, 43.7)	6.18	3	12.9	324	2270
(2.4, 27.4, 43.7)	6.15	35	12.6	316	2280
(3.6, 27.4, 43.7)	5.08	41	13.4	316	2420
(4.8, 27.4, 43.7)	4.56	42	13.4	308	2430
(5.4, 27.4, 43.7)	4.76	35	13.5	309	2430
(1.2, 13.9, 43.1)	5.36	263	12.9	240	2080
(2.4, 13.9, 43.1)	5.86	277	13.0	276	2060
(1.2, 20.1, 43.7)	1.77	616	17.7	324	2920
(2.4, 20.1, 43.7)	2.66	80	17.1	329	2840
(3.6, 20.1, 43.7)	3.30	35	17.0	326	2860
(4.9, 20.1, 43.7)	3.81	44	16.4	321	2740
(5.8, 20.1, 43.7)	4.96	27	15.6	305	2600
(1.2, 23.1, 43.7)	1.62	1180	17.0	341	2790
(2.4, 23.1, 43.7)	2.47	64	16.8	356	2750
(4.6, 23.1, 43.7)	3.26	57	16.5	337	2750
(5.8, 23.1, 43.7)	2.92	59	16.9	315	2700
(1.2, 27.4, 43.7)	1.73	204	18.0	327	2940
(3.6, 27.4, 43.7)	3.01	64	17.3	336	2680
(4.9, 27.4, 43.7)	3.19	69	17.5	318	2540
(5.8, 27.4, 43.7)	3.42	60.8	17.5	312	2620
(14.6, 16.0, 49.1)	9.53	24.1	11.1	228	1330
(13.4, 16.0, 49.1)	6.75	24.5	13.6	255	1780
(12.2, 16.0, 49.1)	7.17	44.2	13.2	230	1910

Table D.2 - continued

Flue gas economizer outlet

	O ₂ (%)	CO ₂ (%)	NO _x (ppm)	Corrected to 3% O ₂ CO (ppm)	SO _x (ppm)
Avg.	3.90	14.3	328	90	2800
Max.	4.58	16.9	378	281	3380
Min.	3.03	13.4	254	16	2310

Air preheater outlet

	O ₂ (%)	CO ₂ (%)	NO _x (ppm)	Corrected to 3% O ₂ CO (ppm)	SO _x (ppm)
Avg.	4.64	14.5	344	16	2610
Max.	6.94	17.0	375	20	2840
Min.	2.32	11.1	320	3	2240

Incident Radiative Heat Flux Densities, kW/m²

(0.92,0.00,0.42)	290 ¹
(0.49,0.00,0.42)	320
(0.10,0.00,0.42)	530
(0.92,1.00,0.42)	440
(0.49,1.00,0.42)	560
(0.10,1.00,0.42)	430
(0.92,0.00,0.35)	160
(0.49,0.00,0.35)	630
(0.10,0.00,0.35)	380
(0.92,1.00,0.35)	400
(0.49,1.00,0.35)	660
(0.10,1.00,0.35)	430
(0.92,1.00,0.28)	240
(0.49,1.00,0.28)	480
(0.10,1.00,0.28)	400
(0.92,0.00,0.79)	230
(0.81,0.00,0.79)	310
(0.63,0.00,0.79)	290
(0.49,0.00,0.79)	220
(0.36,0.00,0.79)	250
(0.19,0.00,0.79)	220
(0.10,0.00,0.79)	160
(0.92,0.00,0.62)	390
(0.49,0.00,0.62)	460
(0.10,0.00,0.62)	360

¹ Values for incident radiative heat flux densities were read off of graphical data plots and are estimated to be within ± 20 kW/m² of the plotted value.

