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INTERNATIONAL RESEARCH CENTERS' ACTIVITIES IN COAL COMBUSTION

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Abstract—Consumption of fossil fuels (i.e., oil, gas, coal) is the major source (86%) for meeting the world's energy needs and is projected to be so for some time to come. Coal accounts for 73% of the world's recoverable reserves of fossil fuels. World consumption of coal is increasing, particularly in Asia. Yet, clean and efficient use of coal presents important research challenges. This paper provides a comparative review of thirteen combustion centers in eight nations, where each has significant research components devoted to coal. Other active combustion centers doing similar work are not included in this review for various reasons. Following an introduction, a section of this review is devoted to each of the thirteen participating centers. In these sections, mission, objectives, research program, representative accomplishments, and directions are addressed. Data are also provided relating to center history, budget, size, and areas of emphasis. Collectively, these centers expend about $72 million per year, conduct over 600 research projects involving 1500 researchers, interact with 700 organizations, and provide an estimated 1000 reports and manuscripts annually.

Though centers vary substantially in years of existence, budget size, personnel, and otherwise, on average, centers have 22 years of experience, involve over 110 research personnel, spend over $5 million per year, and conduct nearly 50 projects. All centers are involved in experimental measurements and applications of computerized combustion models, all work on environmental issues, all do substantial work relating to coal combustion, and all work on transferring center technologies. However, research on other fuels, focus on processes and systems, and emerging technologies vary substantially among the participating centers.

Directions for centers' research typically include increasing international activity, strong environmental focus, more work on biomass and waste materials, emerging coal energy technologies, and improvement in conversion efficiencies.

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1. INTRODUCTION

The central purposes of this review paper are to (1) provide a summary of the scope, magnitude, and focus of coal combustion research in various prominent centers of the world, and (2) assess the direction of coal combustion research in these centers.

The principal author participated as a member of the program planning committee for the Thirteenth Annual International Pittsburgh Coal Conference. One of several sessions recommended by the author and accepted by the committee was a new conference session on Coal Combustion Research Centers. Since there are many such centers around the world, it was thought that an overview of the characteristics and research programs in selected centers conducting coal combustion research would be enlightening, given that coal is the world's second most commonly used energy source.

Table 1. Participating international combustion research centers with significant work in coal

Center name	City/Country
The Advanced Combustion Engineering Research Center	Provo, Utah, USA
The Center of Heat and Mass Transfer in Radiating and Combusting Systems	Lisbon, Portugal
The Cooperative Research Centre for New Technologies for Power Generation from Low-rank Coal	Victoria, Australia
The Cooperative Research Centre for Black Coal Utilization	Callaghan, NSW, Australia
The Division of Coal and Energy Technology (CSIRO)	North Ryde, NSW, Australia
The Energy and Environmental Research Center	Grand Forks, North Dakota, U.S.A.
The Energy Institute	University Park, Pennsylvania, U.S.A.
The Harwell (AEA) Combustion Centre	Oxfordshire, U.K.
The Institute of Process Engineering and Power Plant Technology (IVD)	Stuttgart, Germany
The International Flame Research Foundation	IJmuiden, The Netherlands
The LIEKKI Combustion and Gasification Research Program	Turku, Finland
The National Coal Combustion Laboratory	Wuhan, People's Republic of China
The State Key Laboratory of Efficient and Clean Combustion of Coal	Beijing, People's Republic of China

The use of fossil fuels dominates the U.S. (80%) and world (86%) energy production sources. Coal (1.14 trillion short tons) has by far the most substantial known reserves compared to oil (1000 billion barrels) and natural gas (5000 trillion cu. ft.), being nearly 3/4 of the total known fossil fuel reserves.[1] It is anticipated that fossil fuels will continue to dominate the world energy consumption over at least the next few decades, and that coals must, in that case, play an increasingly important role.[2] At the same time, available funding for coal combustion research and development has been declining in the U.S. in recent years. It has therefore been of substantial interest to assess the directions of coal combustion research as the next millennium is approached.

Six centers participated in the Pittsburgh Coal Conference session, which was sufficiently informative that this review publication was planned. For this review, other research centers were invited to participate. While a participating center need not have had all its work directed toward coal combustion, it was required that each participating center have some work in this field. Other guidelines for inviting participation included the following:

(1) The participating organization should be much larger and more productive than would result from one to a few collaborators.

(2) The participating centers' research agenda should contain coal combustion as an important element.

(3) The nature (e.g., center, laboratory, institute, division, group) or affiliation (e.g. university, industry, government) could vary substantially, but a large majority of the work was expected to be in the public domain. Thus, much important work of a proprietary nature is not included.

(4) It was preferred that included centers have a productive research record over at least a few year's period of time.

Over twenty centers (including institutes and laboratories) were invited to participate. Thirteen provided written materials, as summarized in Table 1. Three Centers (CANMET Energy Technology Centre (Canada), Sandia National Laboratories (U.S.A.), and National Carbon Institute (Spain)) with important coal research programs did not participate, while others contacted had little or no research emphasis in coal (e.g., Yale University Combustion Laboratory (U.S.A.)), are de-emphasizing coal combustion research (e.g., RISØ (Denmark)), or conduct coal research work, but not in combustion (e.g., Consortium for Fossil Fuel Liquefaction Science (U.S.A.)). Also, substantial research efforts are conducted outside the public domain or by individual investigators or small groups, and neither are noted herein.

A strong rationale exists for continuing this research agenda into the next century.[2] The critical role of fossil fuels in meeting U.S. and world energy needs has been strongly reinforced. Fossil energy research is a vital part of one of only six national critical technologies in the Clinton Administration.[3] Further, President Clinton's Assistant for Science and Technology indicated that it takes a half a century to make a full shift from one kind of energy form to another.[4] It seems clear that fossil fuels will continue to provide the major portion of world-wide energy needs for many years to come.

Fossil fuels research in the U.S. is driven strongly by existing and proposed federal clean air legislation. There is some anticipated need for increased energy consumption (base load) in the U.S. through the next ten years (1994–2004).[5] Recent analysis projects U.S. energy use to grow by about 25 percent by 2010.[6] However, estimated electric power industry costs to meet the 1990 CAAA regulations on acid rain (SO_x and NO_x) are $4-5 billion annually to the year 2000.[7] Required technologies for retrofitting of existing power generation and industrial equipment are based on combustion research. Also, during this decade, the U.S. has implemented a joint government-industry program, the Clean Coal Technology Program, to demonstrate several new technologies[7] or clean and efficient use of coal, our most plentiful fossil fuel. Forty-five commercial-scale demonstration projects were included with the joint commitment of billions from government and industry.

International opportunities for the application of new power generation technology in developing nations are substantial. By the year 2000, it is expected that generating capacity in Asia will exceed that of the U.S., which will require a six-fold expansion.[8] Asia is expected to add 720 GW_e by 2010, with over 55% being coal.[8] Eastern Europe and Latin America represent other substantial opportunities. The U.S. Department of Energy (DOE) has projected that the potential, cumulative clean coal technology market for new facilities and retrofits outside the U.S. by 2010 is between $270 billion and $750 billion.[5] Lamarre[6] also projects substantial international growth in energy consumption by 2010, 83% in China and 55% in other developing nations. U.S. research into advanced power cycle development is also creating needs for substantial, new combustion research. High pressure combined cycles,[9] fuel-lean, premixed natural gas combustion, control of toxins, trace metals, greenhouse gases, and international fuels all represent major, new research opportunities. Burgeoning wastes also represent a major challenge and opportunity in the United States. Current domestic wastes now reach nearly 200,000,000 tons/year, with only 17% recycled. U.S. industry also has a substantial interest in waste conversion and disposal. As examples, Dow/Midland incinerates industrial waste, while New York State Electric and Gas Company consumes tires and other waste materials jointly with coal in power generation facilities.

Each participating Center (see Table 1) provided a written section with common materials and tables prescribed by the principal author. These sections follow in alphabetical order by center name, with the authors identified for each section. Then, composite information is provided in the section that follows.

2. THE ADVANCED COMBUSTION ENGINEERING RESEARCH CENTER

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2.1. *Introduction*

The Advanced Combustion Engineering Research Center (ACERC) at Brigham Young University and the University of Utah was established in 1986, based on a grant from the Engineering Education and Centers Division of the National Science Foundation. The mission of ACERC has been to develop advanced combustion technology through fundamental engineering research and educational programs aimed at the solution of critical combustion problems *in the clean and efficient use of fossil fuels and waste materials, particularly coal.* ACERC products include (1) new computer aided-design combustion technology, (2) new understanding of combustion mechanisms and their relationships to fuel properties, (3) advanced combustion concepts for improved combustion or conversion processes, and (4) students educated in the interdisciplinary aspects of combustion engineering. The research team has typically included 40 faculty and professionals and over 100 students from nine departments, in cooperation with up to 42 industrial and governmental members. The Center budget for fiscal year 1996 was about five million dollars. ACERC has 38,000 square feet of space, and research equipment exceeds a value of $16,000,000. Over the past decade, 150 organizations have participated in the research, education, and technology transfer programs, including electric power equipment manufacturers and operators, fuel companies, environmental control firms, natural gas industries, pulp and paper companies, glass manufacturers, chemical refineries, steel makers, gas turbine industries, computer manufacturers, cement producers, contaminated soil remediation contractors, together with state and federal agencies and laboratories. Research highlights in six thrust areas over the past decade have emphasized coal combustion. Basic experimental research has provided insights, parameters, and submodels for comprehensive combustion models. New discoveries in coal structure, coal reaction processes and rates, models for acid rain control, turbulent reacting flows, fuel minerals behavior, and fuel and waste conversion processes have given useful insights, while new software products for large furnaces, gasifiers, and rotary kilns are being used by industry. Development of small, highly-instrumented, pilot-scale test-bed facilities allow industrial and academic researchers to characterize the combustion of fuels and wastes in furnaces, rotary kilns, fixed and fluidized beds, and stokers.

2.2. *Center Characteristics and Mission*

ACERC has recently completed a decade of research activity since its beginning in May of 1986. The author is the founding director of ACERC and, in cooperation with two associate directors, is responsible for the general direction of the Center, establishment of its policies, key decisions on research, projects, budgets, technology transfer and related major issues, and supervision of staff. ACERC has successfully operated for over a decade as a joint, two-campus Center with the University of Utah. The executive committee is comprised of the directorate, manager, and leaders of each of the six research thrust areas. Key characteristics of ACERC are summarized in Tables 2 and 3.

Selection, funding, evaluation, and termination of research projects is a vital activity of the executive committee, with important input from the Industrial Advisory Council and ACERC faculty. Proposals for research have been invited annually, reviewed by the appropriate thrust area, and approved by the directorate. Criteria for selection are (1) relevance to the ACERC mission and strategic plan, (2) supporting funding, (3) team qualifications, and (4) potential for industrial impact. ACERC typically has about 30–35 on-going projects in the six thrust areas, each of which are annually evaluated, anonymously by two peer reviewers. Evaluation is based on the annual report, related publications, and the poster session presentation at the annual meeting. Criteria for the evaluation are (1) relevance, (2) quality, (3) productivity, and (4) industrial

Table 2. General characteristics of the ACERC

Title	The Advanced Combustion Engineering Research Center
Location	Brigham Young University, Provo, Utah, U.S.A. University of Utah, Salt Lake City, Utah, U.S.A.
Director(s)	L. Douglas Smoot (Brigham Young University), Director David W. Pershing (University of Utah), Associate Director Thomas H. Fletcher (Brigham Young University), Associate Director
Starting date	May 1986
Mission/objective	Develop and apply advanced combustion technology through industrially relevant, fundamental, interdisciplinary, experimental and numerical modeling research
Focus	Clean and efficient use of fossil fuels and waste materials, especially coal
Research areas	Fuel structure and reaction processes, behavior of mineral matter, pollutant formation and control, reacting turbulent processes, comprehensive combustion modeling, combustor/furnace data, and process strategies

impact. Industrial impact measures the use by ACERC and industry of the investigator's work. Expected outcomes are adopted patents, new test methods used by industry, placement and use of new submodel codes or comprehensive codes, and new process strategies or control technologies adopted by industry.

About 140 personnel have participated in ACERC (see Table 3) in a given year. The Center's size has been quite consistent over several years, and the organization has been very stable. Twelve faculty and professionals have been added since the inception of the Center. The research environment within ACERC has been cooperative and highly interdisciplinary, and the research has been mission-oriented, but clearly of a fundamental nature. The Center has had a very strong influence on the degree of interdisciplinary interaction within the participating schools. The Center participants have come from four engineering disciplines (chemical and fuels, civil, electrical, mechanical) and four science disciplines (computer, materials, chemistry, and mathematics) at

Table 3. Data for the ACERC

A. Number of personnel (1996)

Professional	11
Professorial	22
Postdoctoral	11
Graduate students	61
Undergraduate students	32
Staff/management	3
Other	0
TOTAL	140

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	6845
1995	5342
1996	4781

C. Budget sources (%) (1996)

Government	58
Domestic industry	29
University	11
Foreign	0
Income (patents, royalties, licenses, software, etc.)	2
Other	0
TOTAL	100

D. Space and equipment

1. Research space	38 000 sq. ft.
2. Research equipment/instruments/ computers	$16 000 000

E. External participants/sponsors/advisors/members

Government	7
Industry	43
University	13
TOTAL	63

F. Research program (1996)

Number of fundamental projects	32
Number of applied projects	2
Number of proprietary projects	0
TOTAL	34

G. Center research projects/activities

	Minor Major
Experimental data	1 2 3 4 **5**
Computer software	1 2 3 4 **5**
Inventions/patents	1 **2** 3 4 5
Project reports	1 2 **3** 4 5
Journal/book publications	1 2 3 4 **5**
Consulting services	1 2 **3** 4 5
Process/system concepts	1 **2** 3 4 5
Graduating students	1 2 3 4 **5**
Academic courses	1 2 **3** 4 5
Technology transfer	1 2 3 **4** 5

Table 4. ACERC research thrust areas over the past decade (1986–1996)

Thrust area	Participants[1]					Projects	Research expenditure ($)	Public[4]
	F/P[2]	B.Sc	M.Sc	Ph.D.	PD[3]			
1. Fuel structure and reaction mechanisms	12	61	17	40	12	10	5 624 000	260
2. Fuel minerals/ fouling, slagging	9	40	10	5	6	11	1 956 000	82
3. Pollutant formation/ control and waste incineration	10	36	9	28	5	10	5 397 000	128
4. Turbulent reacting fluid mechanics and heat transfer	7	9	17	25	3	7	2 762 000	95
5. Comprehensive modeling	14	20	23	20	16	23	5 568 000	94
6. Evaluation sata and process strategies	7	27	32	12	1	9	2 807 000	56
TOTAL	59	193	108	130	43	70	24 114 000	715

[1] Total number participating during decade.
[3] PD = postdoctoral.
[2] Some faculty/professionals (F/P) participate in more than one thrust area.
[4] Books, journals and conference manuscripts.

the two universities (Brigham Young University and the University of Utah) with additional support from the University of North Dakota.

The mission of ACERC has been to develop, apply, and transfer *advanced combustion science and technology* to industry through fundamental engineering research and educational programs aimed at the solution of critical combustion problems. ACERC uses fundamental research, bench- and pilot-scale laboratory experimentation and full-scale field testing to develop and evaluate advanced combustion modeling software tools and process hardware concepts.

2.3. *Research Program*

2.3.1. *Overview*

The Center's research program has been conducted in a coordinated effort in six thrust areas, summarized in Table 4. Each thrust area is headed by a chair and generally a co-chair, and each thrust area is advised by a working group of external professionals from academia, government, and industry who meet periodically to review and evaluate the on-going research efforts. ACERC has emphasized low and high-rank coals and solids waste materials. There has been an increasing emphasis on natural gas relating to advanced turbine systems and solids wastes relating to environmental requirements.

As noted in Table 4, 70 research projects have been conducted over the past decade with over $24 million in research expenditures, resulting in over 700 publications and five books. It is only possible to mention a very small part of these research results by thrust area. Further information on ACERC research results has recently been published by Smoot,[10,11] and Smith *et al.*[12]

2.3.2. *Typical research results*

In Thrust Area 1, structural aspects of eleven standard coals, including the eight Argonne coals, were characterized in detail with MS, FTIR, NMR, and GC instruments, as documented by Smith *et al.*[12] Based on some of these structural features, particularly NMR, an advanced coal devolatilization submodel (Chemical Percolation Devolatilization—CPD) was developed,[13] integrated into three-dimensional codes and distributed as a software product. This code reliably predicted total volatile yield for 16 coals (see Fig. 1).[13] Further, a new char oxidation submodel, based on coal and char structural properties and low-temperature oxidation measurements was developed[14] to reliably predict high temperature reaction rates (see Fig. 2).

In Thrust Area 2, new analytical methods including scanning electron microscopy and image analysis, chemical fractionation, X-ray fluorescence and diffraction, and FTIR, were developed to quantitatively measure chemical and physical transformations of coal minerals, and these advanced methods were applied to the eleven standard coals (see Fig. 3).[12,15] Based on these data and extensive laboratory tests, a set of new computerized coal mineral submodels was developed for distribution and for inclusion in comprehensive codes. These submodels treat ash transformation,[16] ash particle size and composition distribution,[17] and ash particle transport and deposition.[18]

A key contribution in Thrust Area 3 relates to measurement and modeling of NO_x formation. An advanced NO_x submodel now includes fuel NO_x, thermal NO_x, heterogeneous NO_x reduction and reburning, and has been extensively compared with data.[10,11] Laboratory-scale measurements[19] have demonstrated NO levels as low as 0.06 lbs NO_2/mmBtu. These measurements

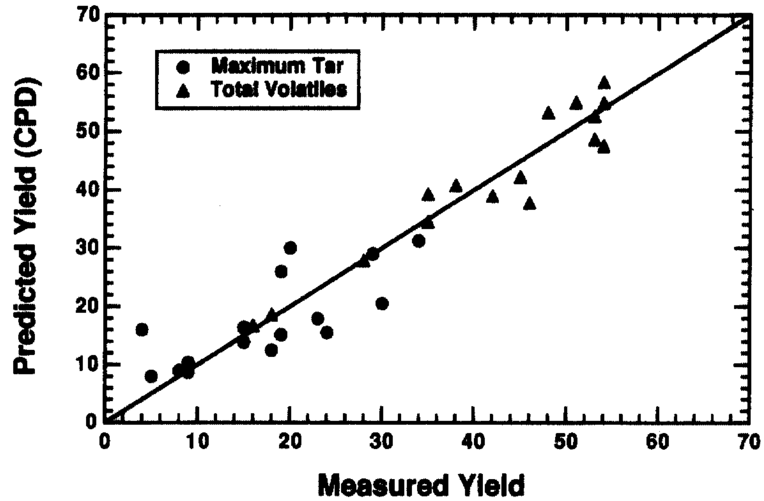

Fig. 1. Comparison of CPD model predictions with measured tar and total volatiles yields. Coal-dependent input coefficients taken directly from NMR data for 16 coals at 0.5 to 10^4 K/s and 1000 to 1300 K.[13]

have included staging, reburning, and SNCR, together with inlet primary velocity optimization (see Fig. 4). Substantial innovative work on thermal treatment of waste materials, including computerized rotary kiln models and industrial testbeds, has also been a productive aspect of Thrust Area 3.[20]

In Thrust Area 4, the theory and code for an advanced, highly efficient gaseous radiation submodel has been developed and evaluated by comparison with lab-scale and utility-scale radiative heat flux data and with other predictive methods. The novel, hybrid, spectral-line-based weighted-sum-of-gray gases method[21] has shown substantial improvement in predictive accuracy and computational efficiency over previous state-of-the-art technologies (see Fig. 5), and has been incorporated into various comprehensive combustion codes. Substantial work in Thrust Area 4 has also been completed by McMurtry and colleagues[22] on linear eddy modeling of reactive, turbulent systems.

Thrust Area 5 has focused on comprehensive modeling of practical furnaces and combustors, and is a culmination of much of the ACERC research work. The principal comprehensive combustion furnace and boiler model developed at ACERC[23] is referred to as Pulverized Coal Gasification and Combustion—3-D (PCGC-3), and can also be applied to gaseous and oil-fired systems and non-reacting flows. A recently published review[11] provides a color figure (see Fig. 11 of reference 11), which compares measured and predicted oxygen concentrations and temperatures from within a large-scale utility, coal-fired boiler. It has been licensed to several industrial firms and widely applied to combustors, boilers, gasifiers and furnaces. Joint work with Fluent, Inc. to incorporate ACERC combustion submodels into Fluent's CFD codes has expanded the industrial use of this technology. Another recent review paper[24] provides detailed comparisons of combustion model computations with measured data for PCGC-3,

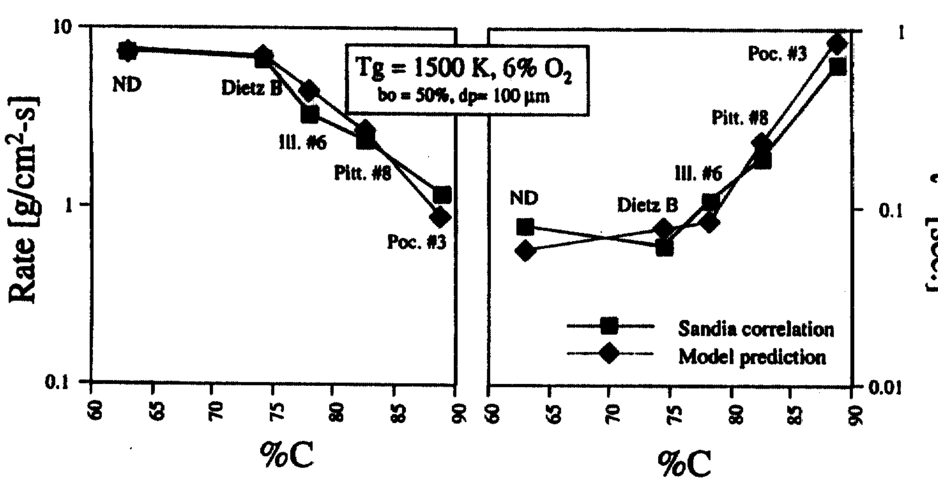

Fig. 2. Char oxidation sub-model predictions of burning rates and times compared to experimentally-based data as a function of the carbon content of the parent coal (bo = burnout; dp = particle diameter; C = carbon).[14]

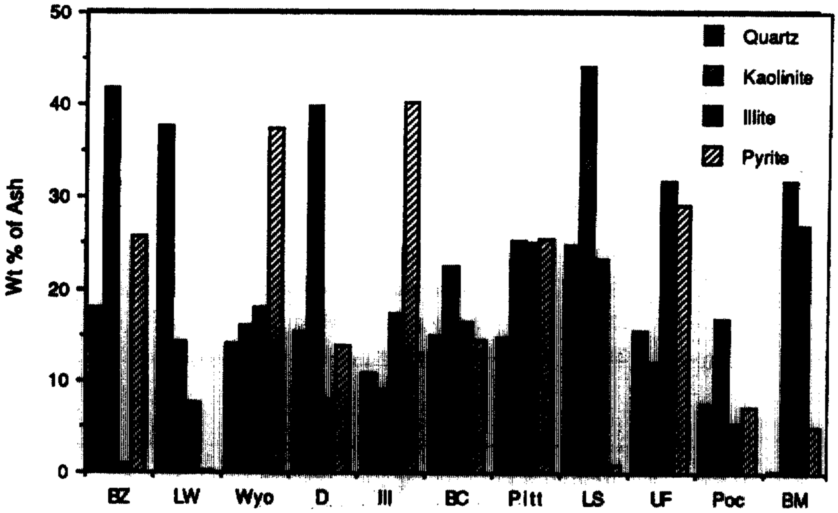

Fig. 3. Content of selected major minerals compared for the 11 recommended coals on a wt. % of ash basis from the CCSEM analysis (BZ = Beluah-Zap, LW = Lower Wilcox, Wyo = Wyodak, D = Dietz, Ill = Illinois #6, BC = Blind Canyon, Pitt = Pittsburgh, LS = Lewiston-Stockton, UF = Upper Freeport, Poc = Pocahontas #3, BM = Buck Mountain).[12]

FLUENT 4.4, and a combined combustion code based on FLUENT 4.4 CFD and ACERC combustion submodels. New modeling work on advanced gas turbine systems[25] shows promise of major advances in treating turbulent kinetics and complex geometries. Figure 6 shows predictions of carbon monoxide and oxides of nitrogen for a lean, premixed laboratory-scale combustor. This simulation includes a five-step methane-oxygen reaction sequence and solves for major species and pollutant species simultaneously with turbulence interactions.[11]

Work in Thrust Area 6 has provided substantial new data for laboratory reactors to utility-scale boilers. ACERC participated with NYSEG to make advanced, laser-based measurements in three test series for two utility boilers (85 MW_e and 150 MW_e, corner-fired).[26] These data have been extensively compared with PCGC-3, with NO_x predictions being consistently reliable. Advanced, laser-based diagnostic measurements, including CARS, PLIF, LDA, PCSV, and PDPA instruments, are being applied to various solids-containing[27] and premixed gas turbine flames,[28] producing comprehensive combustor data on temperature, turbulence properties, species, and radicals.

2.4. *Education and Industrial Collaboration*

During the first decade of ACERC, approximately 250 undergraduate students, 100 M.S. students, and 105 Ph.D. students have been involved in Center research, while over 1,000 students have participated in 20 combustion-related classes at the two universities. ACERC has placed nearly 100 software licenses, and this software is being used in two large DOE advanced pulverized coal system development incentives (LEBS and HiPPS). Six new start-up companies can trace their origins, in part, to ACERC.

ACERC's Industrial Advisory Council has recommended to the directorate how the Center can best realize

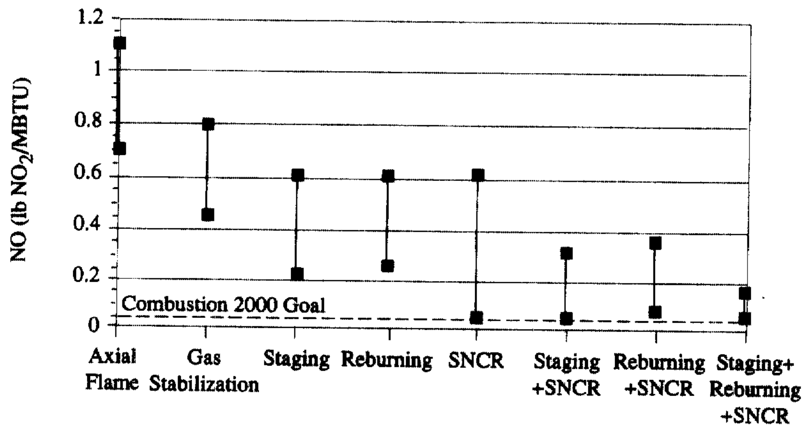

Fig. 4. Summary of integrated NO_x control system experiments.[19]

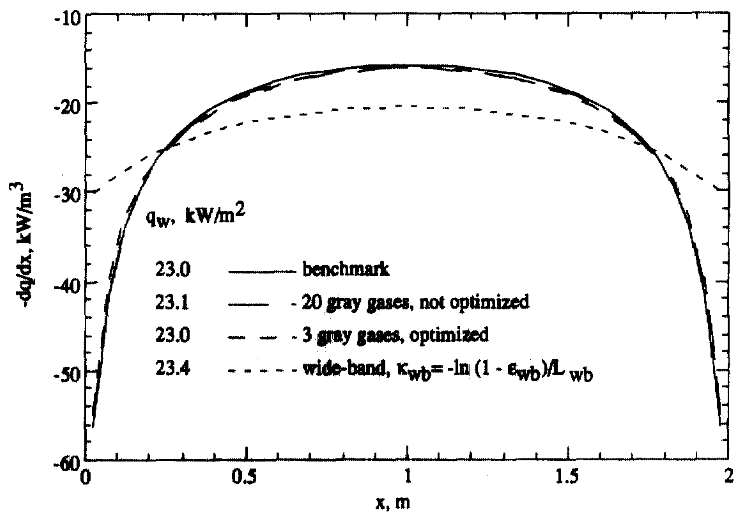

Fig. 5. Comparisons of model predictions for the radiative flux divergence with line-by-line benchmark for 15% H_2O at 1000 K, black walls at 0° K, total pressure 1 atm. Comparisons to the commonly used wide-band model are poor. Both optimized and un-optimized gray gas models yield excellent results. Computer savings of the model over the benchmark line-by-line calculations is over two orders of magnitude (q = heat flux, kW/m^2; w = wall; x = distance from left wall).[21]

the objective of improving U.S. competitiveness in world markets through advanced combustion technology. The Advisory Council has been composed of highly regarded educational, governmental, and industrial executives, professionals and professors from ACERC's membership firms. This advisory group meets periodically on the campus and contributes through correspondence. The Center strategic plan, which is updated periodically, is the responsibility of the directorate with input from the executive committee, the Advisory Council, faculty, working groups, and industrial participants.

Industrial support from membership fees, grants, and contracts has provided about 1/3 of the research budget. Over one hundred-twenty ACERC-related contracts have been received by Center investigators over the past decade, with over half being from industry. Through a recent industrial survey, the following communications methods were rated highly by the industrial respondents: annual conferences, published papers, the Center newsletter (*Burning Issues*), contract research reports, consulting with principal investigators, joint projects, and the annual report.

Fifty-five organizations have obtained license to one or more of the Center's eight software products. Several member companies participated as beta test sites for developing software prior to code releases. The potential for wider distribution and commercialization of Center products has been enhanced through the joint project between Fluent, Inc., to incorporate ACERC combustion submodels into the Fluent, Inc. CFD and combustion codes. ACERC reactor facilities include the following five major pilot-scale combustors that were created as part of the ACERC program and which are now in major demand by industrial members for a wide variety of testing: 120,000 Btu/hr pulverized coal furnace, 750,000 Btu/hr coal/waste/biomass furnace (grate-fired), 700,000 Btu/hr circulating/bubbling bed incinerator, and 150,000 Btu/hr rotary kiln. In addition, a comprehensive 15,000,000 Btu/hr pulverized coal test facility with state-of-the-art NO_x control capabilities was recently constructed. Over forty industrial and governmental organizations have used ACERC's five test-bed facilities. ACERC has participated directly in three U.S. Clean Coal Technology projects, and our research work is related to several more.[29] Further, advanced combustion technology development programs (e.g., Combustion 2000, HiPPS and LEBS) are now underway, and ACERC faculty have major experimental and modeling roles in two of these programs.

2.5. *Center Directions*

Looking toward the future, we plan to promote the use of computerized combustion technology in industry, including refinement, distribution, and application of these codes. We seek to conduct essential research to improve and refine existing combustion modeling technologies, incorporate advanced combustion technology software into prominent commercial CFD codes, and promote cooperative industrial programs through joint projects, industrial consortia, contracts, and consulting. We want to develop advanced, computerized combustion modeling software through fundamental, cross-disciplinary research related to advanced power generation and fuel conversion systems. We will conduct experimental work on fuel structure, reactions and behavior in harsh, new environments such as high pressure systems, lean-premixed systems, and on very low-quality fuels. We will emphasize the development of submodels for fuel gasification, combustion, and conversion under conditions relating to advanced cycles

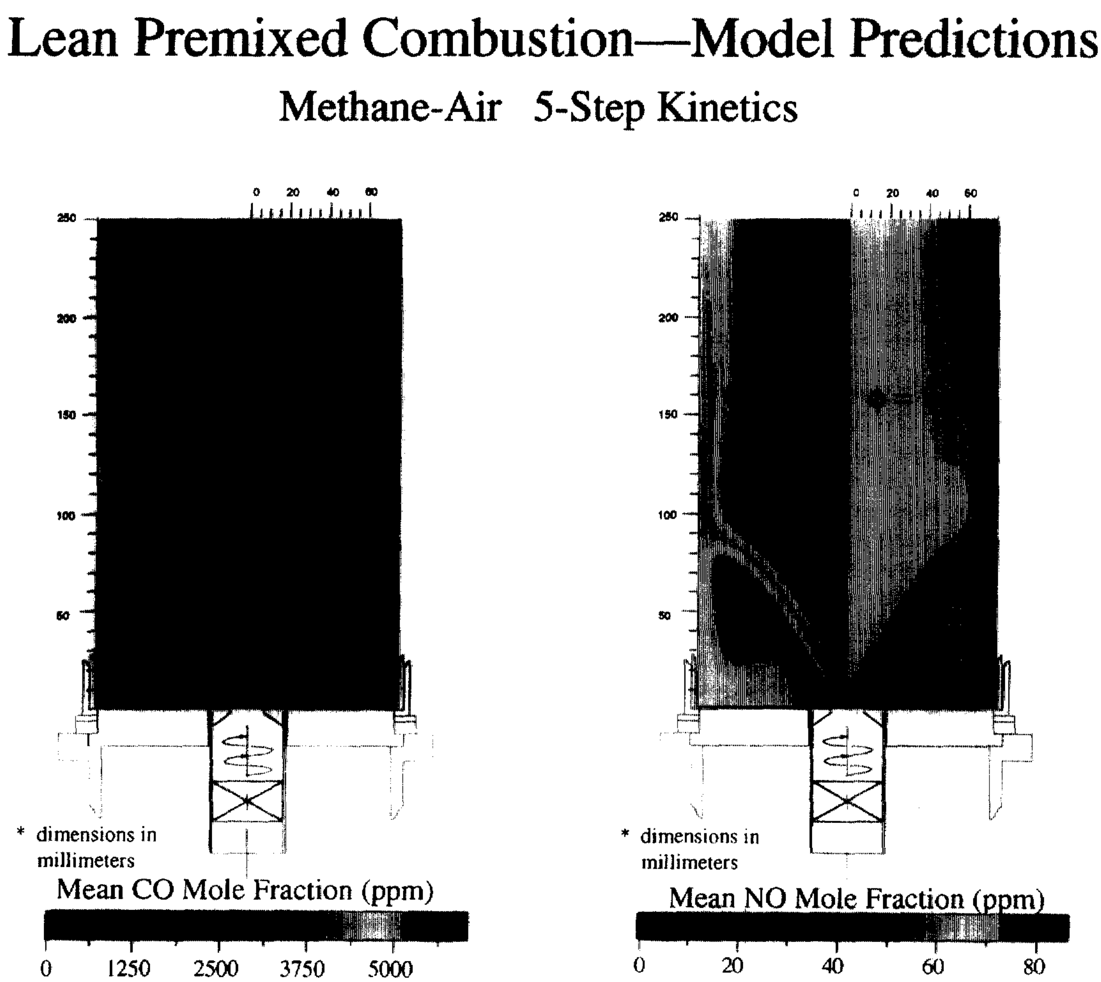

Fig. 6. Predicted (COSMO) carbon monoxide and nitric oxide concentrations for premixed combustion of methane and air in a laboratory-scale lean, premixed combustor (0.8 and 0.65 equivalence ratios) with 5-step methane–air kinetics. Wall temperature = 1000 K.[11]

and perform environmental research work relating to stringent control of acid rain precursors, carbon oxides, particulates, trace metals, hazardous hydrocarbons, and toxic emissions. We will continue to work jointly with industry to develop advanced combustion process concepts, strategies, and technologies (related to industrial hardware) to significantly reduce pollutant emissions, increase thermal efficiency, and provide more environmentally acceptable utilization of fuel and waste materials.

We anticipate a new generation of comprehensive combustion models and advanced combustor design technologies for general application to high pressure, fuel-lean, or mixed fuel systems, and with broad treatment of pollutants. We also anticipate increasing international interaction, expanding industrial use of comprehensive combustion models in industry, continuing demands for control of pollutant emissions from combustion of fossil fuels, and increasing research in waste incineration and conversion. Our greatest challenge will be to obtain the financial resources to replace the NSF-ERC grant which continues through late-1997.

Acknowledgments—A foundational grant from the National Science Foundation, Engineering Education and Centers Division (Dr. Tuppan Mukherjee, Project Officer), has been the cornerstone of Center funding. Substantial financial support through grants, contracts, and membership fees has also come from the U.S. Department of Energy (METC, PETC), the U.S. Environmental Protection Agency, and NASA. Financial support from many industrial companies over the past decade is gratefully acknowledged. Also the technical association with the University of North Dakota, Sandia National Laboratories, and other centers has been invaluable. Particular appreciation is expressed to ACERC Associate Directors, Professor David W. Pershing (U of U) and Professor Thomas H. Fletcher (BYU).

3. THE CENTER OF HEAT AND MASS TRANSFER IN RADIATING AND COMBUSTING SYSTEMS

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3.1. *Mission and Focus*

The main objectives of the Center of Heat and Mass Transfer in Radiating and Combustion Systems (CRCS) are as follows: (1) to make existing combustion models more flexible and easy-to-use (in terms of geometry, operation, and fuels), (2) to extensively validate existing combustion models for industrial applications with combustion data collected at full-scale using robust developed probes, and (3) to develop engineering tools which will incorporate the existing models for training, control, and design (incorporation of the models in knowledge-based systems and coupling the models with optimization techniques for design).

This effort is encompassed by basic research in different areas of importance for the characterization of the full-scale industrial combustion equipment such as radiation modeling, studies on soot morphology, and pollutant formation. Special emphasis is given to the validation of the developed tools at different scales (laboratory, pilot, and industrial scale).

Computational fluid dynamic codes of full-scale industrial equipment exist. However, their use in industrial environments is restricted to large enterprises. This is due to three main reasons: (1) general prediction techniques are highly sophisticated and their use demands a level of commitment which industry for the most part, has so far not been prepared to make, (2) there is a lack of validation for full-scale industrial situations, and (3) general prediction methods are highly computer time-consuming.

Therefore, one of our main objectives is to overcome these barriers, increasing the flexibility of the models in terms of geometry and fuels, validating extensively the existing models in industrial environments, developing faster models through the use of parallel processing, and developing easy-to-use engineering tools which will incorporate the existing models (through model results or knowledge acquired through the models) for training, control and design. In parallel, the group is carrying out fundamental research to create the basis for a new generation of predictive tools.

3.2. *History*

CRCS comprises specialists in the areas of convective and radiative heat transfer and combustion. This group has substantial experience in the field of mathematical modeling of combustion chambers and its application to industrial sectors, such as electricity producers, glass, ceramic, cement, baking and steel. Extensive modeling work has been carried out in recent years. Computer codes directed to industrial use have been realized for utility boilers, glass melting furnaces, ceramic kilns, cement kilns, and baking ovens. We are currently working in collaboration with several factories in the sector of utility boilers, boiler and burner manufacturers, and glass and ceramics producers.

The Center was formed in 1986 (the year Portugal joined European Economic Community) by researchers in the areas of combustion, numerical methods, and heat transfer. External contacts with European universities and industries have been substantially promoted since then. The group participates in several research projects supported by the European Community, through JOULE (Joint Opportunities for Unconventional or Long Term Energy Supply), but also with THERMIE (Projects for the Promotion of Energy Technologies), BRITE (Basic Research in Individual Technologies for Europe), and ESPRIT (European Strategic Programme for Research and Development in Information Technology) programs. The research projects, developed together with the Portuguese Electricity Generating Board (EDP), have been of utmost importance for the Center. In addition, considerable experience has been achieved in glass technology and the group has worked for the major glass companies in the world (European and North American). The research group has also organized several world-wide recognized international conferences in the areas of fluid mechanics, combustion, and numerical methods, including the clean air (Combustion and Technologies for a Clean Environment) conference series.

The Center is included within the Department of Mechanical Engineering (DEM) of the Instituto Superior Técnico (IST). IST is the Faculty of Engineering of the Technical University of Lisbon and was founded in 1911 on the model of the leading schools of engineering in Europe. IST has about 8000 undergraduate students and about 1000 postgraduate students, making it the largest and best known engineering college in Portugal.

3.3. *Characteristics*

The main goal of the present research group has been to simulate and to optimize the design, operation, and control of full-scale combustion equipment. In this context, the present research group has devoted a great deal of time to fundamental research topics, both experimental and theoretical, such as radiative heat transfer and soot morphology, detailed characterization of the near-burner field, and pollutant formation. The group has also developed numerical tools needed for the simulation of full-scale equipment such as grid refinement and parallel computing. Validation of the developed numerical models has been carried out with data obtained in specific experiments at laboratory and pilot-scale combustion equipment. Characterization of full-scale combustion equipment has also been carried out in glass-melting furnaces and in utility boilers with the objective of characterizing the full-scale equipment and validating the application of computational fluid dynamics (CFD) based numerical models. Recently, the group has devoted special attention to the development of diagnostic systems (e.g. heat flux sensor and flame spectral analyzer) and knowledge-based systems of large industrial equipment, such as utility boilers and glass furnaces. Strategies for the inclusion of CFD codes resulting in knowledge- based-systems have been outlined. The fundamental research carried out by this group has been driven by the requirements of the applied research.

3.4. *Administrative Structure and Practice*

Table 5 presents the objective, focus, and research areas of the Center. Table 6 presents the number of

Table 5. General characteristics of the CRCS

Title	The Center of Heat and Mass Transfer in Radiating and Combusting Systems
Location	Instituto Superior Técnico, Lisbon, Portugal
Director(s)	Maria da Graca Carvalho, Professor
Starting date	1986
Mission/objective	Development of tools for operation optimization, design, training and control of full-scale industrial combustion equipment (burning coal, gas, oil and fuel blends)
Focus	Development and validation (at laboratory, pilot and full scale) of CFD codes for large industrial equipment and coupling with optimization techniques for design and incorporation in knowledge-based systems for control. Increase of flexibility of the codes in terms of geometry and fuels. Development of faster and easy-to-use codes. Basic research in areas of importance for the characterization of full-scale industrial combustion equipment such as radiation, soot morphology and pollutants formation
Research areas	● coal, gas and oil combustion ● combustion of fuel blends ● development and validation of CFD codes for large industrial combustion equipment ● scale-up problems ● development of engineering tools for large industrial combustion equipment (CFD codes coupled with optimization techniques for design; incorporation of CFD codes in knowledge-based systems for control) ● radiative heat transfer, radiative properties of particulate matter ● soot morphology ● pollutants formation and control ● characterization of near-burner region ● development of new sensors for large industrial combustion equipment

Table 6. Data for the CRCS

A. Number of personnel (1996)

Professional	1
Professorial	11
Postdoctoral	5
Graduate students	11
Undergraduate students	13
Staff/management	12
Other	0
TOTAL	52

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	1200
1995	1500
1996	1750

C. Budget sources (%) (1996)

Government	32
Domestic industry	12
University	5
Foreign	51
Income (patents, royalties, licenses, software, etc.)	0
Other	0
TOTAL	100

D. Space and equipment

1. Research space	5000 sq. ft.
2. Research equipment/instruments/ computers	$1 250 000

E. External participants/sponsors/advisors/members

Government	2
Industry	1
University	1
TOTAL	4

F. Research program (1996)

Number of fundamental projects	1
Number of applied projects	10
Number of proprietary projects	4
TOTAL	15

G. Center research projects/activities

	Minor Major
Experimental data	1 2 **3** 4 5
Computer software	1 2 3 4 **5**
Inventions/patents	**1** 2 3 4 5
Project reports	1 2 3 **4** 5
Journal/book publications	1 2 **3** 4 5
Consulting services	1 2 **3** 4 5
Process/system concepts	1 **2** 3 4 5
Graduating students	1 2 3 **4** 5
Academic courses	1 2 3 **4** 5
Technology transfer	1 **2** 3 4 5

personnel, budget for the last three years and its sources, space and equipment, number of projects, and the present activities of the Center. The group develops its activities within three organizations, namely DEM-IST (Department of Mechanical Engineering—Instituto Superior Técnico), LASIQ-CNT (Laboratory of Environment and Industrial Combustion Systems—Center of New Technologies), and IrRADIARE (Research and Development in Engineering and Environment). As mentioned in Section 3.2, the group was initially created within IST. In 1994, LASIQ was created within the framework of the PEDIP (National Program for the Development of Industry). The main objective of this laboratory is to support the needs of the Portuguese industry in applied combustion research. Finally, in 1995, IrRADIARE Company was formed to transfer technology and project results to industry. At the present, the group is divided into the following eight areas: (1) coal and biomass combustion, (2) gas, oil, and fuel blends combustion, (3) development of numerical techniques for complex geometries, (4) experimental combustion and measurements in industry, (5) radiative properties of particulate matter, (6) industrial glass furnaces, (7) development of sensors for industrial applications, and (8) control strategies and knowledge based systems.