Table D.2 - continued

(0.92,0.00,0.57)	540
(0.49,0.00,0.57)	610
(0.10,0.00,0.57)	510
(0.92,1.00,0.57)	530
(0.10,1.00,0.57)	460
(0.92,0.00,0.51)	430
(0.63,0.00,0.51)	390
(0.36,0.00,0.51)	520
(0.10,0.00,0.51)	490
(0.92,1.00,0.51)	410
(0.63,1.00,0.51)	580
(0.36,1.00,0.51)	620
(0.10,1.00,0.51)	450

Introduction to Case D3 Duck Creek Furnace (Cetegen, 1987)

Case D3 is taken from an evaluation of the time/temperature characteristics in utility boilers by Energy and Environmental Research Corporation of Irvine, California (Cetegen, 1987). The study included measurements from two full-scale furnaces. Case D3 is from an evaluation of the 420 MW_e wall-fired unit number one of the Duck Creek Furnace located near Canton, Illinois. The furnace was built by Riley-Stoker Corporation and is owned by Central Illinois Light Company.

Dimensioned drawings of the furnace are provided to show the geometrical details needed for modeling. When geometrical details were not provided in the source material, estimation of the correct size and location were made using available information given throughout the report. All measurements in the data set are in the International System of Units. The furnace drawings are superimposed on an X, Y, Z coordinate system used to locate parts of the furnace and test measurements. The X, Y, Z system is used in various parts of the data set. The locations of test measurements were normalized by the width, depth, and height of the furnace for each of the X, Y, and Z axes, respectively.

After the figures of the furnace are given, the operating conditions and experimental data measurements (Table D.3) are listed. The data were taken using the same approximate set of operating conditions throughout the period of testing. Since testing was taken over several days, and the load was varied on a daily basis, the conditions may have been slightly different each day of testing.

The experimental data are presented after the inlet conditions. The data include temperature, velocity in both the Z (vertical) and X directions, and concentrations of several gaseous species. An occasional velocity measurement was given for the X direction. When no velocity was given, the space was left blank.

Figure D.6

Case D3 - Three-Dimensional Drawing of Furnace.

Details of the furnace dimensions are given in Figures D.7 and D.8. $X+$, $Y+$, and $Z+$ refer to the coordinate system used to locate measurements and geometrical features. Information for figure taken from Cetegen (1987).

Figure D.7

Case D3 - Dimensioned Drawing of Furnace.

All dimensions are in meters. Twenty-four burners and eight under-fired air ports are located on the wall at $X=0.0$. Burner dimensions are shown in Figure D.8 Information for figure taken from Cetegen (1987).

Figure D.8
Case D3 - Burner Dimensions.
 All dimensions are given in meters. Information for burner dimensions taken from Cetegen (1987).

Table D.3

Data Set for Case D3 (Cetegen, 1987)

General Information

Location: Canton, Illinois

Owner: Central Illinois Light Company (CILCO)

Installed 1974

Capacity Rating: 420 MW boiler

Solids Type: Crown II mine, Illinois High Volat. Bitum. Coal

Furnace Specifications

Dimensions (X,Y,Z), meters): (16.8,11.6,50.4)

Number of Burners: 24

Burner Locations (X,Y,Z):

Burner ID: U1,U2,U3,U4,U5,U6,U7,U8

(1.566,0.,8.154), (3.513,0.,8.154), (5.460,0.,8.154), (7.407,0.,8.154),
(9.354,0.,8.154), (11.301,0.,8.154), (13.248,0.,8.154), (15.195,0.,8.154)

Burner ID: A1,A2,A3,A4,A5,A6

(2.477,0.,10.593), (4.839,0.,10.593), (7.201,0.,10.593),
(9.563,0.,10.593), (11.925,0.,10.593), (14.287,0.,10.593)

Burner ID: B1,B2,B3,B4,B5,B6

(2.477,0.,14.250), (4.839,0.,14.250), (7.201,0.,14.250),
(9.563,0.,14.250), (11.925,0.,14.250), (14.287,0.,14.250)

Burner ID: C1,C2,C3,C4,C5,C6

(2.477,0.,17.907), (4.839,0.,17.907), (7.201,0.,17.907),
(9.563,0.,17.907), (11.925,0.,17.907), (14.287,0.,17.907)