3.5. *Resources*

Since numerical modeling has been the main activity of the Center, several computing facilities are available, including two parallel computers and access to two main-frame computers. The necessity to perform the validation of the modeling tools led to the acquisition of instrumentation and the construction of experimental facilities. An important part of instrumentation was funded by a grant (LASEF Laboratory of Advanced Sensors for Fluid Flow LASEF—M/93) from the Portuguese government under the program CIENCIA (National Program for Scientific Infrastructures) and through the PEDIP program for the LASIQ.

3.5.1. *Pilot-scale furnace*

The Center's 0.5 MW down-fired, cylindrical furnace is large enough to ensure that the essential physics of full-scale furnaces are simulated. The cylinder is comprised of 8 water-cooled steel segments, each 0.3 m in height and 0.6 m in internal diameter. The roof section and the upper four segments are lined with a layer of refractory and a ceramic fiber blanket sandwiched between the refractory and the water-cooled jacket. Each segment has a pair of diametrically opposed ports for probing and viewing, which are closed with castable refractory inserts in the upper sections and steel inserts in the lower sections. The furnace allows the use of different burners and is equipped with facilities to burn gas, liquid, and pulverized solid fuels.

3.5.2. *Small-scale furnace*

The small-scale furnace is up-fired and is equipped with facilities for flue-gas recycling. The combustion chamber is cylindrical in shape and consists of five interchangeable steel segments each 0.2 m in height and 0.3 m in internal diameter. The furnace allows the use of different burners and is equipped with facilities to burn gas and liquid fuels.

3.5.3. *Instrumentation*

The main instrumentation includes the following: LDA systems; diagnostic equipment for measurements of spectral radiation intensities; diagnostic equipment for collection of OH, C_2, and CH_2 images in flames; analysers of O_2, CO, CO_2, UHC, and NO_x; Malvern Particle Sizer for measurements of droplet/particle size distributions, and several types of probes for temperature measurements, gas sampling and heat flux measurements. These include long probes suitable for the collection of combustion data from industrial furnaces.

3.6. *Research Program and Key Results*

This section presents the work carried out at IST concerning coal combustion, particularly the development and testing of numerical models for the description of fluidized beds and pulverized coal combustion systems.[30]

3.6.1. *Fluidized beds*

Fluidized beds were considered in two projects, in which IST was involved for the use of low calorific-value solid fuels. The projects included the combustion characterization of the fuels and their performance in bubbling and circulating fluidized beds. The fuels considered for the bubbling fluidized bed were Portuguese high ash (~50%) anthracites and forestry wastes, while for the circulating fluidized bed, lignites (from Greece and Germany) were considered together with different absorbents. The role of IST in both projects was mainly concentrated on the development and application of mathematical models to describe combustion, heat transfer, and pollutant formation and retention in the fluidized beds. Work was initiated in modeling the unsteady processes in fluidized beds using general balance equations for particles and gas,[30] but most of the work was performed considering simpler balance models. The modeling of fluidized bed systems is mainly limited by the time necessary to obtain a statistically representative average of the unsteady flow within the bed. For applications with combustion, IST applied the relevant mass and energy balances based on a two-phase description for fluidized beds. This principle was applied for both bubbling and circulating fluidized beds.

The bubbling fluidized bed is divided in emulsion and bubble phases. The evolution of single bubble formation and growth was characterized experimentally using a two-dimensional fluidized bed with both numerical models and analytical solutions.[30,31] The model developed to describe bubbling beds was modified to include

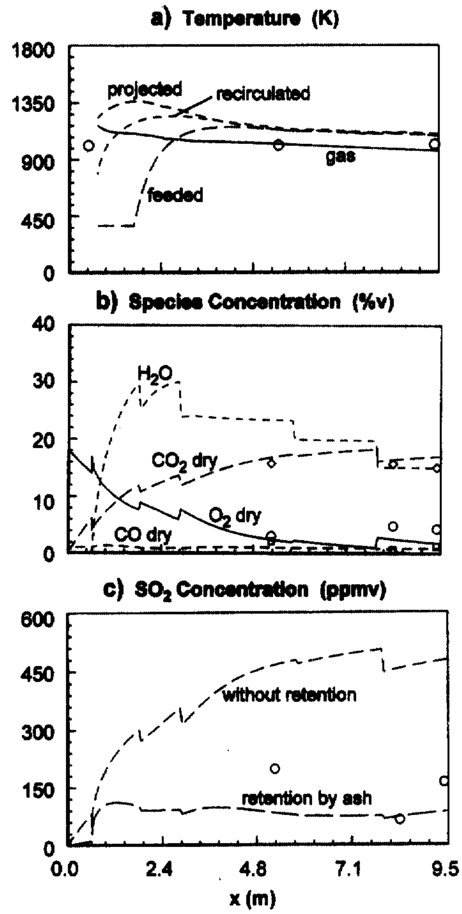

Fig. 7. Comparison of calculated with average measured properties along the vertical height of a 1.2 MW_{th} circulating fluidized bed combustor. (a) Temperature of gas and of 0.6 mm lignite particles, (b) species concentration, (c) SO_2 concentration. Experimental data was obtained by IWBT-TU Braunschweig in the CAFBC installed in RWE Energie AG-Niederaussen, Germany.

mass transfer based on a modified two-phase flow theory, and it was applied for coal[32] as well as wood[33] combustion in fluidized beds. The calculation of heat transfer based on this model was assessed for two combustors.[34]

For the circulating fluidized bed, the model considers a dense region at the bottom treated as a bubbling bed. For the upper part, where an important part of reaction and heat transfer takes place, the circulating fluidized bed structure was described considering a core-annulus structure with dilute flow in the core region and a falling film close to the walls.[35] For a 1.2 MW circulating fluidized bed combustor,[36] the model predicted the evolution of the main properties along the bed height. Figure 7 shows a comparison between the calculated and average measured values observed at different levels in the circulating bed. The figure shows the evolution of temperature for 0.6 mm coal particles from different initial conditions and the calculated gas temperature which is approximately in line with the measured data, except close to the bottom. The main gas species show a large amount of water vapor release, the effects of the staged air injection, and the level of CO close to the outlet. For the sulfur dioxide concentrations, two curves are represented to show the effect of retention by the calcium in the lignite ash.

Two models have been developed and compared with measurements from fluidized beds. At present, with the increased availability of computational resources, models based on a fundamental description of the two-phase flow are possible, although the classical two-phase approach still has an important role for the description of combustion or gasification of coal, wood residues and other solid waste material.

3.6.2. *Pulverized coal combustion*

The main objective of IST research in this area has been the development of simulation tools for the optimization of processes (advanced process development and design). A CFD code for the near-burner region was developed, followed by a CFD code for the boiler. The use of a stochastic Lagrangian dispersion model for the calculation of dispersed, two-phase flows was assessed for free and confined flow configurations where the effects of multiple particle sizes were analysed.[30,37] The model was applied to the calculation of the ICSTM furnace data for two different burners under different operating conditions,[38,39] including the application of a model for NO_x formation based on DeSoete mechanism. The models for coal particle combustion and NO_x formation were included within a three-dimensional numerical model that was previously used at IST to simulate furnaces from gas and oil-fired boilers.[40] Special emphasis has been placed on validation for the single burner and boiler codes. Recently, a large measurement effort was carried out in one of the coal-fired boilers of a Portuguese power station.[41] In order to increase the code flexibility, the three-dimensional numerical model has been adapted to incorporate cylindrical or cartesian coordinates and the possibility of using domain decomposition following the experience for gas/oil firing.[42,43] The developed codes have been extensively used to optimize operating conditions for different power stations in Portugal. For example, the effect of primary measures on NO_x abatement[44,45] and the effect of using recirculated flue gases.[46] At present, the model is being extended to consider reburning and it is used to evaluate different solutions for both gas and coal reburning. Some results obtained under each of the topics mentioned above within the pulverized coal section are given below.

Simulation of burners. Two burners in a cylindrical furnace were simulated by changing the swirl intensity and the position of the primary air/coal feed. In one burner, this stream is fed through a central tube while in the other is fed through an annular section with a central core representing the igniter from a real burner. The position of the internal recirculation zone for the burner, with the central tube for primary air, is predicted to be

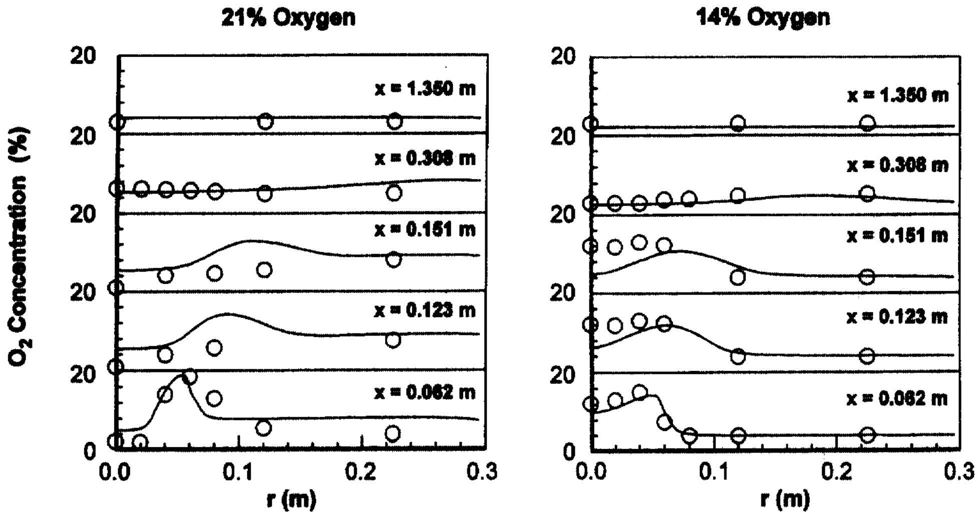

Fig. 8. Comparison of oxygen concentration radial profiles at different axial positions of a swirling pulverized coal flame using pure air or vitiated air for combustion. Experimental data provided by Imperial College of Science, Technology and Medicine, London, United Kingdom.

closer to the burner than from the measurements.[30,38] For the burner with an annular inlet, the internal recirculation is attached to the burner, and the comparison of numerical results with experimental results is more favorable. For the burner with the annular inlet, the use of vitiated air for combustion, instead of pure air for the same coal flow rate, leads to a larger gas flow rate and, consequently, to a larger penetration of the primary and secondary oxidant streams (see Fig. 8). This effect is captured by the numerical model, although, the predictions show a slower oxygen consumption and mixing than observed in the experiments. The simulation of real burners requires the consideration of details that cannot be encompassed in an axisymmetric geometry; therefore, the three-dimensional numerical model has been developed for cylindrical coordinates with periodic boundary conditions. This model version will be used to compare different low-NO_x burner designs and to simulate different experiments reported in the literature on the application of reburning to coal.

Calculation of NO_x formation in boilers using burners out of service. The three-dimensional numerical model was applied to evaluate the use of burners out of service in two, front wall-fired boilers, Sines and Pego power stations in Portugal. These boilers are equipped with low-NO_x burners with an improved burner design for the Pego boiler. IST performed calculations of the NO formation for the two boilers assessing the modification of NO emissions when selected burners are out of service. The calculations showed that in accordance with the data, the NO_x emission for full-load decreased when rows of burners are out of service. Table 7 reproduced from[44] shows a comparison between predicted and measured values at the boiler outlet with the lower emissions being obtained for the case of the upper row of burners out of service. For the Pego power station, four cases were considered, two corresponding to full-load (1 with all burners in service and 2 with the lower row out of service), and the other two at partial load (3 with the lower row of burners out of service and 4 with the upper one). Table 8 presents the calculated values of carbon-in-ash and NO_x emissions. Carbon-in-ash values are larger for the cases with the lower row of burners out of service (case 2 for full load and 3 for partial load), with the lower values being obtained for the case of using overfire air (case 4), as was observed at the plant. The calculated values depend partially on coal reactivity, for which common values from literature were used. For NO emissions, the use of the lower row of burners out of service (case 2) reduces the NO emissions when compared with the case of all burners in operation for full load. For partial load, the use of the upper row of burners for overfire air (case 4) reduces NO emissions compared with the case of using the lower row of burners out of service (case 3).

The model calculates the modifications in NO emissions following the experimental observations. The predicted values are overestimated compared with the experimental data available at the boiler outlet. This is attributed to the limited grid resolution close to the

Table 7. Comparison of predicted and measured NO_x emissions for the Sines boiler

NO_x emission (ppmv)	Base case	Lower row out of service	Upper row out of service
Measured	820 ± 70	780	710
Predicted	919	792	727

Table 8. Predicted carbon-in-ash and NO concentration in the flue gases for the Pego boiler

	Case 1	Case 2	Case 3	Case 4
Carbon in ash (%)	4.8	13.2	3.0	1.1
NO emission (ppmv)	552	528	594	526

burners which does not allow for a proper simulation of the burner. This limitation can be solved with a finer grid close to the burner through domain decomposition. However, the model represents the effects of air-staging resulting from the use of rows of burners out of service, and it is, therefore, also expected that the model would represent the effect of fuel-staging at the boiler level as used in reburning.

Reburning in coal-fired boilers. For coal reburning, the work has been centered on the determination of the influence of operating conditions in the mixing of the reburning injectors and of the overfire air. Another important aspect is the identification of the contribution from the main burners or from the reburning coal injectors to the total carbon loss. Figure 9a shows calculated trajectories for 140 μm coal particles both from the main burners and from the reburning ports for the case of the Vado-Ligure power station from ENEL in Italy. Figure 9b shows the calculated residence time and carbon-in-ash resulting from each starting location in the front wall. The carbon-in-ash from some of the main burners is comparable with the carbon-in-ash resulting from the reburning ports. This is due to the swirl direction which projects the particles from the upper main burners towards the lateral walls being quickly entrained to the boiler outlet. The minimization of carbon-in-ash has been studied through the consideration of different positions and orientation of the injectors for reburning and for the overfire air, and through modifications in the inlet conditions for the main burners.

A global NO_x formation model, considering a single step for reburning, has been included in the NO_x post-processor and applied to the simulation of the Sines boiler using natural gas as a reburning fuel. This model is being applied to the simulation of coal-over-coal reburning, both for the Portuguese Sines and the Italian Vado-Ligure boilers. Reburning is a very promising technology for NO_x abatement for retrofitting existing units. Industrial interest in this technology will increase in Europe and in countries with emerging economies. Therefore an increase of interest in this research area is foreseen in the Center.

Flue gas recirculation with oxygen injection. The work of IST in this project was to calculate the appropriate recirculation ratio to achieve a balance between the heat removed in the furnace and in the

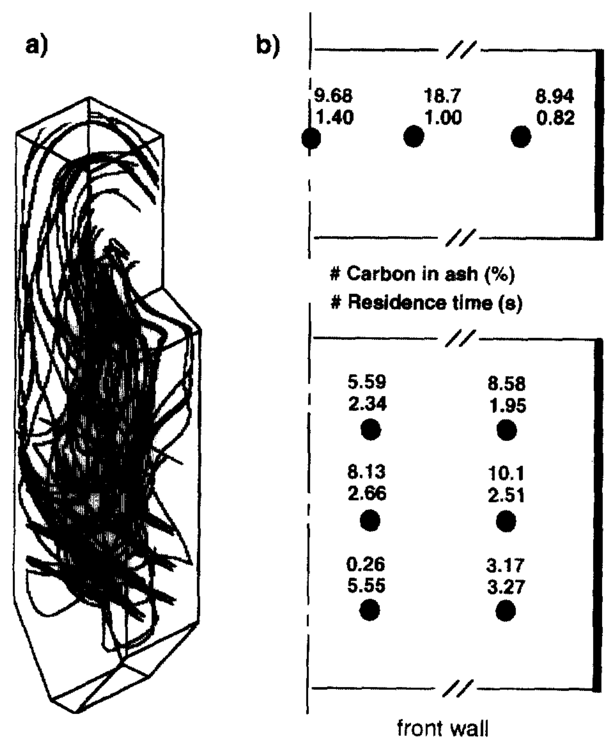

Fig. 9. Results obtained for the Vado-Ligure, opposed wall-fired boiler under conditions of coal over coal reburning. (a) Trajectories of 140 m coal particles, (b) carbon in ash and average residence time of coal particles from individual burners and reburning injectors.

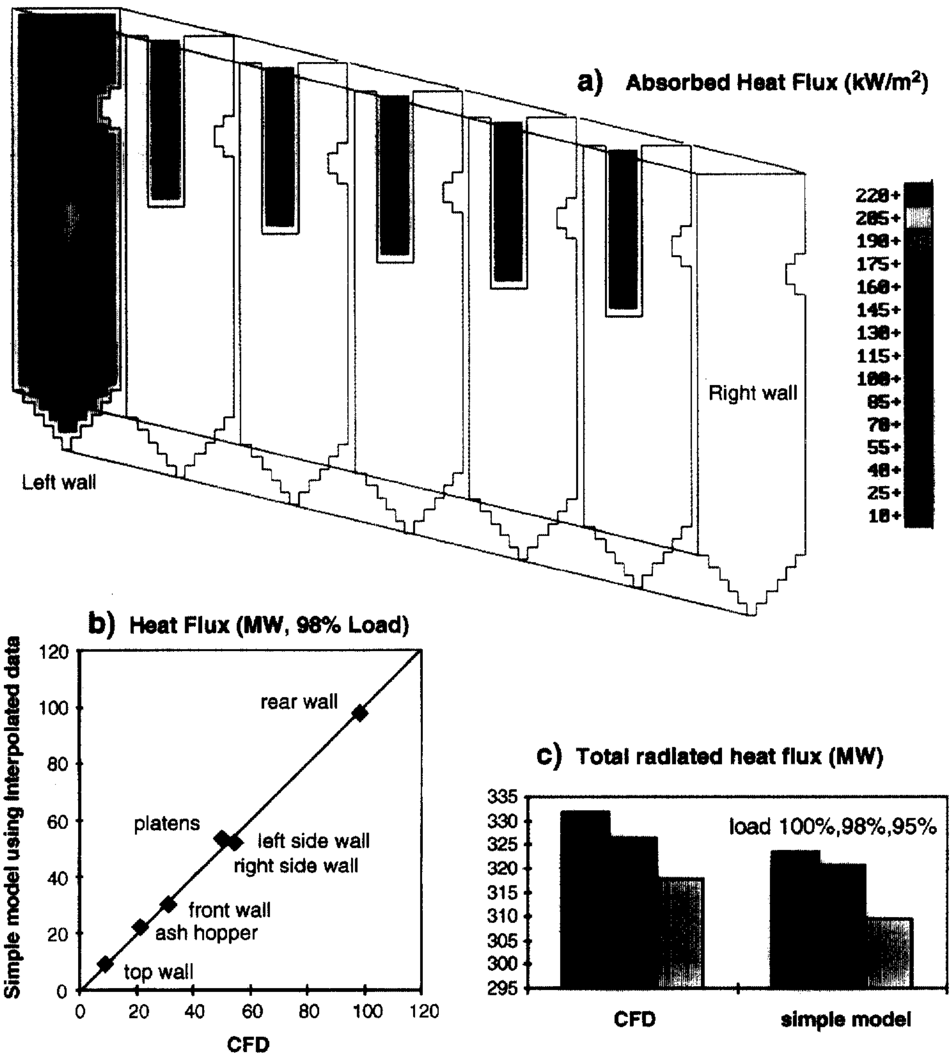

Fig. 10. Absorbed heat fluxes in a front wall-fired boiler using a simplified procedure. (a) Distribution of heat fluxes, (b) comparison of the integral results obtained from the simple model for heat transfer based on interpolated data from CFD and the solution from the application of the comprehensive CFD model, (c) comparison of the total radiated heat flux between the CFD solution and of the simple model for different loads.

convection banks. This trade-off was analyzed using a boiler model[47] where radiative heat transfer is calculated using radiosity equations considering only four zones. For a more detailed analysis, the three-dimensional numerical model was also applied to calculate CO and NO_x formation, to analyze the conditions close to the boiler walls and to calculate boiler emissions. As the inert gas in the case of recirculated gases is carbon dioxide, the gas absorption coefficient is larger, leading to a more uniform temperature distribution in the furnace. Therefore, to achieve a similar heat transfer rate, the adiabatic temperature has to be larger than for the case of combustion in air. The three-dimensional numerical model uses the discrete heat transfer model which was extended to incorporate scattering, while the radiative properties of the gas-particle mixture are calculated using, respectively, the wide-band model and results from Mie theory.[48] The incorporation of scattering led to the decrease of the predicted radiative heat flux to the boiler walls, resulting from the more uniform temperature distribution within the boiler furnace, as in the case of flue gas recirculation.

Heat transfer degradation. During furnace operation, the heat transfer rates at boiler surfaces typically decrease along time, due to slagging and fouling, being somewhat restored after soot blowing. To monitor this process, and to control the operation of these soot blowers, a boiler model was developed and installed at the Sines power plant. The system, which allows for the quantification of the relative degradation of heat transfer using on-line plant data,[49] is used to control the operation of soot blowers. The quantification of heat transfer degradation using the normal plant data only allows for global characterization of each heat exchange surface. For a boiler equipped with heat flux meters, heat transfer degradation will be characterized using the discrete heat transfer method to calculate local heat transfer resistance at the boiler walls. The heat transfer calculation is performed in a simplified procedure, using stored results from the complete numerical model concerning flow and heat release patterns, which are scaled with the input flow rates to the boiler. The calculation domain includes the superheater panels existing in the front wall-fired boilers being considered. Figure 10a shows the calculated heat flux distribution at the boiler walls and at the superheater panels. Figure 10b compares the absorbed heat flux at the different surfaces obtained with the full CFD numerical solution and using the simplified model procedure for a boiler load of 98%. The heat transfer calculation in this procedure was performed considering the flow and heat release patterns interpolated from CFD numerical solutions for boiler loads of 95 and 100%. Figure 10c shows that the procedure leads to the prediction of a modification of heat transfer rate comparable with the one calculated with the full numerical simulation. This simplified procedure is developed as a faster tool for evaluation of modifications of the heat transfer conditions at the boiler walls. The important problems of fouling, erosion, and corrosion in industrial applications leads to the application of the models to define conditions close to the walls and the coupling of flow models with material science. Related with this topic, detailed models for the deposition of particles and aggregates on the walls are under development.

3.7. *Center Directions*

The numerical models for coal combustion will continue in use within the center to compare firing configurations and to study boiler retrofitting of power stations. The center will also perform extensive comparisons of model predictions and in-furnace measurements at pilot and industrial scales. Development of the models to describe coal evolution and the interaction of coal particles with the walls will be done in the near future. These developments will be performed in parallel with experimental work to obtain analysis of char samples obtained in an industrial boiler at different positions and continuous measurements of local heat transfer characteristics.

4. THE COOPERATIVE RESEARCH CENTRE FOR NEW TECHNOLOGIES FOR POWER GENERATION FROM LOW-RANK COAL

Dr. David J. Brockway and Dr. Dong-ke Zhang, Melbourne, Victoria 3170, Australia

4.1. *Introduction*

Australian Cooperative Research Centres are designed to address the three major elements of the Australian Government's strategy for science and technology. These are (1) to ensure that the basic infrastructure for research and education in higher education institutions, CSIRO and other government laboratories, is as strong as possible, (2) to improve the competitiveness of industry through higher levels of research and development, and (3) to strengthen the interaction between government research organisations and the private sector.

At the present time, one-third of the electricity generated from coal in Australia relies on low-rank coal as the primary energy resource. Low-rank coals are a major energy resource for Australia and contribute significantly to the economies of Victoria and South Australia.

Substantial deposits of low-rank coals are found in southern Australian states and in a number of other countries including Indonesia, Thailand, India, Turkey, China, USA and Germany. Properties that mitigate against their widespread use for power generation are high water content, low ash-melting temperature, and the highly fouling nature of the ash. Victoria and South Australia have large deposits of readily accessible low-rank coals. Victorian deposits have been used for many years for power generation and generally have high water contents (60–70%), but are low in ash (1–3% db) and low in total sulphur (< 0.5% db).[50,51] Sodium in ash is usually low in coals currently utilised in Victoria (generally <5%). While the South Australian coal (Leigh Creek) which is presently utilised for power generation has a moisture content of <38%, other deposits generally have higher moisture (50–61%), higher ash contents (generally <20% db), and higher sulphur (generally <5% db). Sodium in ash is often relatively high (3 to 16%). The relatively high sodium-in-ash mitigates against their use because of the problems associated with the low-melting-point ash in conventional pulverised-fuel fired systems.

The Cooperative Research Centre for New Technologies for Power Generation from Low-Rank Coal was formally established in June 1993 to conduct research and technology development into those new generation technologies and processes that have the best prospects of overcoming the principal challenges (cost and environmental impact) facing the use of low-rank coal as a competitive energy source for electricity generation. New generation technologies are the key to the objectives of reducing both costs and emissions to the environment.

4.2. *Mission and Objectives*

The mission of the Centre is, through cooperative R&D by Australian industry, research bodies, and universities, is as follows: (1) promote the development and commercialisation of new, cost-effective and environmentally acceptable technologies for power generation from low-rank coal, (2) provide basic understanding of power generation processes and coal behaviour, (3) provide scientific and engineering support for the development of process technologies and their commercial application, and (4) become a leading world research centre in the area of power generation from low-rank coal.

The objectives of the Centre are as follows: (1) take a

Table 9. General characteristics of the CRC-NTPGFLRC

Title	The Cooperative Research Centre for New Technologies for Power Generation From Low-rank Coal
Location	Victoria, Australia
Director(s)	David J. Brockway, Executive Director Peter J. Jackson, Manager Research Malcolm J. McIntosh, Manager Technology Development
Starting date	July 1993
Mission/objectives	Mission: through cooperative research and development by Australian industry, research bodies and universities: ● to promote the development and commercialization of new, cost-effective and environmentally acceptable technologies for power generation from low-rank coal; ● to provide basic understanding of power generation processes and coal behaviour; ● to provide scientific and engineering support for the development of process technologies and their commercial application; ● to become a leading world research centre in the area of power generation from low-rank coal. The objectives of the centre are: ● to take a leading role in the development of new, efficient, cost-effective and environmentally acceptable technologies for electricity generation systems using low-rank coals; ● to enhance the potential of low-rank coal as a competitive fuel for future power generation by increasing scientific understanding of its behaviour in advanced technology systems; ● to increase the effectiveness and collaborative synergy of low-rank coal research in Australia by strengthening the interaction between the participants; ● to ensure that there is a resource of suitably trained graduates with advanced knowledge in future power generation systems for Australian companies and electricity authorities; ● to provide the necessary technical support for the export of such technologies that will have application in many developing nations where coal resources are low-rank and often low grade.
Focus	Developing clean, efficient and competitive technologies for power generation from low-rank coal
Research Areas	● coal-water beneficiation ● coal gasification and combustion ● ash and deposit formation ● fluid bed process development ● technology development

leading role in the development of new, efficient, cost-effective, and environmentally acceptable technologies for electricity generation systems using low-rank coals, (2) enhance the potential of low-rank coal as a competitive fuel for future power generation by increasing scientific understanding of its behaviour in advanced technology systems, (3) increase the effectiveness and collaborative synergy of low-rank coal research in Australia by strengthening the interaction between the participants, (4) ensure that there is a resource of suitably trained graduates with advanced knowledge in future power generation systems for Australian companies and electricity authorities, (5) provide the necessary technical support for the export of such technologies which will have application in many developing nations where coal resources are low-rank and often low grade.

The Centre aims to contribute substantially to the development of the science and engineering required to underpin the commercial development of new power generation technologies. The benefits from such commercial development include the following: (1) better technologies for electricity generation, (2) export of newly developed electricity generation technologies or applications, knowledge, and skills to other countries, (3) initiatives to transfer new, efficient (low greenhouse gas emission) technologies into Asia and the Pacific-Rim nations, and (4) a sustainable and appropriately sized technology base for low-rank coal utilization in Australia.

The participants in the Centre include universities, sections of the electricity supply industry and major Australian private companies. The organisations collaborating in the Centre are the following: Loy Yang Power Ltd; Yallourn Energy Pty Ltd; Hazelwood Power; Optima Energy; CSIRO Division of Minerals; Transfield Technologies Pty Ltd; Lurgi (Australia) Pty Ltd; Monash University; University of Adelaide; Swinburne University of Technology; Strategic Industry Research Foundation; and Memtec Limited. Royal Melbourne Institute of Technology and HRL Limited are also involved in the research program. Funding for the Centre is provided jointly by the Commonwealth Government and participating organisations with total funding over the first seven years of about $34 million, of which about $14 million is from the Commonwealth. Table 9 provides a summary of general characteristics of the Centre, while Table 10 gives some of its dimensions and activities.

Table 10. Data for the CRC-NTPGFLRC

A. Number of personnel (1996)

Professional	42
Professorial	15
Postdoctoral	9
Graduate students	26
Undergraduate students	3
Staff/management	7
Other	10
TOTAL	110

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	3507
1995	4613
1996	4934

C. Budget sources (%) (1996)

Government	40
Domestic industry	32
University	18
Foreign	0
Income (patents, royalties, licenses, software, etc.)	0
Other	10
TOTAL	100

D. Space and equipment

1. Research space	15 000 sq. ft.
2. Research equipment/instruments/ computers	$2 720 000

E. External participants/sponsors/advisors/members

Government	2
Industry	8
University	4
TOTAL	14

F. Research program (1996)

Number of fundamental projects	0
Number of applied projects	42
Number of proprietary projects	0
TOTAL	42

G. Center research projects/activities

	Minor Major
Experimental data	1 2 3 4 **5**
Computer software	1 2 3 **4** 5
Inventions/patents	1 2 **3** 4 5
Project reports	1 2 3 4 **5**
Journal/book publications	1 2 3 **4** 5
Consulting services	1 **2** 3 4 5
Process/system concepts	1 2 3 4 **5**
Graduating students	1 2 3 4 **5**
Academic courses	1 **2** 3 4 5
Technology transfer	1 2 3 4 **5**

4.3. *Structure of the Centre*

The Centre and its activities are under the direction of a Board of Management, comprising representatives of the major participating organisations with an independent Chairman. The activities of the Centre are managed by the Executive Director both directly and through an incorporated company, Generation Technology Research Proprietory Limited. The Executive Director is supported by a Research Advisory Committee, comprising a group of experts in the area of power generation, coal research and utilization and by an Industry Advisory Panel. The Centre's Research and Technology Development programs are under the responsibility of two Program Managers. The Program Managers are supported by a Program Advisory Panel who consider the establishment of new research projects, review the progress of existing projects, and advise on funding allocations.

The Centre's research is undertaken in its own laboratories at Mulgrave, Victoria, and at Thebarton Commerce and Research Precinct of the University of

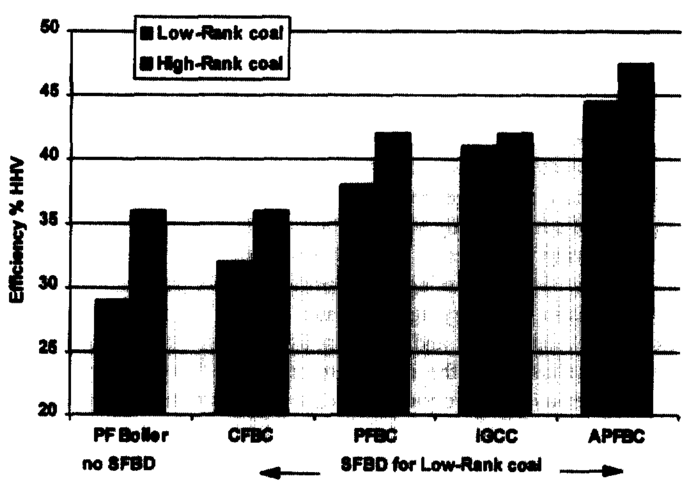

Fig. 11. Efficiencies of power generation cycles.

Adelaide, South Australia, as well as at the laboratories of the participants. The Thebarton Laboratory is under the management of the Principal Researcher, Adelaide, who is responsible for the day-to-day operation of the Centre's research activities in Adelaide. The Principal Researcher, Adelaide, also has significant responsibility for the Centre's international collaborations, particularly with south-east Asian countries.

The Centre recognises the importance of, and commits to, the education and training of scientists and engineers for power generation. The Education Program is under the direction of the Centre's Education Manager. Strategies of the Education Program have been defined in the following four main areas: postgraduate research training, undergraduate teaching and research, continuing education, and technical and further education.

4.4. *Research and Technology Development*

The Centre is undertaking a large number of research and technology development projects. With the active involvement of its participants comprising industry, CSIRO and academia, the Centre is a powerful new organisation for research and technology development. More than 100 research scientists, engineers and technical officers are involved in the Centre, including 26 post-graduate students (see Table 10).

The Centre's research and technology development activities are divided into the following five program areas: Coal–Water Beneficiation, Combustion and Gasification, Ash and Deposit Formation, Fluid Bed Process Development, and Technology Development. The program areas are divided into sub-programs which contain a number of research projects.

4.4.1. *Coal–water beneficiation*

A key issue in the efficient use of low-rank coal in existing or advanced power generation technologies is the dewatering of the coal prior to gasification and/or combustion. The high moisture content of low-rank coals (up to 2 kg of water per kg of dry coal) leads to low energy efficiency, high carbon dioxide emissions, and high capital costs in conventional pulverised fuel power generation systems. The program objectives are directed to obtaining a comprehensive understanding of the behaviour of low-rank coals in drying and slurry production technologies, understanding the impact of various drying technologies on new power generation processes, and the development of commercially viable drying, dewatering and coal slurrying processes.

Current beneficiation projects are addressing as follows: (1) the behaviour of coals in steam drying and hydrothermal dewatering (HTD) processes and the optimisation of processing conditions,[52] (2) the characterization and treatment of wastewaters from drying or dewatering,[53] and (3) the production of high coal (energy) loadings in slurries. Key achievements to date include the following: (1) substantial increase in the solids loading in HTD coal slurries in batch experiments by optimisation of heating rate and feed solids loading, and by improved washing of product, (2) development of a method of maintaining high porosity of steam dried coal, which may give a more reactive dried coal than conventional steam drying, and (3) demonstration that further reduction in coal porosity is possible, as shown by preliminary experiments on press dewatering of HTD coal, indicating that higher solids loading slurries can be achieved.

Future research in coal–water beneficiation will include the following: (1) development of a bench scale continuous reactor to optimise processing conditions to achieve higher HTD coal solids loading for potential industrial application, (2) extension of press dewatering work to higher temperatures through the use of a new compression cell and construction of a continuous press dewatering unit, (3) continuation of HTD and steam drying wastewater studies to enable selection of appropriate wastewater treatment technologies, and (4) study of the structure of raw brown coal and the changes in structure that occur during the drying processes.

4.4.2. *Combustion and gasification*

Most of the advanced power generation technologies being considered involve gasification or combustion of coal at high pressures. There are little kinetic data available in relation to the behaviour of low-rank coal at high temperatures and pressures. Consequently, the major aim of this program area is to obtain reaction data at appropriate conditions to facilitate the evaluation of various technologies and to provide design data for the preferred process configurations.

Specific goals are thus: (1) establish chemical reaction kinetics for the gasification and combustion of low-rank coals under practical gasification and combustion conditions, (2) develop and validate predictive models for performance, (3) develop processes for low-rank coal gasification and combustion to minimise greenhouse emissions, and (4) develop processes for sulphur emission control from low-rank coal gasification and combustion.

Current projects are as follows: (1) measurement of reaction kinetic data relevant to devolatilisation, gasification, ignition, and combustion of low-rank coal, beneficiated coal and char at high pressure,[54,55] (2) optimisation of burner and combustion chamber designs for beneficiated coal slurry,[56] (3) determination of reaction mechanisms and kinetic data relevant to ignition and combustion of low specific energy gas (containing high concentrations of water vapour and nitrogen), particularly for pollutant formation,[57] (4) char formation and the fate of inorganic species during coal devolatilisation,[58] (5) the effect of volatile combustion on char reaction rate,[59] (6) the effects of inherent and added catalysts on gasification, (7) mathematical modelling of gasification, (8) coal devolatilisation and volatile combustion during fluid bed gasification,[60,61,62] and (9) desulphurisation of product gases using additives in fluid bed gasifiers.

Key achievements to date include the following: (1) the commissioning of a pressurised drop tube furnace (PDTF) to enable measurement of high temperature and high pressure kinetics of devolatilisation, gasification, and combustion reactions, (2) development of computational fluid dynamics (CFD) models of combustion processes[63] which have also formed the basis of a consulting project on the modelling of the performance of a proposed waste-heat recovery boiler for a customer, (3) the quantification of the effects of inherent and added catalysts on the kinetics of gasification of South Australian low-rank coals, demonstrating significant catalytic effects, and (4) the development of a mathematical model of a fluid bed gasifier which has achieved good matching of the published performance of the High Temperature Winkler Gasifier.[64,65]

Future research will include areas such as: (1) continuation of PDTF experiments to obtain high temperature and high pressure kinetic data for devolatilisation and gasification reactions, (2) completion of a project on CFD modelling of high intensity slurry combustion, and initiation of CFD modelling of other combustion systems, (3) extension of studies of combustion of low specific energy gas to pressurised combustion, (4) completion of development of the mathematical model of a fluid bed gasifier, with incorporation of reaction kinetics based on actual data, (5) design, construction, and commissioning of a new laboratory scale circulating fluid bed combustor to enable closed loop CFB studies, (6) identification of effective, in-situ additives for sulphur emission control.

4.4.3. *Ash and deposit formation*

The inorganic constituents in low-rank coal can cause significant operational problems in both conventional and advanced power generation technologies. Ash deposition in pulverised fuel combustion boilers results in reduced heat transfer efficiency, and the need to periodically shut down plants for cleaning. In advanced technologies involving fluid bed combustion and gasification processes, agglomeration of bed particles due to sticky ash deposits can lead to defluidisation and the subsequent shutdown of the process. The objectives of this program are to develop methods for alkali metal measurement and removal from hot gases, to obtain a comprehensive understanding of the physical changes and chemical reactions undergone by inorganic constituents during gasification and combustion, particularly in fluid bed systems, and to develop methodologies for the mitigation of operational problems due to ash deposition.

Specific goals are as follows: (1) reduce the alkali metal content in gasification and combustion products to minimise fouling, (2) establish the relationships between the inorganic species in coal, with or without additives, and bed material as they affect ash deposition, agglomeration and defluidisation in fluid bed combustion and gasification, (3) develop methodologies for the mitigation of defluidisation arising from ash behaviour in fluid bed gasification and combustion processes, and (4) develop and validate predictive models for agglomeration and defluidisation in fluid bed combustion and gasification.

Current projects on ash and deposit formation include the following: (1) monitoring and removal of vaporised sodium compounds from hot gases,[66,67,68] (2) the role of inorganics in fluid bed combustion and gasification,[69,70] (3) the effect of additives on inorganics in fluid bed combustion and gasification, (4) cold modelling of defluidisation in combustion and gasification, (5) studies of agglomeration and defluidisation during fluid bed combustion and gasification, and (6) studies of ash rheology at high temperatures.[71] Key achievements to date include the following: (1) completion of construction of Millijet high temperature prototype microwave spectrometer for measurement of sodium species in high temperature gases, (2) demonstration of ability to detect sodium presence in pf furnace flames, (3) completion of new laser laboratory with improved lasers and spectroscopic instruments for detection and measurement of sodium species, (4) identification of effective additives for mitigation of agglomeration and defluidisation in fluid bed combustion utilising high sodium content South Australian coals, (5) completion of the construction and commissioning for a high temperature rheometer for study of ash rheology.

Future research will be as such: (1) demonstration of measurement of sodium species in combustion and gasification product gases using the prototype Millijet HT spectrometer, (2) development of a gauge to quantify sodium levels in pf furnace flames and use of information provided to assist control of furnace fouling, (3) development of models for the agglomeration and defluidisation processes to enable prediction of the potential onset of defluidisation, (4) demonstration of effective additives for mitigation of agglomeration and defluidisation in fluid bed combustion and gasification for a range of coals, and (5) construction and commissioning of the high temperature rheometer, and the commencement of ash rheology experiments.

4.4.4. *Fluid bed process development*

In order to achieve increased efficiency and reduced pollutants emissions, most of the new technologies being developed by the power generation industry incorporate fluidised bed units as a key component of the process. The fluidised beds may be employed in drying, gasification, combustion, cooling, or heating processes. These beds may either be circulating fluidised beds with fast or slow riser speeds; or bubbling fluidised beds. The attraction of fluidised beds is that heat transfer and thermal mixing is highly efficient, engendering convenient and effective temperature control. The relevance of fluidised bed technology to low-rank coal combustion or gasification is the need to be able to keep temperature uniform and low and hence minimise or avoid sticky ash formation in the bed and sodium vaporisation into the fuel or combustion gas. Present understanding of multiphase flow processes typical of those found in fluidised beds is incomplete. As a result, comprehensive numerically based design, scale-up, and operational analysis tools are of very limited value outside geometric and operational areas where detailed reliable data exists for validation. Indeed, the lack of good quality physical data in areas of engineering interest is of great concern and is a major driver for the work covered in this program area. The objectives of this program area are to develop a comprehensive understanding of the multi-phase fluid dynamics of fluidised bed gasification, combustion and drying processes, including the development and validation of comprehensive numerical tools to support performance optimisation and plant scale-up. The program is focussing on both numerical and physical modelling to address these objectives.