Burner ID: D1,D2,D3,D4,D5,D6

(2.477,0.,21.565), (4.839,0.,21.565), (7.201,0.,21.565),
(9.563,0.,21.565), (11.925,0.,21.565), (14.287,0.,21.565)

Primary Stream

Solids Total Feedrate (kg/s) 42.95

Gas Total Feedrate (kg/s) 52.88

Gas and coal Temp., K 328 (all burners)

	A1	A2	A3	A4	A5	A6
Solid Feedrate, kg/s	1.660	1.660	1.660	1.660	1.660	1.660
Gas Feedrate, kg/s	2.043	2.043	2.043	2.043	2.043	2.043
	B1	B2	B3	B4	B5	B6
Solid Feed Rate, kg/s	1.722	1.722	1.722	1.722	1.722	1.722
Gas Feedrate, kg/s	2.118	2.118	2.118	2.118	2.118	2.118

1- Four rows, each with six burners.

2- Each burner row and column is assigned a letter A - D and a number from 1-6. For example, A1 is the first burner listed above. Coordinate location is at the center of the burner.

Table D.3 - continued

	C1	C2	C3	C4	C5	C6		
Solid Feed Rate, kg/s	1.820	1.820	1.820	1.820	1.820	1.820		
Gas Feedrate, kg/s	2.242	2.242	2.242	2.242	2.242	2.242		
	D1	D2	D3	D4	D5	D6		
Solid Feed Rate, kg/s	1.957	1.957	1.957	1.957	1.957	1.957		
Gas Feedrate, kg/s	2.410	2.410	2.410	2.410	2.410	2.410		
Secondary Stream								
Gas Total Feedrate, kg/s	338.5							
Gas Temp., K	860 (all burners)							
	A1	A2	A3	A4	A5	A6		
Gas Feedrate, kg/s	18.47	18.47	18.47	18.47	18.47	18.47		
Theor. Swirl No.	1.0	1.0	1.0	1.0	1.0	1.0		
Swirl Direction	CCW	CW	CCW	CW	CCW	CW		
	B1	B2	B3	B4	B5	B6		
Gas Feedrate, kg/s	12.77	12.77	12.77	12.77	12.77	12.77		
Theor. Swirl No.	1.0	1.0	1.0	1.0	1.0	1.0		
Swirl Direction	CCW	CCW	CW	CCW	CW	CCW		
	C1	C2	C3	C4	C5	C6		
Gas Feedrate, kg/s	7.058	7.058	7.058	7.058	7.058	7.058		
Theor. Swirl No.	1.0	1.0	1.0	1.0	1.0	1.0		
Swirl Direction	CCW	CW	CCW	CW	CCW	CW		
	D1	D2	D3	D4	D5	D6		
Gas Feedrate, kg/s	4.345	4.345	4.345	4.345	4.345	4.345		
Theor. Swirl No.	1.0	1.0	1.0	1.0	1.0	1.0		
Swirl Direction	CW	CCW	CW	CCW	CW	CCW		
UFA Air, kg/s	U1	U2	U3	U4	U5	U6	U7	U8
	10.33	10.33	10.33	10.33	10.33	10.33	10.33	10.33
Stoichiometric Ratio								
	A1	A2	A3	A4	A5	A6		
	1.61	1.61	1.61	1.61	1.61	1.61		
	B1	B2	B3	B4	B5	B6		
	1.12	1.12	1.12	1.12	1.12	1.12		
	C1	C2	C3	C4	C5	C6		
	0.66	0.66	0.66	0.66	0.66	0.66		
	D1	D2	D3	D4	D5	D6		
	0.45	0.45	0.45	0.45	0.45	0.45		

1- Flow rate is estimated to be different on each row of burners. Values used in the data book were taken from chapter five of Cetegen (1987) where information used to model the data set were provided.