Numerical model development. Development is currently underway of a comprehensive computational fluid dynamics (CFD)-based numerical model of the three-dimensional, unsteady multi-phase (fluid/particles) flow processes in fluidised beds including hydrodynamics, erosion, heat transfer, combustion and gasification chemistry, and multiple particle sizes/densities. Validation is continuing by comparison with data from the literature or with data drawn from relevant centre physical modelling projects.

Key achievements to date include the following: (1) development and validation of a numerical model (based on the CFD code CFX4) of the three-dimensional unsteady flow bubbling fluidised bed accounting for hydrodynamics,[64,65] heat transfer, and gasification for a single particle size; and the negotiation of a license for these developments to the supplier of CFX4, namely AEA Technology, in the UK, and (2) inclusion of erosion and an accounting for multiple particle sizes.[72]

Future developments of CFD will include issues such as: (1) further refinement and validation of erosion, heat transfer, and multiple particle size/density models, (2) validation of the hydrodynamic model for scale-up in bubbling and full solids recirculation beds, and (3) development and validation of a steady flow, high solids recirculation rate, Circulating Fluid Bed Combustion (CFBC) numerical model.

Physical modeling. Concurrent with the numerical modelling, the Centre is conducting detailed physical modelling for mathematical model validation and for development of scale-up criteria. This physical modelling includes detailed multi-phase flow measurements in cold, isothermal flow models of fines recirculation fluidised beds (0.3 m and 1.6 m *id*), cold and combusting full solids recirculation (0.6 m and 0.4 m *id* respectively) fluidised bed combustors and a steam fluidised bed drier.

Key achievements to date include the following: (1) significant progress on a fluid bed characterization and measurement program in the 0.3 m cold model, (2) development of a capacitance tomography system, and its application to the measurement of voidage fraction in the bed, (3) completion of construction and commissioning of the 1.6 m *id* cold model, (4) constructioning and commissioning of a pressurised steam fluidised bed drier.

Future developments involving physical modelling will include the following detailed measurement programs in the 1.6 m, 0.6 m, 0.3 m *id* and in the pressurised steam fluidised bed models, together with the development of companion physical diagnostics capability for each rig.

4.5. *Technology Development*

The Technology Development Program is designed to complement and give focus to the existing Research and Education programs. The overall objectives of the Technology Development program are: (1) assessment of technologies for power generation from low-rank coal to determine the relative viability of developing technologies[73] and the priorities for research and technology development activities, (2) development of specific technologies for application to processes for power generation from low-rank coal, covering current (existing pf boiler), developing (intermediate)[74] and advanced technologies,[75] and (3) development of component and system integration strategies to optimise the balance between cost, performance and environmental acceptability.

To date, the program activities have focused on evaluating advanced technology developments in high-rank coal systems, with a view to choosing or adapting the more relevant of these for use with high moisture low-rank coals.

The advanced technologies of integrated gasification combined cycle (IGCC) and pressurised fluid bed combustion (PFBC) have been of particular interest to the Centre as these are being demonstrated at full scale or are in the early phases of commercialisation. The efficiencies from these technologies, which employ both gas and steam turbines in combined cycle, is higher than those from conventional boiler plant. These efficiencies will be further improved as parallel programs to improve gas turbine and steam plant are realised.

The Centre has undertaken a systematic study of selected power generation cycles fuelled with a typical low-rank coal (Loy Yang coal, moisture content 62%). The cycles were simulated using ASPEN Plus and/or GTPRO software.[73] The cycles simulated consider, in particular, the requirements of coal drying, and aspects relating to the feeding of these materials (which are difficult to handle) into pressurised reactors. The main technologies studied are as follows: (1) CFBC—circulating fluid bed combustion, (2) IGCC—integrated gasification combined cycle process, (3) PFBC—pressurised fluid bed combustion, and (4) APFBC—advanced PFBC. The overall efficiencies of these processes are shown in Fig. 11 for the case of drying in an integrated atmospheric pressure steam fluid bed drier (SFBD). Included in Fig. 11 for comparison are the efficiencies expected from similar technologies when fueled with high-rank coal. A feature of the results is that the relatively low efficiency of a conventional plant caused by the high moisture content of low-rank coals is dramatically increased by the use of advanced technologies and approaches that of a similar technology utilising black coal. This applies particularly for APFBC cycles.[73] The Technology Development program also has a key focus on technology aspects of drying and dewatering. The requirements for drying or dewatering processes are the major difference between low-rank and high-rank coal technologies for power generation. Predrying or dewatering of low-rank coal offers the potential of higher cycle efficiencies than those achieved with current technologies.

In addition to the above projects, others currently underway include: (1) coal handling and feeding, particularly into a pressurised reactor, (2) low temperature carbonisation/gasification to investigate the technical viability of an advanced power generation technology using low temperature carbonisation and char combustion for low-rank coals (APFBC), and (3) circulating fluid bed combustion (CFBC) as a possible technology for the medium term horizon which may be suitable to repower existing low-rank coal power plant to improve efficiency. CFBC offers potential to control fouling when predried coal is used. The future emphasis of projects in this program is to assess their potential to become viable power generation processes. Specific evaluation and development projects under investigation include the following: coal handling systems, coal drying systems, fluid bed combustion systems, gasification and char residue characterization, and hydrothermal dewatering.

4.6. *Key Research Facilities*

Key research facilities at the Centre include the following: a circulating fluid bed combustion pilot plant; high pressure, high temperature drop tube furnace; experimental high temperature atmospheric pressure fluid bed reaction systems; experimental pressurised high temperature fluid bed reactor; experimental pressurised steam fluid bed drier; laser, microwave and infrared spectroscopic diagnostic systems; large-scale (0.3 m, 0.6 m and 1.6 m *id*) fluid dynamic cold models; and computational fluid dynamic modelling facilities.

4.7. *Education*

The overall objective of the Education Program is to provide specialised, advanced education and training in the sciences and technologies of low-rank coal utilization to ensure an adequate flow of skilled graduates into power generation and associated industries. Appropriate strategies to achieve this objective have been defined in the areas of postgraduate research training, undergraduate teaching and research, continuing education, and technical and further education. In just three years to 1996, a total of 26 postgraduate research students have been or are being supported by the Centre. All postgraduate students are under joint university and industry supervision. This blend of academic and industrial guidance is working well and providing a strong industry focus to the research of each postgraduate student. Research topics are developed as adjuncts to projects defined within the program areas of the Centre's Research program. A number of undergraduate research projects are also supervised by Centre researchers. Assistance to undergraduate teaching is being provided with specialist guest lectures. The Centre is also involved in design projects for final year chemical engineering students. The Centre provides experimental rigs to universities for undergraduate teaching. The Centre and HRL Ltd conducted a short course on: 'The Science and Technology of Low-Rank Coal: Structure, Properties and Consequences for Utilization in Power Generation' at Monash University in 1996. A second course—'Fluidised Bed Processes for Coal Utilization'—was developed for presentation in 1997. A graduate degree course in 'Fuels and Combustion Engineering', as part of the Centre's Continuing Education effort, is being developed with a focus on low-rank coal utilization.

In partnership with its university participants, the Centre has established three new CRC Power Generation lectureships. These are located in the Department of Chemical Engineering at the University of Adelaide, the Department of Chemical Engineering at Monash University, and in the School of Mechanical and Manufacturing Engineering at Swinburne University of Technology.

4.8. *Centre Directions*

The participants in the Centre are committed to the commercialisation of intellectual property arising from the Centre's activities and to the application of high efficiency technologies to the environmentally-acceptable generation of electric power from low-rank coals. It is confidently expected that advanced technologies for power generation utilising low-rank coal can result in electricity generation with CO_2 emissions that are 30% lower than for conventional technology. Further, this can be achieved with a cost of power sent out that is below that for black coal using similar technologies at the same site. Outcomes of this type would make low-rank coals at least as attractive as bituminous coal as a source of energy in the future.

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5. THE COOPERATIVE RESEARCH CENTRE FOR BLACK COAL UTILIZATION

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5.1. *Introduction*

The Cooperative Research Centre for Black Coal Utilization was formally established in 1995, with the

Table 11. General characteristics of the CRC-BCU

Title	The Cooperative Research Centre for Black Coal Utilization
Location	Three major research nodes in Newcastle (Pacific Power, University of Newcastle), Brisbane (University of Queensland, ACIRL) and Sydney (CSIRO Division of Coal and Energy Technology and the University of New South Wales)
Director	John Hart, Executive Director
Starting date	July 1995
Mission/objective	to use the resources of participating organizations cooperatively and synergistically for quality research on thermal coal utilization that adds value to Australian black coal resources in overseas and domestic markets and to transfer research results effectively to the coal, power and metallurgical industries for: ● best use in major mature markets (pulverized-fuel boilers); ● more use in growing markets (pulverized-coal injection into iron-making blast furnaces); ● access to emerging markets (integrated gasification with combined cycle pressurized fluidized-bed combustion).
Focus/aims	● to carry out world-class research to help maximize the value and environmental performance of Australian black coal resources; ● to expand undergraduate and postgraduate education in black coal utilization; ● to increase the level of collaboration of Australian and overseas laboratories and be a focus for dissemination of information about developments in advanced coal technologies; ● to develop an improved capability to assess coals for the new clean coal technologies and options for reduction of greenhouse gas emissions; ● to ensure commercialisation and technology transfer of the CRC's research to the coal, power and metallurgical industries.
Research areas	the CRC research and education programs cover three areas of technological development: ● pulverized-fuel combustion; ● advanced power generation, particularly integrated gasification gombined cycle and pressurized fluidized-bed combustion; ● pulverised-coal injection (into blast furnaces).

mission to be a focus for Australian research in this field and its technology transfer to the coal, power, and metallurgical industries. The aim is to maximise the value and environmental performance of Australian black coal resources in overseas and Australian applications and to develop an improved capability to assess new high efficiency clean coal technologies and options for reduction of greenhouse gas emissions. The Cooperative Research Centre for Black Coal Utilization is one of 62 such centres in the Australian Government's CRC Program. They include another coal utilization centre, the CRC for New Technologies for Power Generation from Low-Rank Coal (see Section 4), and the Centre for Mining Technology and Equipment, which includes coal mining and processing activities. The coverage of the coal-related CRCs is therefore complementary. The headquarters of the Black Coal CRC is co-located with The University of Newcastle's Institute for Coal Research, on the University campus, but whereas the Institute now specialises in mining and preparation of coal, the activities of the Centre are concerned with conversion of coal in utilization processes.

The objectives of CRCs are to impart and apply knowledge by education, training, technology transfer and commercialisation, as well as to obtain it by research and collaboration. The Centre has activities in all these areas but this report is concerned mainly with technical aspects of the Research Program. However, it is relevant to note that, in large part, the education objective is achieved by using postgraduate students and post-doctoral fellows to do the research. The expected benefits are an increase in the quality of engineering postgraduate training, by ensuring that their research contributes to practical applications of knowledge, and in the supply of skilled and expert people technically equipped to continue being productive in the coal utilization industries. Also, the essence of CRCs is cooperative collaboration of professionals from different institutions with a range of disciplines and backgrounds, such that research can be done that would not otherwise be done, or be done as well, in the individual organisations. Further, it is intended that availability of knowledge be increased by scientific collaboration with overseas centres of black coal utilization and that the Black Coal CRC be a prime point of dissemination in Australia of international research on utilization of black coals.

The general characterization and data for the CRC are given in Tables 11 and 12. The Participants in the Centre are listed in Table 13. They include six major Australian coal companies, which together account for some 70% of Australia's coal exports. Australia's largest electricity generator, Pacific Power, is both a coal producer and user, and the Centre's biggest single participant in terms of resources contributed. Pacific Power also participates directly in the research program, as does CRA Ltd's Advanced Technical Development organisation, Technological Resources Party Limited, together with the research participants. Research program activities

Table 12. Data for the CRC-BCU

A. Number of personnel (1996)	
Professional researchers	18
Professorial	13
Postdoctoral	5
Graduate students	14
Undergraduate students	0
Staff/management	4
Other	0
TOTAL	54
(Total equivalent person years	17)

B. Fiscal year budget (U.S.$ thousands equivalent)	
1996	2851
1997	4858
1998	4894

C. Budget sources (%) (1996)	
Government	33
Domestic industry	50
University	17
Foreign	0
Income (patents, royalties, licenses, software, etc.)	0
Other	0
TOTAL	100

D. Space and equipment

Space and equipment is available in the individual laboratories of the research providers

E. External participants/sponsors/advisors/members	
Government	1
Industry	11
University	3
TOTAL	15

F. Research program (1996)	
Number of fundamental projects	15
Number of applied projects	10
Number of proprietary projects	0
TOTAL	25

G. Centre research projects/activities	Minor Major
Experimental data	1 2 3 4 **5**
Computer software	1 **2** 3 4 5
Inventions/patents	**1** 2 3 4 5
Project reports	1 2 3 4 **5**
Journal/book publications	1 2 3 **4** 5
Consulting services	1 2 **3** 4 5
Process/system concepts	**1** 2 3 4 5
Graduating students	1 2 3 4 **5**
Academic courses	1 2 **3** 4 5
Technology transfer	1 2 3 4 **5**

are conducted in Brisbane, Newcastle, Sydney, and Melbourne.

5.2. *Research Strategy*

The Centre is focused on black (thermal) coals, by decision of the participants. The principal research objective is to evaluate the performance of Australian black coals in utilization technologies that are in, or entering, commercial service. The Centre is not aiming to develop or improve utilization technology, except insofar as research may disclose opportunities for modifying or tuning plant designs to extract best performance with Australian coals. The targeted technologies are pulverised fuel combustion (PF), integrated gasification with combined cycle (IGCC), and pressurised fluidised bed combustion (PFBC) for electricity generation and pulverised coal injection into ironmaking blast furnaces (PCI). The nomination of technologies is indicative rather than prescriptive, except that use of thermal coals in direct smelting processes is presently excluded. The emphasis of the research program is intended to shift progressively from PF to new technology but the initial program includes work relevant to all targeted technologies. A particular focus of PF-related projects is environmental improvement, while a major driver of PCI work is to demonstrate acceptability of low-volatile coals. A desired ultimate outcome of the Research Program is a set of computational models that enable the performance of a particular coal in a particular technology to be predicted from coal quality and plant design specifications. The users of these products would be technical coal marketing personnel and engineers responsible for selecting plant technology and fuel in user organisations.

The results of research will provide data and information for constructing process evaluation models and will, of course, be interesting and useful in their own right, because fundamental understanding must underpin the use of such models. It is also likely that methods for measuring coal quality characteristics used in models could find direct application in the field for routine process and product control. Measurement systems that improve on what is presently available in terms of

Table 13. Participants in the CRC-BCU

ARCO Resources Ltd
AUSTA Energy
BHP (CRA-ATD) Coal Pty Ltd
Coal & Allied Operations Pty Ltd
CSIRO Division of Coal and Energy Technology
Delta Electricity
Oakbridge Pty Ltd
Pacific Power
Peabody Resources Ltd
Queensland Department of Mines and Energy
Technological Resources Pty Ltd (Rio Tinto Research and Technology Development)
The University of Newcastle
The University of New South Wales
The University of Queensland
Australian Coal Industry Research Laboratories Ltd. is an Associate

Table 14. Illustrative budget projected for 1999/2000 (U.S. $ millions)

Education and training	0.2*
Technology transfer and management	0.7
Advanced characterisation	0.5
Technology assessment	0.8
Coal matter reactions	0.9
Environmental issues	1.1
Mineral matter reactions	1.8
Total	6.0

* Value of postgraduate scholarships is included in research program area budgets.

capability for rapid (preferably on-line) and relevant characterization are also a desired outcome of the Centre's Research Program.

5.3. *Research Program*

The main objective of the research program is to characterise the performance of utilization technologies with Australian black coals. Coal quality characterisations and technology performance assessments will provide the Australian coal supply industry with data, methods, and techniques to match coals to customer requirements. The need for better tools arises particularly from competitive pressures in the world coal market, from regulatory constraints, and from the rapid emergence of new and improved coal utilization technologies.

Underlying the technologies for converting the fuel value in coal and for dealing with byproducts are many common technical features. The program structure reflects this engineering science perspective and the research is accordingly organised into five program areas based on research issues related to the overall objective and targeted technologies, namely: (1) Advanced Characterization, (2) Coal Matter Reactions, (3) Mineral Matter Reactions, (4) Environmental Issues, and (5) Technology Assessment.

The Advanced Characterization and Technology Assessment program areas are designed to produce the above-mentioned end products. The core research program areas—Coal and Mineral Matter Reactions and Environmental Issues—will increase understanding of the behaviour of coal types in utilization technologies and provide data and relationships to be built into the process models. There is very limited information available for high-intensity reaction environments typical or emerging technologies. There are good reasons for thinking that comprehensive process modeling should now be achievable, whereas in the past it has been a largely unsatisfied aspiration of coal scientists and technologists. One reason is the availability of powerful material analysis techniques and interpretative methodologies, which have emerged in the past few years from basic chemical and physical research. Another is the computing power and software accessibility offered by modern PC systems.

Research into conversion of coal (organic) matter is obviously important, because it is the objective of technology, but may not be a critical technical or economic issue with traded coals. For example, burnout of coal in PF boilers is typically high and, unless there is a stability problem, the main incentive for combustion improvement is more likely to be reducing carbon-in-ash than increasing fuel utilization. At the same time, reactivity of high-rank Australian coal could be significant issue at the relatively low temperatures in pressurised fluidised bed combustors and gasifiers.

On the other hand, mineral (inorganic) matter reactions resulting in ash or slag formation often are crucial. Thus, in dry-bottom PF boilers, refractory ash characteristics are advantageous, whereas the same characteristics are potentially disadvantageous in slagging gasifiers. This, then, is likely to be a major research issue for Australian coals because high temperature, entrained-flow gasification is expected to be the benchmark technology for IGCC and the solution for refractory ash-fluxing is expensive.

Equally, control of environmentally-sensitive emissions, both gaseous and solid, is critical to future political acceptance of coal as a fuel, and minor constituents can devalue a coal if their transforms in the emissions present (or are perceived to present) environmental or waste disposal problems. Allocation of Centre resources among program areas is shown in Table 14. Priorities have been determined with the above-mentioned factors in mind but the distribution of resources is subject to periodic review and change as required.

In the following sections, research in progress or about to be commenced is outlined for each program area. A complete list of projects is given in Table 15, while references 76–99 from the Centre provide further details of Centre research accomplishments.

5.3.1. *Advanced coal characterization*

The requirement from this area is to develop rapid methods for measuring coal quality characteristics that are relevant to production and utilization processes. Industry applications would be for routine (preferably on-line) monitoring of product quality and for process control or optimisation. Characterisations to define coal quality for purposes of technology performance modelling similarly need to be process-related, where quantities measured or inferred must differentiate coal properties relevant to behaviour.

Other, usually more detailed, characterization techniques may be required to fully define properties relevant to research projects, e.g. to quantify mineral composition for ash and slag formation studies. Failure to *relevantly* characterise material characteristics is a common shortcoming of historical coal utilization research, resulting in inability to accurately classify other coals compared to those whose behaviour was studied. The importance of appropriate characterization in all three areas of application - routine monitoring, technology assessment and research support - means that this program area has a significance that was perhaps not fully appreciated originally. It also includes the important task of

Table 15. CRC-BCU research projects

No.	Title	Leader
	Program Area 1: Advanced Characterization	
1.1	Computer-controlled scanning electron microscopy (CCSEM) and image analysis of coal minerals, ash and slag	UN
1.2	CRC coals	UQ
1.3	Coal quality monitoring via magnetic resonance spectroscopy	UN
1.4	Coal quality monitoring via near-infrared spectroscopy	UN
1.5	Assessment of carbon burnout in combustion and gasification	UN
	Program Area 2: Coal Matter Reactions	
2.1	Volatile matter evolution at high temperature and pressure	CSIRO
2.2	Coal particle behaviour in high intensity reaction conditions	CSIRO/UQ
2.3	Reactivity of coals to O_2, CO_2 and H_2O at elevated pressures for gasification and PFBC conditions	CSIRO
2.4	Coal structure and its influence on coal/gas reactions	UNSW
2.5	Mechanistic modeling of single particle and cloud reactions	UN
2.6	Coal gasification measurements in entrained-flow reactors	CSIRO
	Program Area 3: Mineral Matter Reactions	
3.1	Fundamental investigations of slag/char/gas interactions and char reaction kinetics	UNSW
3.2	Ash formation during pulverized-fuel combustion and gasification in a reducing atmosphere	UN
3.3	Prediction of liquidus temperatures and high temperature phase equilibria for the system SiO_2–Al_2O_3–Fe_2O_3–FeO–CaO	UQ
3.4	Demonstration of true ash fusibility characteristics of Australian thermal coals, Stage 2: Proving a commercial laboratory test for a complete range of coal ashes	UN
3.5	Characterization of flux needs of coals for IGCC gasifiers: evaluation of the TMA technique	UN
3.6	Measurement of the viscosity of particle/slag mixtures: proof of concept	UQ
	Program Area 4: Environmental Issues	
4.1	Improved techniques for the prediction of NO_x formation from char nitrogen	CSIRO
4.2	Mechanisms for trace element partitioning in Australian coals	CSIRO
4.3	Identification of research issues for environmental release of pollutants from new thermal coal processes	UQ/CSIRO
	Program Area 5: Technology Assessment	
5.1	Coal predictor for pulverized coal injection	UQ
5.2	Nitrogen oxides predictor for pulverized-coal-fired boilers	UQ
5.3	Combustion predictor for pulverized coal-fired boilers	Pacific Power
5.4	Sensitivity of carbon dioxide recovery technologies to Australian black coals	UQ
5.5	Preliminary evaluation of pressurized fluidized-bed combustion for Australian black coals	UNSW

* UN, University of Newcastle; UNSW, University of New South Wales; UQ, University of Queensland.

establishing a representative suite of Australian coals for CRC and other research. The existence and use of a fully characterised reference set, is expected to considerably enhance the value of future coal research.