Table D.3 - continued

Fuel Compositions (All burners have same fuel compositions)

Gas - Primary

N ₂	0.79
O ₂	0.21

Gas - Secondary

N ₂	0.79
O ₂	0.21

Solids (same for all burners)

Ultimate Analysis Dry (wt%)

Carbon	68.28
Hydrogen	4.97
Nitrogen	1.22
Oxygen	12.38
Sulfur, Total	4.28
Ash	8.88

Proximate Analysis Dry (wt%)

Volatile Matter	40.86
Ash	8.88
Fixed Carbon	50.26

Moisture (wt%) 16.72

Heating Value Dry (J/kg) 6.050 E06

Size

% through 50 mesh	97.3
% through 100 mesh	92.7
% through 200 mesh	78.9

Temperature and velocity

(X,Y,Z)	Temp. (K)	$\bar{y}$ (m/s)	V_y (m/s)	V_z (m/s)
(1.2,11.2,14.6)	1519	-	-	-
(2.4,11.2,14.6)	1546	-	-	-
(3.7,11.2,14.6)	1617	-	-	5.9
(6.0,10.4,14.6)	1622	-	-	-
(6.0,9.4,14.6)	1774	-5.4	-	5.4
(10.8,10.4,14.6)	1696	0.0	-	5.5
(10.8,9.4,14.6)	1844	0.0	-	5.9
(13.1,11.2,14.6)	1690	-	-	-
(14.3,11.2,14.6)	1604	-	-	7.6
(15.5,11.2,14.6)	1470	-	-	7.2
(6.0,10.4,21.9)	1824	-26.0	-	-
(6.0,9.4,21.9)	1916	-26.8	-	-

1- Velocities were reported in either the X or Y direction but not both. Measurements that were not given have a "-". At some locations, only temperature was reported.

Table D.3 - continued

Temperature and velocity (X, Y, Z)	Temp. (K)	y (m/s)	V _y (m/s)	V _z (m/s)
(10.8, 10.4, 21.9)	1849	-24.2	-	-
(10.8, 9.4, 21.9)	1907	-26.7	-	18.9
(0.3, 0.9, 37.9)	1547	1.3	-	13.7
(0.3, 2.7, 37.9)	1584	0.0	-	7.5
(0.3, 3.5, 37.9)	1358	-	-	-
(5.6, 0.9, 37.9)	1556	0.0	-	-
(5.6, 2.7, 37.9)	1659	0.0	-	16.5
(5.6, 3.5, 37.9)	1615	-	-	-
(11.2, 0.9, 37.9)	1535	0.0	-	12.1
(11.2, 2.7, 37.9)	1626	-	-	-
(16.4, 0.9, 37.9)	1306	0.0	-	19.0
(16.4, 2.7, 37.9)	1253	0.0	-	-
(16.4, 3.5, 37.9)	1307	-	-	-
(0.3, 0.9, 44.7)	1079	-	-	10.2
(0.3, 2.7, 44.7)	1275	-	-	13.1
(0.3, 4.0, 44.7)	1302	-	-	13.2
(5.6, 0.9, 44.7)	1381	-	-	7.7
(5.6, 2.7, 44.7)	1463	-	-	12.0
(5.6, 4.0, 44.7)	1235	-	-	14.2
(11.2, 0.9, 44.7)	1235	-	-	8.6
(11.2, 2.7, 44.7)	1500	-	-	15.9
(11.2, 4.0, 44.7)	1535	-	-	17.5
(16.4, 0.9, 44.7)	1073	-	-	11.0
(16.4, 2.7, 44.7)	1197	-	-	21.0
(16.4, 4.0, 44.7)	1191	-	-	-
(1.2, 13.0, 46.9)	1030	2.2	-	-3.8
(2.4, 13.0, 46.9)	1000	3.4	-	-5.9
(4.3, 13.0, 46.9)	1035	-	-	-
(6.1, 13.0, 46.9)	1078	4.4	-	-4.4
(10.7, 13.0, 46.9)	1074	-	-	-
(12.5, 13.0, 46.9)	985	-	4.1	-4.1
(14.3, 13.0, 46.9)	958	-	5.5	-5.5
(15.5, 13.0, 46.9)	1001	-	5.3	-5.3
(1.2, 11.3, 46.9)	1094	-	1.8	6.9
(2.4, 11.3, 46.9)	1063	-	-7.8	-9.3
(4.3, 11.3, 46.9)	1089	-	-7.7	-
(6.1, 11.3, 46.9)	1115	-	-	-
(10.0, 11.3, 46.9)	1115	-	-	-
(12.5, 11.3, 46.9)	1064	-	-8.3	0.0
(14.3, 11.3, 46.9)	1011	-	7.0	-
(15.5, 11.3, 46.9)	1039	-	4.4	-4.4
(1.2, 15.4, 45.2)	860	-	-	-
(2.4, 15.4, 45.2)	876	-	0.0	-4.9
(4.3, 15.4, 45.2)	871	-	0.0	-4.0
(6.1, 15.4, 45.2)	934	-	0.0	-10.1
(10.7, 15.4, 45.2)	892	-	-4.0	-7.0
(12.5, 15.4, 45.2)	909	-	-0.5	-9.1
(14.3, 15.4, 45.2)	863	-	0.6	-6.9
(15.5, 15.4, 45.2)	885	-	-	-4.9