Work includes two spectroscopic techniques that yield information-rich measurements, such as profiles of performance-related quantities appropriate for technology assessment applications, which may be transferable to the field for routine monitoring. One project uses magnetic resonance imaging (MRI), otherwise known as nuclear magnetic resonance (NMR), and the other near-infrared spectroscopy. In both cases, the response functions have to be interpreted in practical terms (e.g. volatile matter) by sophisticated statistical correlation methods. Preliminary research has been extremely encouraging in terms of the amount of information that can be extracted and the accuracy achieved.

Detailed examination of constituent species for interpretative and definition applications in research projects is being undertaken in two projects. One is computer-controlled scanning electron microscopy (CCSEM) and image analysis of coal minerals, ashes and slags, which continues research initiated by Pacific Power and The University of Newcastle. The second project involves assessment of unburnt carbon in combustion and gasification, using an automated reflectance technique. One project is underway, in collaboration with the Australian Coal Association, in the area of process-related methods of determining behavioural attributes for contractual monitoring and operational guidance applications, namely demonstration of true ash fusibility of Australian thermal coals. This employs thermomechanical analysis (TMA).

5.3.2. *Coal matter reactions*

The objective in this program area is to determine reaction rates of coal under high-intensity (elevated temperatures and/or pressures) conditions typical of emerging technologies. Volatile matter evolution at high temperature and pressure is being studied principally at CSIRO and the influence of coal and char structure on particle/gas reactions at the universities of NSW and Queensland. Projects to measure coal particle behaviour in high-intensity reaction conditions and reactivity of coals to O_2, CO_2 and H_2O under pressurised, fluidised-bed gasification and combustion conditions have been initiated and preliminary work, with very promising results, has been done at The University of Newcastle. Mechanistic modelling of single particle and cloud reactions will enable these research results to be used in technology assessment projects.

Initial work in the Coal Matter Reactions program area is bench-scale science, using equipment such as heated-grid reactors, with single particles or small quantities of coal. These studies are essential to obtain basic data and understanding of coal conversion processes in conditions that have not been closely or extensively investigated previously. Equally, it is essential that the work progress to an engineering scale in which reaction environments are simulated more realistically. This is the purpose of a newly conceived Advanced Gasification Research Facility. In the meantime, we are seeking collaborative arrangements to do preliminary coal gasification measurements in the Low-Rank Coal CRC's pressure droptube furnace and, overseas, in pressurised, entrained-flow reactors similar to the proposed facility.

5.3.3. *Mineral matter reactions*

The aim is to quantify transformations of inorganic matter in coal to ash and slag during combustion and gasification. These transformations are important in all the targeted technologies and are often critical for effective operation. Thus, for example, economic operation of PF boilers requires that fouling and slagging be controlled so that off-load cleaning is infrequent. This topic has been extensively studied but the transformation may be affected by introduction of NO_x control measures, for instance, which is in part the reason for a project on ash formation during PF combustion and gasification in a reducing atmosphere, at The University of Newcastle.

Other projects relevant to IGCC and PCI are fundamental investigations of slag/char/gas interactions and char reaction kinetics and prediction of liquidus temperatures and high-temperature phase equilibria for the system SiO_2–Al_2O_3–Fe_2O_3–FeO–CaO, being carried out principally at the Universities of New South Wales and Queensland respectively. New projects commenced recently address the important issues of characterising flux needs for IGCC gasifiers using the TMA technique and measurement of the viscosity of particle-slag mixtures. As noted previously, high-temperature, entrained-flow gasification is expected to be the preferred technology for converting high quality traded coals and it requires reliable formation of a fluid slag to drain solid wastes. The behaviour of slag-forming constituents and the economics of fluxing to achieve the slagging objective are therefore factors critical to acceptance of Australian coals in this market.

5.3.4. *Environmental issues*

In this program area, the aim is to develop predictive techniques and control strategies for emissions of gaseous and particulate pollutants from utilization processes. The initial focus is on NO_x and trace element emissions from PF combustion. A project centred at CSIRO North Ryde is directed toward development of improved techniques for prediction of NO_x formation from char nitrogen. Although it is clear that most NO_x is formed from fuel rather than atmospheric nitrogen, it does not follow that the nitrogen content of coal entirely determines the resulting emission levels. Indeed, it is certain that this is primarily if not overwhelmingly a function of combustion conditions, which are the base of low-NO_x burner control strategies. Scientific elucidation of char nitrogen behaviour is expected to sustain the contention that NO_x can be satisfactorily controlled regardless of coal nitrogen content.

At Lucas Heights, CSIRO researchers are continuing studies of the minor constituents of coal in a project designed to determine mechanisms for trace element partitioning in Australian coals. This addresses the fate of species that are partly emitted as vapours with stack emissions, and sometimes referred to as air toxins, and partly in condensed form with fly ash as solid waste. In the latter case, wet ashing methods of disposal can lead to high levels of elements such as selenium in effluents. Although Australian coals do not generally have trace element contents that should cause concern, the toxicity of some species at significant concentrations is such that persuasive scientific data on actual emission levels is needed to provide appropriate reassurance. CSIRO's prior research into measurement of extremely low concentrations assures a sound scientific basis for this work.

Identification of research issues for environmental release of pollutants from new thermal coal processes is currently being initiated in a new project. The forms in which N, S and inorganic species are released during gasification and combustion at high pressure may be rather different from those released during conventional PF combustion at atmospheric pressure. For instance, S can appear in fuel gas as H_2S, COS, CS_2, mercaptans and thiophene, rather than SO_x. This project will lead on to substantive projects and to research issues identified as significant.

5.4. *Technology Assessment*

From this program area should emerge robust methodologies to predict performance of thermal coals in utilization processes, for use as tools to facilitate export coal marketing and selection of coals and technology by domestic coal users. It is the area in which the results of R&D in the other program areas, together with related data and information gathered from all available sources, are brought together. Initial projects have concentrated on PF and PCI technology. Work is most advanced on modelling for a NO_x predictor for PF boilers. This project is led by Queensland University and has involved an industry fellow from Pacific Coal, which is a mechanism devised for the Black Coal CRC to enhance collaboration and technology transfer. Pacific Power is leading a project to develop a coal predictor for PF boilers, which eventually will include burnout and ash/slag models. Rio-Tinto initially led the project to develop a coal predictor for PCI but this responsibility has now been transferred to The University of Queensland. The initial focus has been to evaluate available information, from which it is hoped that a first-cut model can be developed and research issues identified.

A small scoping project is being done at The University of Queensland to determine sensitivity of carbon dioxide recovery technologies to Australian black coal. This will provide a basis for specification of possible future research if and when development of the greenhouse debate warrants work in this area, which does look more prospective now than formerly. In conjunction with the Australian Coal Association, an eighteen-month project to assess PFBC technology has commenced. This includes contracted work at the Coal Research Establishment (CRE) in the UK to evaluate a set of Australian coals in comparison with international coals and critical assessment of the CRE tests by UNSW and Pacific Power experts, together with exploratory research at the universities of NSW and Queensland. The results will be used to define research issues for future project study and to provide the basis for technology performance modelling.

PFBC is important because it is the most commercially advanced of the new technologies but there may be a question as to whether high-rank coals are sufficiently reactive to suit the relatively low temperatures used. Similar technology can be used for gasification and the main vendor, ABB Carbon, is working towards a hybrid PFBG/C process for the longer term, as a British consortium with its topping cycle proposal.

5.5. *Final Comments*

The CRC for Black Coal Utilization is an unique research centre as it brings together several research organisations, universities and industry in order to focus Australia's research effort, yet relies on the research participants each to make their agreed contribution to the cooperative program in their own laboratories. The concept is that the combined effort should exceed that if the participant organisations were to work independently. Even though the Centre has now operated for just one year, there is evidence that this objective is being achieved with joint projects having been developed on PCI and PFBC issues as well as on new characterization techniques and on coal performance at the extreme conditions of new utilization technologies.

Acknowledgments — The authors wish to acknowledge the support of the CRC for Black Coal Utilization which is funded in part by the Cooperative Research Centres Program of the Commonwealth Government of Australia.

6. THE DIVISION OF COAL AND ENERGY TECHNOLOGY (CSIRO)

John K. Wright, North Ryde, Australia

6.1. *Introduction*

The Division of Coal and Energy Technology is part of Australia's leading research organisation, CSIRO (Commonwealth Scientific and Industrial Research Organisation). In the Division's beginnings 50 years ago, it was known as the Coal Research Section of CSIR. Australia has abundant supplies of good quality coal, and the need to support the continued use of coal as an energy source in Australia, and to support the growth of an export industry are major drivers in our research. This paper concentrates on CSIRO's current developments in coal combustion research, particularly work being done for advanced power generation and new metallurgical technologies.

A prime factor guiding our research is the recognition that, if the industries which use coal are to operate more efficiently and with a minimum impact on the environment, then it is essential that coal combustion is researched in the context of its position in the coal-production and coal-using chain. This begins with coal mining and coal preparation and follows through to encompass the environmental consequences of coal use, including the impact coal use has on greenhouse gas emissions. There are gains to be made in all parts of this continuum, but dividends will be made when coal ceases to be an undifferentiated commodity and we learn to produce and specify our coals for specific tasks, fully aware of how they will perform, including the industrial and environmental consequences of their use. This premise is fundamental to CSIRO research, and this section will touch on our strategy to provide this sort of quality information to the coal industry.

6.2. *Commonwealth Scientific and Industrial Research Organisation*

CSIRO is a large R&D organisation employing over 7000 people and undertaking research in support of the Australian industry and community. The only areas excluded from our charter are nuclear, defence, and medical research. The work of the organisation is conducted through 33 Divisions, each addressing a particular industrial sector or scientific/engineering discipline. Currently, coal research is divided between the Division of Exploration and Mining and the Division of Coal and Energy Technology (DCET). CSIRO is undergoing a major restructuring, part of which is to link research in specific industry sectors. The Coal and Energy Sector has an annual budget of some US$19 million and incorporates all the links in the coal chain from exploration and mining, through preparation and handling, to utilization and environmental impact. This reorganisation will enable us to look at the coal chain as a whole and to organise R&D effort where it will have the most effect.

Table 16. General characteristics of DCET

Title	The Division of Coal and Energy Technology (CSIRO)
Location	North Ryde, NSW, Australia
Director	John K Wright, Chief of Division
Starting date	1946
Mission/objective	To improve the competitive advantage and environmental acceptability of the coal, energy and related industries
Focus	Clean and efficient use of Australian coals through developing new and improved processes and technologies for coal preparation and the utilization of coal in power generation and metallurgical industries
Research areas	Coal reactivity in combustion and gasification processes, advanced analytical methods for coal characterization, environmental impact and control (NO_x and SO_x emissions, trace elements) hot-gas cleaning (bag filters and electrostatic precipitation)
The Centre is also active in coal in preparation, natural gas utilization, energy storage, renewable energy sources, air and water studies to monitor industry impact on the environment and developing process controls to reduce this impact.	

The Sector also includes research groups working on natural gas utilization, renewable energy sources, energy storage, and advanced fuel-cell development. The incorporation of these topics into the Sector will improve our ability to make decisions on the type of research needed to support Australia's future energy requirements, taking into consideration the potential of all sources of energy, not just coal.

6.3. *The Division of Coal and Energy Technology*

There is a long history of coal research at CSIRO. The present laboratories in Sydney were established over 50 years ago, reflecting the importance the Australian government placed on Australia's coal resources immediately after World War II. Since that time, there have been many changes in name and research direction, reflecting the prevailing scientific and economic environment at the time. Through all these changes, CSIRO has maintained a core of coal expertise which has held CSIRO in good stead to take a current leading role in support of one of Australias now most important industries.

In the early years, CSIRO was a fully government-funded research organisation, and the Division's early work focussed on the application of coal science to building up a sound knowledge of Australian coals and their behaviour. This storehouse of knowledge is still serving us well as we continue to work more closely with industry in developing and introducing new technologies. This philosophy is embodied in our Vision and Mission Statements:

Vision: To be the first choice provider of research and development to the Australian coal, energy, and related environmental sectors.

Mission: To improve the competitive advantage and environmental acceptability of the coal, energy, and related industries.

Table 16 provides further information on Division characteristics.

While still a government agency, the Division now relies on industry for around 40% of its income, as noted, with other data in Table 17. Coal and Energy Technology now has two coal research laboratories in Sydney and one in Brisbane, and it has developed strong links with a range of other R&D organisations, particularly the Cooperative Research Centre for Black Coal Utilization.

6.4. *Coal Combustion-related Work*

The work of DCET is now more broad than at any time in its history. A major part of our work is in preparation, utilization, and the environmental impact of the coal process industry. We are now taking a much more holistic view of the energy chain and attempting to integrate our work by applying a systems approach wherever possible. The following concentrates on coal combustion.

6.4.1. *Combustion and pyrolysis*

Coal utilization research represents some 30% of DCETs effort in coal research. Our work on the behaviour of Australian coals in traditional technologies continues, but increasingly we are focussing on the reaction rates and behaviour of coal under the high temperatures and/or high pressures that will be required in new power generation and metallurgical processes.

Starting at the single coal particle scale, a recent success has been the development of a nanobalance and laser microreactor which can measure the changes in mass of a single coal particle during combustion under controlled conditions. This instrument (see Fig. 12) allows the direct measurement of particle temperature, size, mass, and reaction rate during combustion in a controlled atmosphere. By measuring combustion rates

Table 17. Data for DCET

A. Number of personnel (1996)

Professional	125
Professorial	0
Postdoctoral	25
Graduate students	0
Undergraduate students	0
Staff/management	5
Support technical	65
TOTAL	220

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	14900
1995	14500
1996	15000

C. Budget sources (%) (1996)

Government	60
Domestic industry	40
University	0
Foreign	0
Income (patents, royalties, licenses, software, etc.)	0
Other	0
TOTAL	100

D. Space and equipment

1. Research space	10500 m^2
2. Research equipment/ instruments/computers	$13400000—Australian

E. External participants/sponsors/advisors/members

Government	2
Industry	60
University	6
TOTAL	68

F. Research program (1996)

Number of fundamental projects	40
Number of applied projects	50
Number of proprietary projects	50
TOTAL	140

G. Center research projects/activities

	Minor Major
Experimental data	1 **2** 3 4 5
Computer software	1 **2** 3 4 5
Inventions/patents	1 **2** 3 4 5
Project reports	1 2 3 **4** 5
Journal/book publications	1 2 **3** 4 5
Consulting services	1 2 **3** 4 5
Process/system concepts	1 2 **3** 4 5
Graduating students	1 **2** 3 4 5
Academic courses	**1** 2 3 4 5
Technology transfer	1 2 3 **4** 5

of individual particles (see Fig. 13), it is possible to examine the behaviour of different coal macerals. The technique has already been used to demonstrate that Australian coal inertinites are far from inert. The terminology had been transferred from Northern Hemisphere coals, but Australian inertinites behave quite differently from Northern Hemisphere coals. Research has shown that chars from inertinite particles, in many instances, actually burn faster than similar char particles produced from more fusible coal. The wider acceptance of this has benefited the marketing of Australian coals. We have also made some exciting breakthroughs using NMR techniques to monitor the behaviour of coal blends during the coke-making process. The technique provides

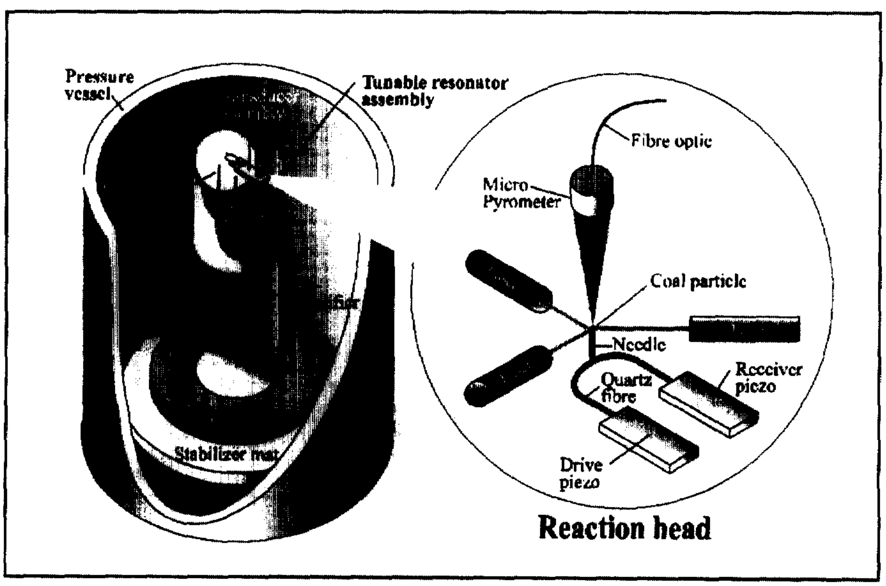

Fig. 12. Nanobalance and microreactor.

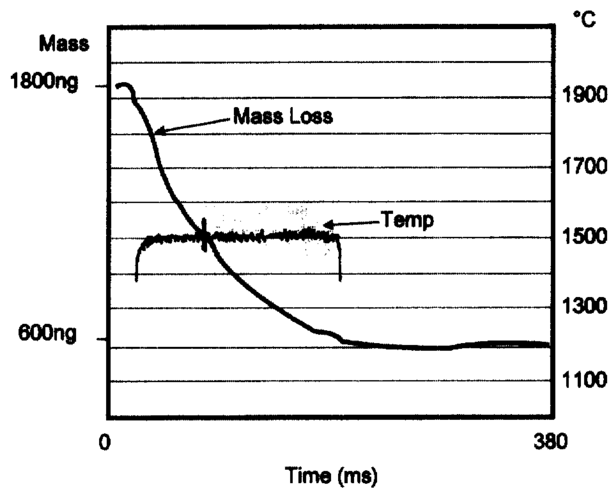

Fig. 13. Weight loss and temperature during combustion of a single coal particle.

a quick and reliable means of predicting the fluidity of coal blends, even when the coals interact during the coking process (see Figure 14). Also in the metallurgical area, we have carried out research on the combustion efficiency of coals in pulverised coal injection (pci) using an entrained flow reactor which allows the study of high temperature pyrolysis and combustion under controlled conditions. From our research we have developed a fast test method which can measure the yield of volatile matter and the overall conversion efficiency of coal particles as they burn in conditions similar to those in the raceway of the blast furnace.

In conventional power generation, DCET is conducting studies of the secondary reactions of primary coal volatiles under conditions relevant to PF combustion. In spite of the importance of these secondary reactions to overall combustion efficiency, and to gaseous pollutant and soot formation, little previous work has been done with volatiles produced under high heating rate conditions. Kinetics of secondary processes including pyrolysis (or cracking) and oxidation are being determined, and the products are being characterised using various chromatographic and spectroscopic techniques. In the next stage of this work, interactions of NO with the coal volatiles will be examined. These interactions are important in determining the ultimate conversion of coal N to NO during combustion.

6.4.2. *Gasification and minerals behavior*

Gasification of coals is a featured R&D area. Coal gasification as part of the IGCC (Integrated Gasification Combined Cycle) power generation offers increases in both flexibility and efficiency over conventional coal-fired power generation technology. The introduction of new power generation technologies, not only in this country, but on a global scale, has the potential to dramatically decrease the CO_2 emissions per unit of power generated over conventional PF plants. If we continue to use coal as a primary energy source, and

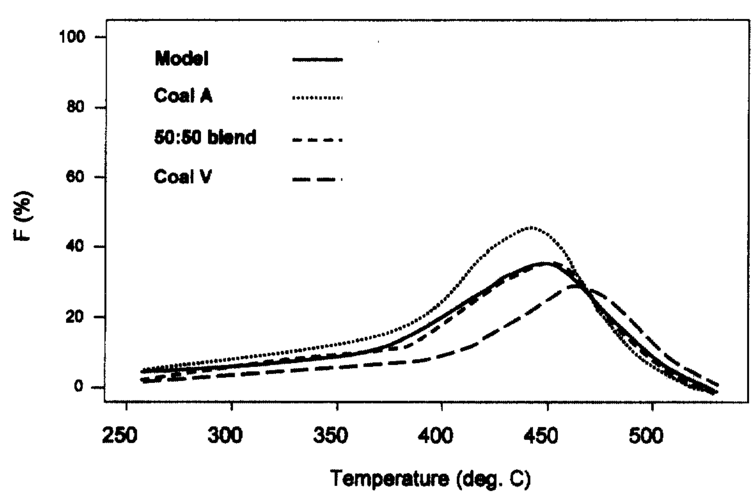

Fig. 14. Coking predictions. *F* is fluidity.