Table D.3 - continued

Temperature and velocity (X, Y, Z)	Temp. (K)	V (m/s)	V _y (m/s)	V _z (m/s)
(1.2, 15.4, 41.8)	816	-	-12.1	-12.1
(2.4, 15.4, 41.8)	779	-	0.0	-14.9
(4.3, 15.4, 41.8)	851	-	-8.9	-8.9
(6.4, 15.4, 41.8)	814	-	-13.7	-13.7
(11.3, 15.4, 41.8)	834	-	-6.0	-10.6
(12.5, 15.4, 41.8)	841	-	-2.5	-13.9
(14.3, 15.4, 41.8)	832	-	-	-14.5
(15.5, 15.4, 41.8)	837	-	-	-17.1
(1.2, 7.8, 41.8)	1039	-	-	-
(14.6, 7.8, 41.8)	1039	-	-3.0	0.5
(15.5, 7.8, 41.8)	1049	-	-	-2.8

Species Composition (dry) (X, Y, Z)	O ₂ (%)	CO (ppm)	CO ₂ (%)	NO _x (ppm)	SO ₂ (ppm)
(1.2, 11.2, 14.6)	14.3	56	6.5	276	840
(2.4, 11.2, 14.6)	13.6	122	7.0	302	984
(3.7, 11.2, 14.6)	13.0	167	7.9	307	1158
(6.0, 10.4, 14.6)	12.5	144	8.0	261	1102
(6.0, 9.4, 14.6)	11.8	78	8.5	352	1193
(10.8, 10.4, 14.6)	7.6	2011	11.1	266	1786
(10.8, 9.4, 14.6)	7.7	3700	11.0	256	1668
(13.1, 11.2, 14.6)	12.0	1211	5.8	231	542
(14.3, 11.2, 14.6)	13.4	900	7.7	210	1213
(15.5, 11.2, 14.6)	15.5	100	4.9	165	1394
(6.0, 10.4, 21.9)	10.5	78	9.2	362	1373
(6.0, 9.4, 21.9)	13.5	167	7.0	271	958
(10.8, 10.4, 21.9)	8.1	1344	11.6	312	1594
(10.8, 9.4, 21.9)	8.4	1922	11.3	261	1739
(0.3, 0.9, 37.9)	8.6	1686	11.0	202	1921
(0.3, 2.7, 37.9)	10.4	281	9.6	247	1726
(5.6, 0.9, 37.9)	0.6	7000	16.7	222	2915
(5.6, 2.7, 37.9)	0.4	8000	16.3	276	2824
(11.2, 0.9, 37.9)	1.8	4324	16.0	291	3041
(11.2, 2.7, 37.9)	1.7	4324	16.6	301	3124
(16.4, 0.9, 37.9)	5.8	541	13.7	301	2506
(16.4, 2.7, 37.9)	8.3	562	11.8	336	2072
(5.6, 0.9, 44.7)	2.2	989	16.4	320	3306
(5.6, 2.7, 44.7)	1.0	-	16.9	367	3524
(5.6, 4.0, 44.7)	1.1	3768	16.9	357	3486
(11.2, 0.9, 44.7)	3.2	2800	14.8	335	2313
(16.4, 0.9, 44.7)	8.2	168	11.3	341	2327
(16.4, 2.7, 44.7)	7.7	105	11.5	382	2222
(16.4, 4.0, 44.7)	8.2	84	11.3	378	2234
(2.4, 13.0, 46.9)	4.6	80	14.3	366	2488
(4.3, 13.0, 46.9)	3.8	60	15.0	346	2776
(6.1, 13.0, 46.9)	0.8	3400	17.0	301	3065
(10.7, 13.0, 46.9)	0.4	-	17.2	334	3246
(12.5, 13.0, 46.9)	4.0	312	14.6	380	2734