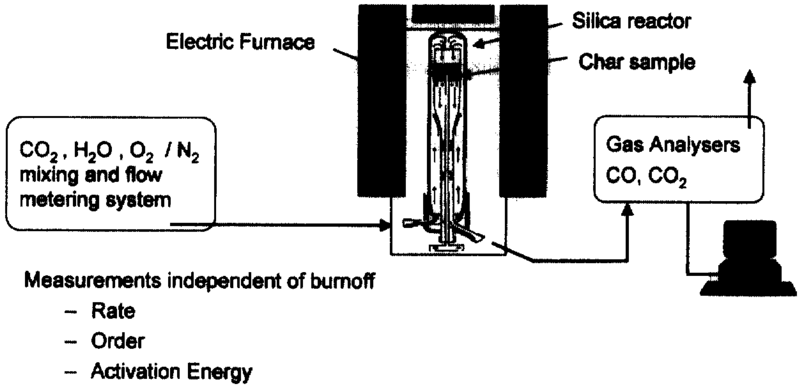

Fig. 15. Intrinsic reactivity apparatus.

there is little choice in this, then we also have little choice but to develop, test, and tailor coals to suit these high efficiency processes. DCET has a number of projects in this area which are staged to build up our expertise, facilities, and understanding of the processes involved. (1) One of the first facilities to be built was a bench-scale reactor which operates at atmospheric pressure and low temperatures and measures the intrinsic char reactivity to CO_2, O_2 and H_2O (see Fig. 15). (2) This was followed by an entrained flow reactor, still operating at atmospheric pressure but capable of reaching temperatures in excess of 1500°C. This is being used to investigate gasification yields and conversion efficiencies of different coals under conditions relevant to entrained flow gasification processes (see Fig. 16). (3) Complementing this, we are setting up a high temperature thermobalance to look at effects of pressure on char reactivity to oxidising gases. (4) We are developing high pressure heated grid apparatus which will determine the effect of pressure on volatile yield and composition at heating rates of around 10^4°C per second. (5) Linked to these combustion studies is research—now well advanced—on the viscosity of coal ash and slag. On the whole, Australian bituminous coals are well suited to gasification, but an area of concern is the high ash fusion temperature of some coals—often greater than 1500°C. Under the temperatures prevailing in entrained flow slagging gasifiers it is essential that the molten slag has a viscosity low enough for optimum slag flow at 1400–1500°C. DCET is undertaking research to establish models which allow slag viscosity and flux requirements to be predicted from the ash composition (see Fig. 17). Overseas models do exist but do not provide good agreement with the behaviour of many Australian coals, because of the generally high silica, high silica to alumina ratios and low calcium contents of Australian coals. This work is being undertaken on prospective coal deposits which are to be marketed overseas into advanced power generation technologies. (6) DCET also develops modelling related to advanced processes. We completed an evaluation of the potential of IGCC technology to reduce CO_2 emissions, again, for Australian coals. (7) We are now attempting to set up a 20 kg/hr high pressure entrained flow reactor (see Fig. 18). This is being pursued through the CRC for Black Coal Utilization, in which CSIRO is a participant. Greater interaction between industry and the research groups will ultimately make the transfer of the technology from the science laboratory to the workplace much smoother.

Coal minerals play an important role in utilization processes particularly in slagging and ash fusibility. DCET has developed a commercial software package, based on X-ray diffraction, which allows the identification

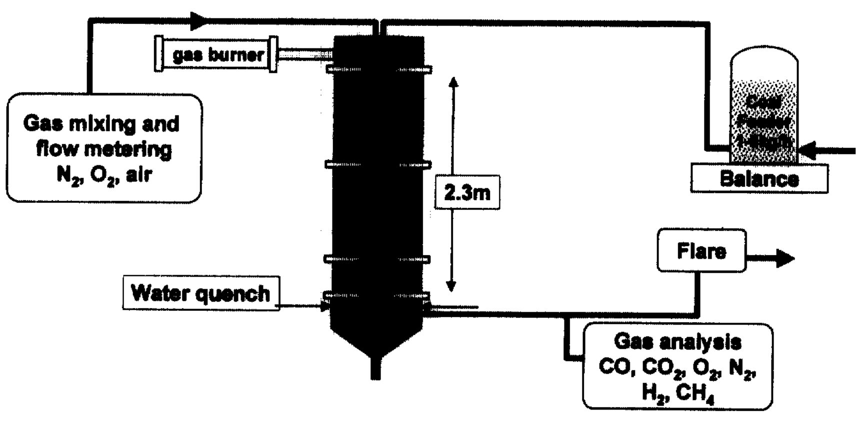

Fig. 16. Entrained flow reactor.

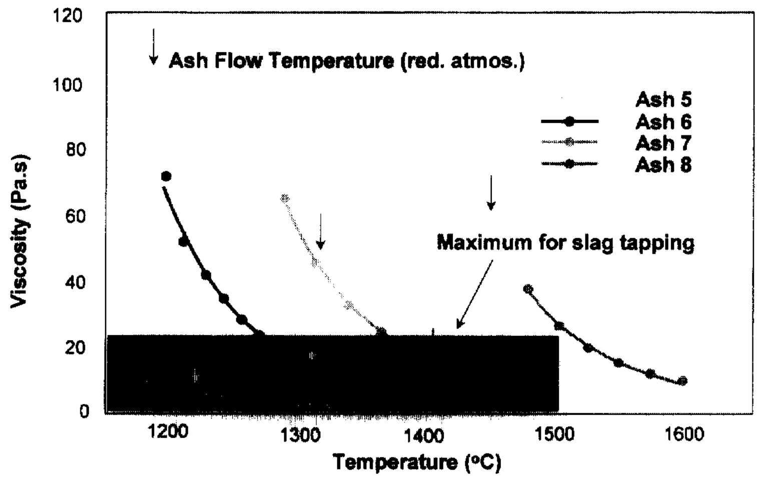

Fig. 17. Viscosity versus temperature relationships for molten coal ashes.

and accurate determination of mineral phases in specific coals. This package, known as SIROQUANT, is currently being distributed internationally.

6.5. *Environmental Implications of Coal Combustion*

Linked with our combustion work is research to monitor and reduce the environmental impact of coal use. This relates to the management of ash, to gaseous emissions such as NO_x and SO_x and levels of trace elements in both the ash and emissions.

6.5.1. *Fly ash*

DCET has considerable expertise in both electrostatic precipitation and fabric filtration technologies. A few years ago we linked our pilot-scale electrostatic precipitator with a 10 kV pulsed power supply to look at ways of improving precipitator performance. This work has produced some novel insights into ways of improving precipitator performance and has inspired new ideas and research into specific areas of advanced gas-cleaning technology.

In fabric filtration, much of our work is done in collaboration with power generating companies in New South Wales. This has resulted in changed collection techniques that increase the lifetime of the filter fabric and reduce the overall pressure drop across the filter, thereby reducing the operating costs. Currently the researchers are evaluating new fabrics and the effectiveness of various commercially available surface treatments aimed again at reducing operating costs.

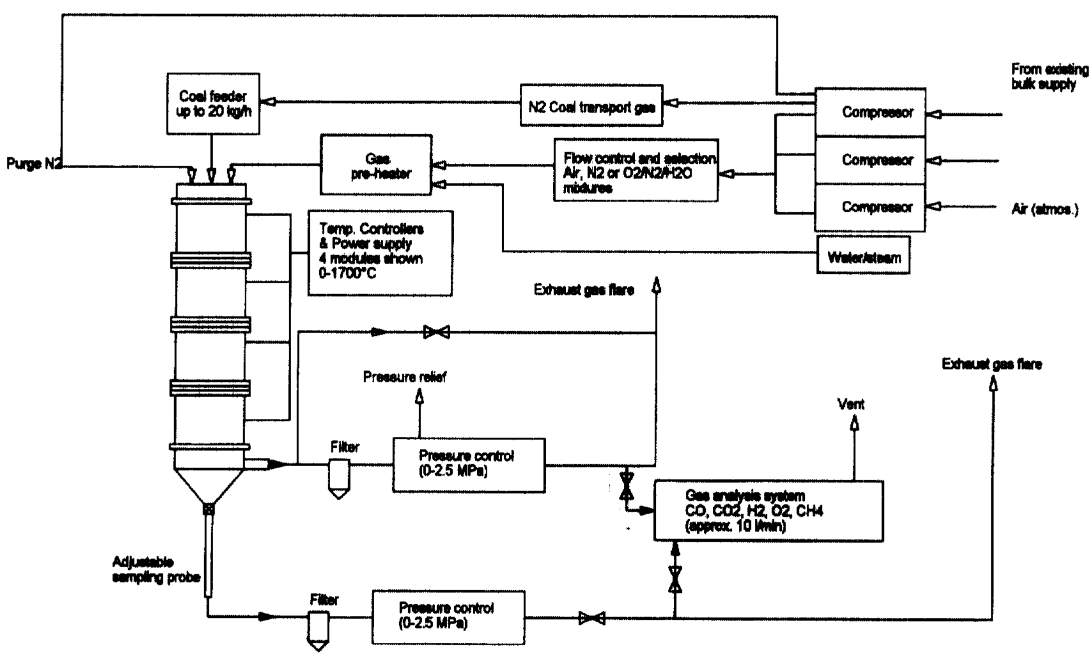

Fig. 18. Proposed 20 kg/h pressure gasification reactor.

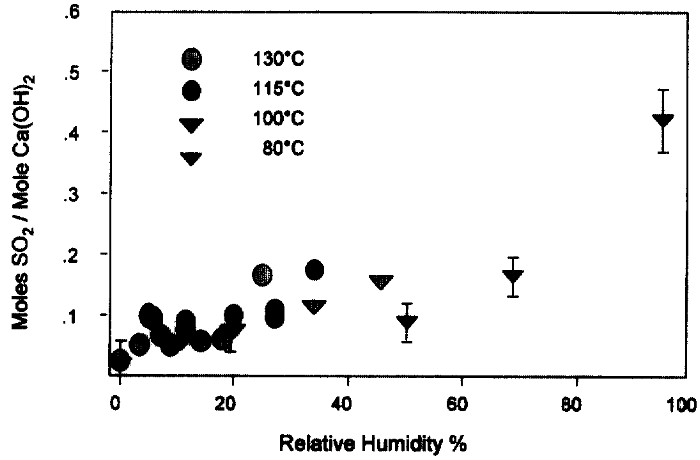

Fig. 19. Close approach to saturation required for effective SO_2 capture.

6.5.2. *NO_x and SO_x*

Australian coals have relatively high nitrogen levels, and this has been perceived as a problem in their industrial use. To alleviate this concern, research has targeted the prediction of NO_x levels when Australian coals are burnt under a variety of combustion conditions. Whilst it is clear that the major source of NO_x is conversion of nitrogen in the coal rather than fixation of atmospheric N_2, there is no simple relationship between the nitrogen content of the coal and the NO_x produced. While the characteristics of the coal nitrogen, particularly the proportions released during initial pyrolytic decomposition, play some role, it is clear that combustion conditions, such as local stoichiometry and temperature, exert the major influence on the amount of NO_x produced. These effects of combustion conditions have been profitably exploited in the design of low-NO_x burners.

Emissions of SO_2 have not been a major problem in Australia, in part because of the relatively low sulphur contents of these coals. Recently, however, Pacific Power Company has investigated sulfur capture techniques in which hydrated lime sorbents are used in combination with the fabric filters described above. In support of this work, the Division has conducted laboratory experiments, which demonstrated that close approaches to saturation were necessary to obtain efficient sulphur capture, and that the components of the flyash may play some role in activating the sorbents (Figure 19).

6.5.3. *Trace elements*

Trace elements, though generally found at very low levels in Australian coals, is an area in which coal users require more information. This is particularly true for certain heavy metals such as mercury, lead, arsenic, selenium, copper, zinc, and chromium. DCET has developed new analytical techniques capable of measuring the low concentrations found in our export thermal coals. Research includes the following: (1) establishing a comprehensive database of trace element levels in Australian thermal coals, (2) determining the levels of potentially harmful trace elements in thermal export coals, and (3) determining trace element mass balances in major NSW power stations.

6.6. *Greenhouse Gas Concerns*

Because of its reliance on coal, Australia has one of the world°s highest per capita emissions of CO_2 (but only producing 1.5% of the total anthropogenic-derived CO_2). To demonstrate its commitment to international treaties, Australia will have to work hard to reduce emissions. Process efficiency gains in the order of 10% over traditional PF technology will yield big reductions in CO_2 emissions for the newer power generation technologies. R&D organisations need to understand the relative benefits of the different technologies and fuel sources. We have a responsibility to ensure our governments are well informed on the various options. No nation wants its energy policy to be driven by ill-informed, emotive arguments. There remains substantial public concern over the use of coal. Much of the blame for Greenhouse effects falls on the coal-fired power generators. Whether or not we believe global warming through Greenhouse gas is, or is not, an issue, we need to communicate the improvements that have been and will be made in coal combustion, and that coal and a clean environment are compatible.

7. THE ENERGY AND ENVIRONMENTAL RESEARCH CENTER

G. H. Groenewold and S. A. Benson, University of North Dakota, Grand Forks, North Dakota, U.S.A.

7.1. *Introduction*

The Energy & Environmental Research Center (EERC) was originally established in 1948 under the Bureau of Mines, was later transferred to the Energy Research and Development Administration (ERDA), and then to the U.S. Department of Energy (DOE), and in

Table 18. General characteristics of the EERC

Name	The Energy and Environmental Research Center
Location	University of North Dakota, Grand Forks, North Dakota, USA
Director(s)	Gerald H. Groenewold, Director Michael L. Jones, Associate Director Steven A. Benson, Associate Director for Research Edward N. Steadman, Associate Director for Research
Starting date	Established 1948, dedicated 1951
Mission/Objective	The mission of the EERC is to improve global quality of life by providing leadership in visionary, multi disciplinary research and development leading to demonstration and commercialization of innovative, clean, efficient energy technologies and of environmental technologies addressing the protection of air, water, and soil. The EERC accomplishes this mission by: ● being cognizant of the interconnected nature of the environment and energy; ● being focused, practical, and sensitive to the marketplace; ● being international in scope; ● being committed not only to research and development, but also to demonstration and commercialization of innovative energy and environmental technologies; ● fostering cooperation among industry, government, and the research community; ● providing opportunities for economic development and job creation; ● providing fundamental and applied research and training opportunities for highly motivated students and professionals at all levels.
Focus	Research, development, demonstration and commercialization opportunities focus on energy and environmental technologies that result in the conversion of energy to appropriate and environmentally acceptable forms, cost-effective remediation of past environmental contamination and prevention of future environmental contamination.
Research areas	Groundwater, coal, gas, oil, renewable energy, non-fuel carbon products, advanced power systems, advanced materials science, reclamation of disturbed lands, atmospheric emission control, waste utilization and disposal, contaminant clean-up and site remediation, and experimental design and analytical methods development are the areas of key importance.

1983 was defederalized, becoming part of the University of North Dakota (UND). For the first 35 years, work at the Center focused primarily on low-rank coal research and related emission-control technologies. Since becoming part of UND in 1983, the EERC focus has broadened, and projects have included high-rank fuels and related emission-control technologies as well as non-fossil-fuel-related environmental work. Today, EERC's mission is to improve the global quality of life by providing leadership in visionary, multidisciplinary research and development leading to demonstration and commercialization of innovative, clean, and efficient energy technologies and of environmental technologies addressing the protection of air, water, and soil. The EERC's efforts are carried out by a team of more than 260 professionals representing a wide variety of science and engineering disciplines. The EERC is currently working on 220 projects, 75% of which are from industry and 25% from government sources. The EERC client-base represents federal and state agencies, universities, coal companies, utilities, research and development firms, equipment vendors, architecture and engineering firms, chemical companies, agricultural product companies, renewable energy firms, and environmental companies, including small businesses, working on technologies to clean up weapons facilities. In addition, last year the EERC worked on several international projects involving 12 countries.

The Energy & Environmental Research Center (EERC) of the University of North Dakota is one of the world's leading energy and environmental research organizations. Since its founding in 1948, the EERC has conducted fossil energy-related research, testing, and evaluation of fuels, combustion and gasification technologies, emission control technologies, ash use and disposal, analytical methods, groundwater, waste-to-energy systems, and advanced environmental control systems. The EERC has and is expanding its role beyond fossil energy and environmental issues to environmental management, water management, groundwater, contaminant cleanup, agricultural chemical cleanup, advanced materials, renewable energy, education, training, and other areas. The EERC is committed to solving complex energy and environmental problems by performing practical research and development to identify applicable technologies, demonstrating these technologies and processes, and commercializing successful technologies and processes through partnerships with industry.

The EERC engineering and scientific research staff has at its disposal state-of-the-art analytical and engineering facilities. The main EERC facilities—with 169,000 square feet of laboratory, pilot plant, and office space—are located on the southeast corner of the University of North Dakota campus. High-severity processes can be developed from conceptual ideas

Table 19. Data for the EERC

A. Number of personnel (1996)

Professional	87
Professorial	4
Postdoctoral	0
Graduate students	4
Undergraduate students	25
Staff/management	116
Other	24
TOTAL	260

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	13 054
1995	22 142
1996	24 609

C. Budget sources (%) (1996)

Government	77
Domestic industry	19
University	2
Foreign	2
Income (patents, royalties, licenses, software, etc.)	0
Other	0
TOTAL	100

D. Space and equipment

1. Research space	169 000 sq. ft.
2. Research equipment/instruments/ computers	$15 000 000

E. External participants/sponsors/advisors/members

Government	16
Industry	75
University	2
TOTAL	93

F. Research program (1996)

Number of fundamental projects	36
Number of applied projects	120
Number of proprietary projects	51
TOTAL	207

G. Center research projects/activities

	Minor				Major
Experimental data	1	2	3	4	**5**
Computer software	1	2	**3**	4	5
Inventions/patents	1	2	**3**	4	5
Project reports	1	2	3	4	**5**
Journal/book publications	1	**2**	3	4	5
Consulting services	1	2	3	**4**	**5**
Process/system concepts	1	2	3	**4**	5
Graduating students	1	**2**	3	4	5
Academic courses	1	**2**	3	4	5
Technology transfer (commercialization)	1	2	3	4	**5**

through proof-of-concept demonstration in the flexible, EERC reactor systems. Laboratory- and pilot-scale combustors and gasifiers with capacities of up to 4.0 million Btu/hr, as well as diesel and gas turbine simulators, are available for evaluating new fuels and assessing new emission control technologies. Testing equipment is also available for full-scale sampling and measuring of system flow and temperature. Analytical techniques and instrumentation are available for the characterization of solid, liquid, and gaseous materials. Computer modeling and database development are available to assist in predicting the effects of fuel characteristics on conversion and environmental systems. Further environmental research programs include combustion by-product utilization and disposal, waste-water treatment, mined land reclamation programs, an extensive groundwater program, and others. EERC emphasizes total-systems assessment of a wide variety of energy, environmental, and mineral resource research topics. The general characteristics of the EERC are summarized in Table 18, while Table 19 provides specific data for the Center.

7.2. *Research Program*

The research programs at the EERC encompass expanding initiatives and research areas. The expanding initiatives are areas the EERC has identified as having significant growth potential or need. The research areas are programs for which the EERC has a long-established history and show continued growth.

The expanding combustion-related initiatives being addressed at the Center include the following: (1) Environmental Management Technology Demonstration and Commercialization In this program, the EERC is working with the Department of Energy's (DOE) Federal Energy Technology Center to develop, demonstrate, and commercialize technologies in partnership with the private sector to clean up environmental contamination at nuclear weapons facilities and other sites across the nation. (2) Center for Air Toxic Metals The EERC is working with the U.S. Environmental Protection Agency and industry to prevent and control the release of metal emissions from energy-producing and incinerating systems. (3) American Indian Initiative The EERC is developing partnerships with a growing network of American Indian organizations to address the energy and environmental needs on Indian lands. (4) Education and Training The EERC's education and training program strives to disseminate critical scientific and engineering knowledge in a timely manner to students and professionals through international conferences, short courses, workshops, participation in academic programs, and practically oriented field experiences. Another initiative is waste-water management.

The major research program areas specifically related to combustion at the EERC are as follows: (1) Coal The

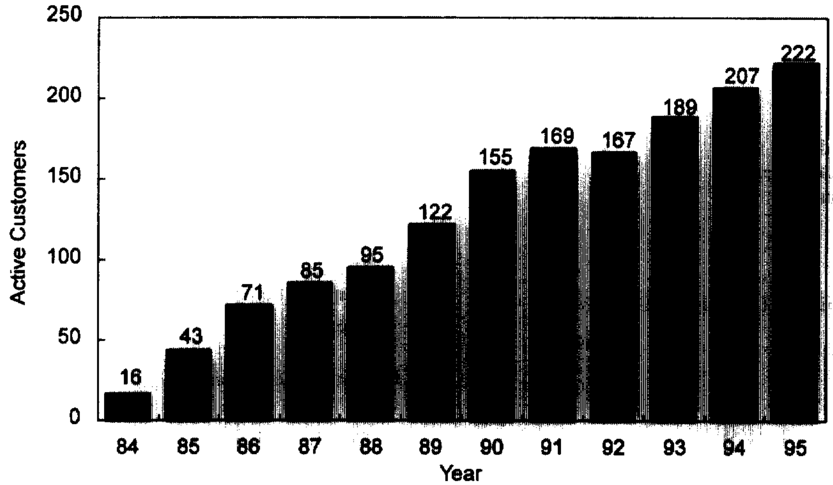

Fig. 20. Active customer base by fiscal year.