Table D.3 - continued

Species Composition (dry) (X, Y, Z)	O ₂ (%)	CO (ppm)	CO ₂ (%)	NO _x (ppm)	SO ₂ (ppm)
14.3, 13.0, 46.9)	4.3	180	14.5	380	2932
(15.5, 13.0, 46.9)	4.5	70	12.3	513	2084
(1.2, 11.3, 46.9)	6.7	40	12.5	502	2218
(2.4, 11.3, 46.9)	4.4	60	14.3	392	2504
(4.3, 11.3, 46.9)	2.8	360	15.8	336	2931
(6.1, 11.3, 46.9)	0.8	3400	17.3	311	3217
(10.0, 11.3, 46.9)	-	4180	17.0	328	3145
(12.5, 11.3, 46.9)	-	971	15.8	357	-
(14.3, 11.3, 46.9)	-	129	13.7	351	-
(15.5, 11.3, 46.9)	-	103	12.3	496	-
(1.2, 15.4, 45.2)	7.1	57	12.5	373	2217
(2.4, 15.4, 45.2)	5.5	114	13.8	328	2685
(4.3, 15.4, 45.2)	3.9	305	14.9	328	2878
(6.1, 15.4, 45.2)	2.0	1486	16.3	313	3156
(10.7, 15.4, 45.2)	2.5	1606	15.8	281	3272
(12.5, 15.4, 45.2)	3.5	703	15.3	311	3031
(14.3, 15.4, 45.2)	7.1	176	12.3	335	2402
(1.2, 15.4, 41.8)	5.8	105	13.6	347	2603
(2.4, 15.4, 41.8)	3.7	147	15.1	342	3109
(4.3, 15.4, 41.8)	2.3	400	16.5	332	3128
(6.4, 15.4, 41.8)	1.7	989	17.1	347	3571
(11.3, 15.4, 41.8)	2.6	810	16.1	322	3273
(12.5, 15.4, 41.8)	4.0	356	15.0	342	2935
(14.3, 15.4, 41.8)	6.2	92	13.3	381	2604
(15.5, 15.4, 41.8)	6.8	92	12.9	411	2475
(1.2, 7.8, 41.8)	5.9	63	13.5	427	2627
(14.6, 7.8, 41.8)	6.0	42	13.0	492	2502
(15.5, 7.8, 41.8)	7.0	42	11.2	472	2448

Incident Radiative Heat Flux Densities, kW/m²

(0.00, 0.25, 0.21)	16.19
(0.00, 0.75, 0.21)	9.95
(1.00, 0.75, 0.21)	9.48
(1.00, 0.25, 0.21)	16.19
(0.00, 0.25, 0.28)	21.37
(0.00, 0.75, 0.28)	11.99
(0.20, 1.00, 0.28)	11.39
(0.40, 1.00, 0.28)	24.97
(0.60, 1.00, 0.28)	24.97
(0.80, 1.00, 0.28)	13.20
(1.00, 0.75, 0.28)	11.03
(1.00, 0.25, 0.28)	21.00
(0.00, 0.25, 0.36)	18.35
(0.00, 0.75, 0.36)	14.51
(0.20, 1.00, 0.36)	14.51
(0.40, 1.00, 0.36)	28.37
(0.60, 1.00, 0.36)	26.67
(0.80, 1.00, 0.36)	12.30

Table D.3 - continued

(1.00, 0.75, 0.36)	12.30
(1.00, 0.25, 0.36)	22.13
(0.00, 0.25, 0.43)	18.63
(0.00, 0.75, 0.43)	15.42
(0.20, 1.00, 0.43)	14.55
(0.40, 1.00, 0.43)	28.00
(0.60, 1.00, 0.43)	27.24
(0.80, 1.00, 0.43)	13.41
(1.00, 0.75, 0.43)	21.37
(1.00, 0.50, 0.43)	24.59
(1.00, 0.25, 0.43)	13.3
(0.00, 0.50, 0.50)	25.5
(0.00, 0.75, 0.50)	18.0
(1.00, 0.75, 0.50)	13.2
(1.00, 0.50, 0.50)	25.2
(0.80, 0.00, 0.62)	13.2
(0.60, 0.00, 0.62)	27.8
(0.40, 0.00, 0.62)	28.0
(0.20, 0.00, 0.62)	15.3
(0.80, 0.00, 0.71)	7.19
(0.60, 0.00, 0.71)	16.5
(0.40, 0.00, 0.71)	15.3
(0.20, 0.00, 0.71)	7.19
(0.00, 0.25, 0.71)	6.24
(1.00, 0.25, 0.71)	6.60
(0.80, 0.00, 0.79)	4.20
(0.60, 0.00, 0.79)	9.48
(0.40, 0.00, 0.79)	8.15
(0.20, 0.00, 0.79)	2.40
(0.00, 0.25, 0.79)	3.01
(0.80, 0.00, 0.86)	2.27
(0.60, 0.00, 0.86)	7.68
(0.40, 0.00, 0.86)	7.79
(0.20, 0.00, 0.86)	2.04

Appendix E

Sample Calculations Used for Data Evaluations.

Material Balance Calculation

- 1) Velocity measurement locations in a furnace cross section

$$\begin{bmatrix} V_{11} & V_{12} & V_{13} \\ V_{21} & V_{22} & V_{23} \\ V_{31} & V_{32} & V_{33} \end{bmatrix}$$

- 2) Divide furnace cross sectional area into three equal areas = A_1 :

$$\begin{bmatrix} V_{11} \\ V_{12} \\ V_{13} \end{bmatrix}, \begin{bmatrix} V_{21} \\ V_{22} \\ V_{23} \end{bmatrix}, \begin{bmatrix} V_{31} \\ V_{32} \\ V_{33} \end{bmatrix}$$

- 3) Adjust flows for temperatures at each measurement location:

$$F = \begin{bmatrix} V_{11} \\ V_{12} \\ V_{13} \end{bmatrix} \times \begin{bmatrix} \rho_{11} \\ \rho_{12} \\ \rho_{13} \end{bmatrix} \text{ with dimensions of } \frac{m}{t \cdot l^2}$$

- 4) Calculate an average flux for each section using numerical integration:

$$F_{avg} = \frac{1}{A} \int F dA$$

do for each of areas 1, 2, and 3 using simpson's integration or trapezoidal rule.

- 5) The partial area multiplied by the average flux for the partial area equals the mass flow for that section:

$$m_1 = A_1 \cdot F_{avg}$$

- 6) The total of the three areas equals the total mass flow:

$$m_{total} = \sum_{i=1}^3 m_i$$

- 7) Mass flow rates or volumetric flow rates can be used to compare estimations and specified flow rates. Care must be taken to compare flows on an equal basis (i.e. same temperature, pressure, etc.)

- 8) If solids needed to be taken into account, a similar method was used. The mass flux of the particles was added to the gas mass flux for each measurement location before integrating.

Appendix F

Additional References to Combustion Data

Additional References to Combustion Data

During the extensive search for combustion data, many articles and reports were found that referred to both two-dimensional and three-dimensional combustion data or combustion-related topics. The references listed in Appendix F were not directly referred to in this document but have been included as part of the documentation of the literature search made for this study.

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