EERC has more than four decades of experience in basic and applied research, with particular emphasis on low-rank coals. The foundation of scientific understanding of the physical, chemical, and mineralogical nature of coal is the basis for the development, demonstration, and commercialization of clean and efficient coal utilization technologies. In addition, the EERC utilizes this knowledge-base of coal properties to more cleanly and efficiently utilize coal in existing facilities as well as in emerging technologies. (2) Gas The EERC has conducted research programs that have spanned three decades focusing on solving environmental issues facing the gas industry and in producing and conditioning synthetic or substitute natural gas by conventional coal gasification, pyrolysis, and underground coal gasification. (3) Oil The EERC has been working with the oil industry for three decades to provide technologies and services to clean up water produced during drilling operations, petroleum desulfurization using bioremediation, site characterization, waste utilization, and contaminant characterization, transport, and fate assessment. (4) Renewable Energy EERC efforts in this area have included work on wind energy and alternative fuel development. Wind energy programs have been initiated by Tribal Governments interested in evaluating appropriate technologies and resources. Alternative fuel development and combustion testing have been conducted on a wide range of fuels derived from biomass and waste materials focusing on environmental and combustion efficiency issues. (5) Nonfuel Carbon Products The EERC is working to develop products that take advantage of the chemical treasure trove inherent in coal and other resources. Efforts are currently focused on production of form coke, activated carbon sorbents, and chemicals. (6) Advanced Power Systems The EERC has over four decades of experience in testing and developing power systems. This work has involved demonstrating fluidized-bed combustion, pressurized combustion, advanced gasification, advanced heat exchangers, and hot-gas-cleaning technologies for a wide range of fuel types. (7) Atmospheric Emission Control The EERC research in this area has led to retrofit acid gas and particulate removal technologies for existing energy facilities. The work in this area is providing understanding critical to the design of the next generation of equipment needed to control particulate as well as gaseous organic and inorganic emissions from utilities, incinerators, refineries, and other industrial sources. (8) Experimental Design and Analytical Methods Development The EERC has a wide range of analytical capabilities that have been tailored to fuels, ash, and other materials associated with energy and environmental issues. These techniques include a full range of organic, inorganic, surface and mineralogical, thermal, and physical analysis. Analytical methods development is an ongoing research activity at the EERC. The development of new analysis techniques has been integral to the EERC's most successful projects. Other major research areas include groundwater, materials science, land reclamatory, clean up and remediation, and waste utilization and disposal.

7.3. *Partnerships*

The EERC recognizes that partnerships are the key to successfully solving complex energy and environmental problems through the development of innovative processes and technologies. The EERC has had outstanding successes in developing partnerships between industry and government to address critical barrier issues that could not be addressed by a single institution alone. Being sensitive to client needs and developing partnerships have been vital components in EERC's culture since it was defederalized in 1983.

The growth in the active customer base shown in Fig. 20 demonstrates that the EERC has the ability to be sensitive to the marketplace. The EERC has emphasized working with industry or commercial clients. The number of commercial clients contracting with the EERC by year is shown in Fig. 21. Further, the

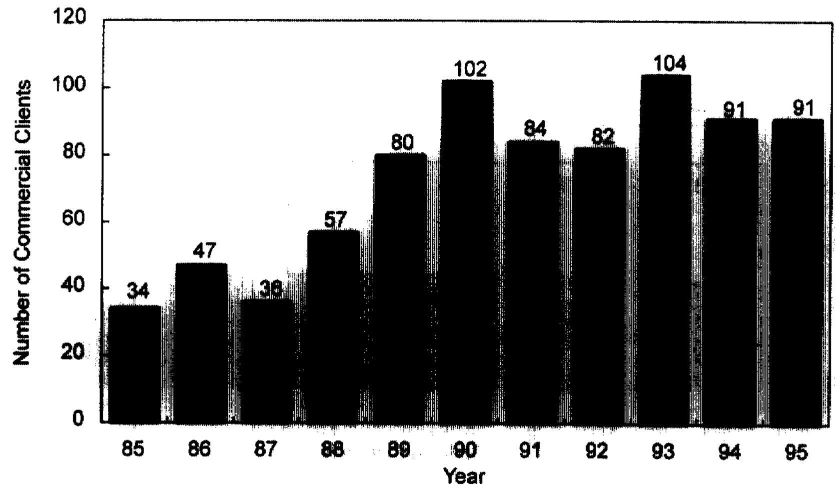

Fig. 21. Number of commercial organizations contracting with the EERC by year.

number of repeat customers, as illustrated in Fig. 22, has exceeded 60%, indicating not only that the EERC has many returning clients, but also that the EERC is still being aggressive in looking for new opportunities.

An example of industry and government partnerships developed at the EERC is the Jointly Sponsored Research Program (JSRP) which is part of the Cooperative Agreement between the U.S. Department of Energy and the EERC. The JSRP program was initiated in 1990 to leverage federal dollars with commercial dollars to perform projects based on leading-edge scientific and engineering principles that provide practical solutions to energy and environmental problems associated with the utilization of fossil fuels. Since 1990, the DOE has invested $14.9 million in 83 projects, totaling over $34.3 million in co-funded research. The DOE federal funding and the nonfederal match are shown in Fig. 23. In 1994, the EERC increased the nonfederal-to-federal match to 60%.

The EERC client list includes hundreds of domestic and international companies as well as scores of national and international academic institutions and government agencies. Today, the number of contracts at the EERC has exceeded 200 per year. More than 70% of the contracts are with private industrial partners. The EERC maintains a highly flexible business approach, tailoring contractual agreements to an individual client's needs.

7.4. *Conclusions*

Since defederalization in 1983, the EERC has undergone significant changes. Changing the culture from being a federal laboratory to a not-for-profit research organization was the most significant and essential change. The EERC learned that in order to obtain industrial clients and competitive procurements, it must be responsive to client needs and goals and complete work on time and within budget. In addition, the EERC evolved from being only a research and development laboratory to a facility that also performs demonstrations

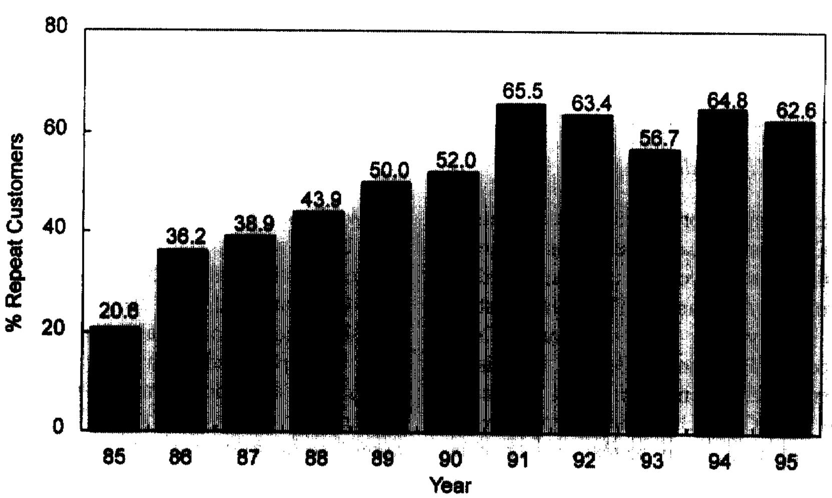

Fig. 22. Repeat customers as a percentage of total customers.

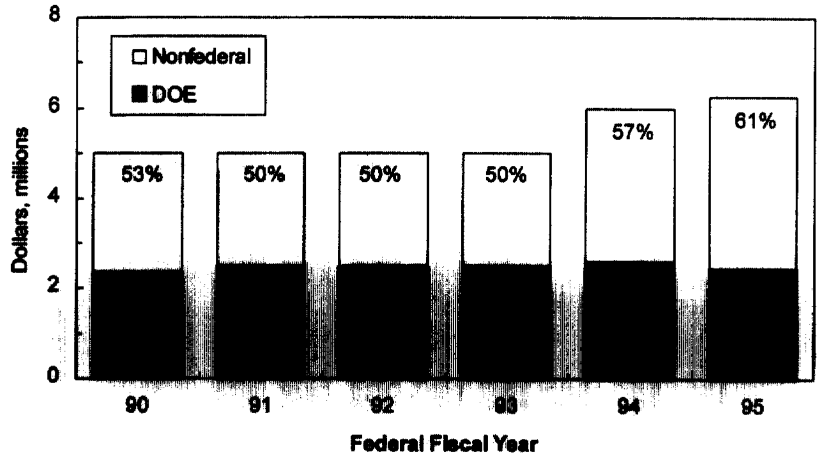

Fig. 23. Jointly Sponsored Research Program—non-federal matching for federal funding.

of promising technologies and works closely with industry to commercialize those technologies. In order to effectively demonstrate and commercialize technologies, EERC personnel have aggressively developed partnerships that involve industry, government, and research organizations.

The personnel at the EERC represent a wide range of expertise and are able to develop multidisciplinary teams tailored to meet client needs. The staff is practically oriented and has extensive experience related to energy and environmental issues. The unique working environment at the EERC provides the entire staff with the freedom and flexibility to pursue a wide range of opportunities in the area of energy and environment. The EERC recognizes and rewards innovations made by the EERC team. The EERC is considered a model for research, development, demonstration, and commercialization partnerships between government, industry, and the applied science and engineering research community.

8. THE ENERGY INSTITUTE

Alan W. Scaroni, Bruce G. Miller and Sarma V. Pisupati
Pennsylvania State University, University Park, PA

8.1. *Introduction*

Penn State has a long history of coal and combustion research. The Combustion Laboratory was formed in 1949 and continues to serve the university and the combustion community as a unit of The Energy Institute (formerly the Energy and Fuels Research Center (EFRC). A second EFRC unit added in 1992 is the National Center of Excellence for Coal Utilization (referred to as the Coal Utilization Center) which focuses on demonstration-scale combustion activities. General characteristics of, and data for the Center are given in Tables 20 and 21, respectively. The purpose of this paper is to highlight selected accomplishments of the Center over the past decade. During this time, almost $30 million of sponsored research has been conducted for dozens of sponsors by hundreds of researchers. The nature of research conducted includes both fundamental and applied. The following provides a flavor of the research and the results obtained.

8.2. *Coal-water Slurry Fuel*

Coal-water slurry fuel (CWSF) research and development have been an integral part of the Center's activities since the early 1980's. The focus has been on establishing acceptable formulation and preparation procedures and obtaining satisfactory combustion performance in fuel oil-designed industrial boilers, and during cofiring with pulverized coal in utility boilers. Fundamental, pilot, and demonstration scale activities have provided detailed understanding of the chemical and physical phenomena involved in CWSF rheology and stability, atomization and combustion, mineral matter transformations, atomizer tip and boiler tube erosion, ash settling and deposition, boiler derating, and emissions. The scale at which research has been conducted in this area ranges from single droplet combustion to tons of CWSF per hour in an industrial boiler.

8.2.1. *Formulation and preparation of coal-water slurry fuel*

CWSF formulation and preparation have progressed from bench-scale (pound quantities) to pilot-scale (tons/h) production levels. Highly loaded and stable CWSFs have been prepared from deeply-cleaned coals for fuel oil substitution in industrial boilers. Low solids CWSFs have been prepared from fines from active cleaning plants and abandoned impoundments to cofire with pulverized coal in utility boilers.[100] Formulation procedures have been documented, and potential problems and solutions in the preparation and handling of CWSF have been identified.[101] (see Table 22). It has been found that oxidation of impounded coal fines had not occurred to an

Table 20. General characteristics of the Energy Institute

Title	The Energy Institute (formerly the Energy and Fuels Research Center)
Location	Pennsylvania State University, University Park, Pennsylvania, U.S.A.
Directors	Alan W. Scaroni, Director Bruce G. Miller, Associate Director, Coal Utilization Center Sarma V. Pisupati, Associate Director, The Combustion Laboratory
Starting date	1949 (Combustion Laboratory) 1992 (Coal Utilization Center)
Mission/objective	To advance the development of fuel utilization technologies
Focus	The environmentally acceptable use of fossil fuels
Research areas	Fuels characterization, conversion and utilization, including fixed-bed, fluidized-bed and pulverized-coal gasification and combustion; gaseous and liquid fuel combustion; environmental aspects of fuel use

extent that affected CWSF formulation, and the same formulation, preparation, and utilization procedures could be used as for fines from active cleaning plants.[100]

8.2.2. *Fundamental studies*

Early studies focused on increasing the combustion rate of CWSFs so that acceptable burnout could be achieved in the available residence time in retrofitted boilers. Oxygen enrichment of combustion air was found to improve the combustion efficiency by increasing the flame temperature and hence the char combustion rate. NO_x emissions increased, however, while SO_2 emissions were relatively unaffected.[102] Secondary atomization of CWSF droplets due to explosive boiling required a heat flux in excess of that associated with conventional boilers, regardless of the additives used in the formulation.[103] Combustion enhancement by imposing a high-intensity acoustic field to generate large and rapidly fluctuating gas velocities (relative to the CWSF droplets) was attributed to increased convective heat and mass transfer rates.[104] Atomization quality, mineral matter size, and occurrence of mineral matter in coal particles affected the resulting ash particle size.[105] An erosion–corrosion

Table 21. Data for the Energy Institute

A. Number of personnel (1996)

Professional	18
Professorial	15
Postdoctoral	5
Graduate students	30
Undergraduate students	4
Staff/management	3
Other	0
TOTAL	75

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	4065
1995	3829
1996	4607

C. Budget sources (%) (1996)

Government	82
Domestic industry	7
University	11
Foreign	0
Income (patents, royalties, licenses, software, etc.)	0
Other	0
TOTAL	100

D. Space and equipment

1. Research space	30 000 sq. ft.
2. Research equipment/instruments/ computers	$12 000 000

E. External participants/sponsors/advisors/members

Government	8
Industry	25
University	10
TOTAL	43

F. Research program (1996)

Number of fundamental projects	10
Number of applied projects	15
Number of proprietary projects	2
TOTAL	27

G. Center research projects/activities

	Minor Major
Experimental data	1 2 3 4 **5**
Computer software	1 **2** 3 4 5
Inventions/patents	1 **2** 3 4 5
Project reports	1 2 3 4 **5**
Journal/book publications	1 2 3 **4** 5
Consulting services	1 2 3 **4** 5
Process/system concepts	1 2 **3** 4 5
Graduating students	1 2 3 **4** 5
Academic courses	1 **2** 3 4 5
Technology transfer	1 2 3 4 **5**

Table 22. Summary of CWSF characteristics for fuel oil substitution, cofiring applications and reburning in cyclone-fired units

	Fuel oil substitution	CWSF prepared for cofiring in utility boilers		Cyclone reburning
		Wall or tangentially-fired	Cyclone-fired	
Historical perspective				
Timeframe	Pre-1990s; limited interest post-1990	Post-1990	Post-1990	Post-1990
Utilization driving force	Reduction in fuel oil consumption and dependency on foreign oil	Elimination of drying wet coal fines, reduced fuel costs, NO_x trimming	NO_x trimming, reduced fuel costs	NO_x reduction
Combustion parameters				
Primary fuel	CWSF	Pulverized coal	Crushed coal	Crushed coal (cyclone furnaces)
Secondary fuel	Fuel oil/natural gas	CWSF	CWSF	CWSF
Boiler (cyclone furnace) bulk gas residence time	Less than a coal-designed boiler (< 1 s)	Adequate for good combustion (1–3 s)	Adequate for good combustion (< 1 s)	Adequate for good combustion (< 1 s)
Atomized CWSF droplet size	Critical because of short residence time ($d_{50} < 80\,\mu m$)	Less stringent than in fuel oil substitution applications	Less stringent than in fuel oil substitution applications	Critical because of short residence time ($d_{50} < 80\,\mu m$)
CWSF injection location	Burner	Burner	Burner end of cyclone furnace	Above cyclones
Ash handling equipment	Usually inadequate, requires extensive modifications depending on the coal mineral matter characteristics	Adequate	Adequate	Adequate
CWSF preparation parameters				
Typical production mode	Single/double-stage grinding circuits required	Fine coal re-entrainment, specially designed mixing circuits	Fine coal re-entrainment, specially designed mixing circuits	Fine coal re-entrainment, specially designed mixing circuits
Solids loading	High for good flame stability (55–70 wt.%)	Lower (50–60 wt.%), flame is stabilized with the primary fuel	Lower (40–60 wt.%), flame is stabilized with the primary fuel	50 wt.%
Additive package	Critical (dispersant, pH modifier and stabilizer used)	Less important, typically prepared without additives	Less important, typically prepared without additives	Less important, typically prepared without additives
Stability requirements	Long term (months)	Short term (days)	Short term (days)	Short term (days)
Apparent viscosity	< 500 cp @ 100/s, pseudoplastic flow behavior	Less critical	Less critical	Less critical
Coal particle size distribution	Broad, $d_{50} < 20\,\mu m$	Typical pulveerized coal grind ($d_{50} \simeq 45\,\mu m$)	60% minus 60 mesh (250 μm) with d_{50} = 50 mesh (297 μm)	70% minus 200 mesh (74 μm)
Coal ash characteristics	< 5 wt.%, high-ash fusion temperatures	Ash content limited by boiler design, typically < 15 wt.%	Less stringent than cyclone specifications which are ash content (6–25 wt.%), composition (S, Fe, Ca), and slag viscosity ($T_{250} < 2600°F$)	Ash content ≃ 10 wt.%
Coal volatile matter content	> 30 wt.% for flame stability	Less stringent than in fuel oil substitution applications	Less stringent than in fuel oil substitution applications	Less stringent than in fuel oil substitution applications

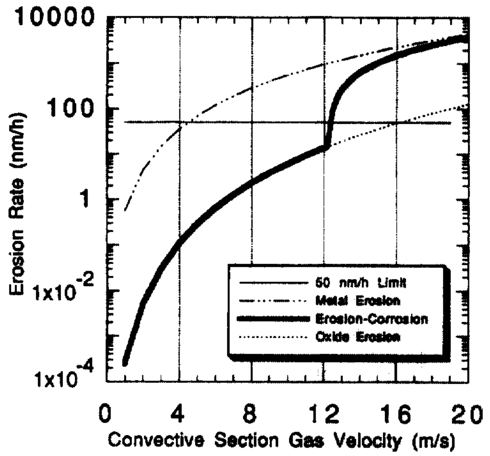

Fig. 24. Erosion rate prediction for CWSF combustion for typical convective section conditions. (particle concentration 2.7 g/m^3, particle size 87m, particle density 1,250 kg/m^3, 30° impaction angle, 50% of the particles colliding, and 600 K metal temperature)

model, based on accelerated erosion tests, indicated that significant boiler tube erosion does not occur if the flue gas velocity in the convective section is below the value required to keep the erosion in the oxide scale regime[106] (see Fig. 24).

8.2.3. *Cofiring CWSF and pulverized coal in utility boilers*

Interest in cofiring CWSF and pulverized coal stems mainly from its potential as a low cost NO_x control technique. CWSFs produced from coal cleaning plant filter cake, and from impounded coal fines, were handled and cofired with pulverized coal in an utility boiler.[100] Cofiring reduced NO_x emissions by as much as 26.5% by the CWSF acting as a reburn fuel.[107] The burner configuration increased the concentration, and changed the spatial distribution, of hydrocarbon radicals within the combustor, with the net effect of reburning to N_2 the NO_x produced in the pulverized coal flames.[107]

8.3. *Micronized Coal*

A fuel oil-designed boiler was modified to fire dry, micronized coal. Major accomplishments, obtained while developing three commercial burners, were: integrating the coal handling and micronizing systems with the burner;[108] obtaining targeted NO_x emissions of <0.6 lb/million Btu while maintaining combustion efficiencies of 98%;[109,110] and designing a compact, easy to retrofit burner with commercially acceptable combustion air pressure drop (< 8″ W.C.).[110]

8.4. *Oxidized Coal and Coal Blends*

Blending of coals is becoming increasingly important from a utility standpoint in order to comply with stringent emission regulations. The sulfur contents of naturally oxidized coals are significantly lower than those of the laboratory-oxidized and fresh coals, due primarily to the oxidation of pyrite in the former.[111] Laboratory-oxidized coals contained primarily ester groups and naturally weathered coals primarily acid functional groups with associated cations.[112] Volatiles for naturally weathered coals were released at a slower rate and over a wider temperature range and were leaner in aliphatic and aromatic hydrocarbons and other combustible gases and richer in oxygenated species.[113] The reactivities of chars from weathered coals and laboratory-oxidized coals were higher than those for the

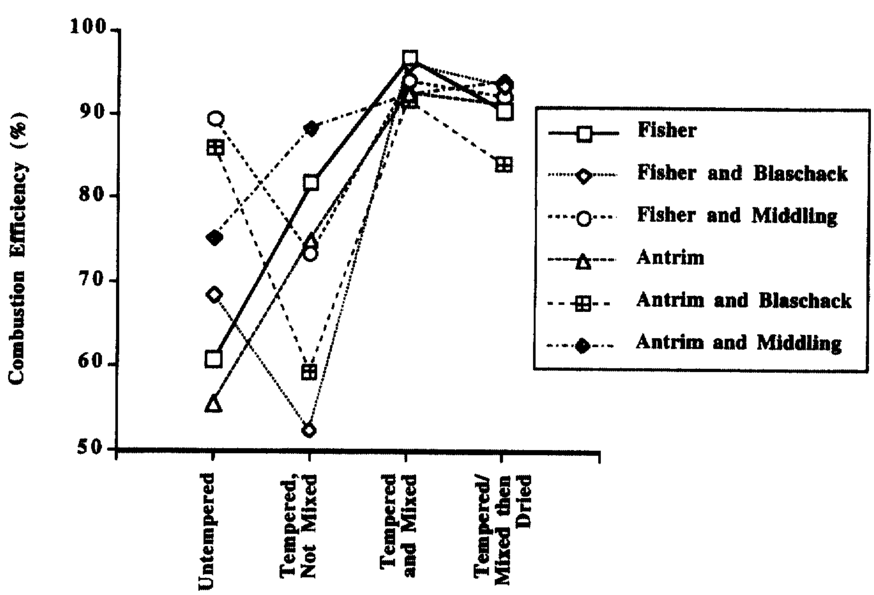

Fig. 25. Combustion efficiency related to the tempering procedure for each of the bituminous coals (Fisher and Antrim) and blends with anthracites (Blaschack and Middling).

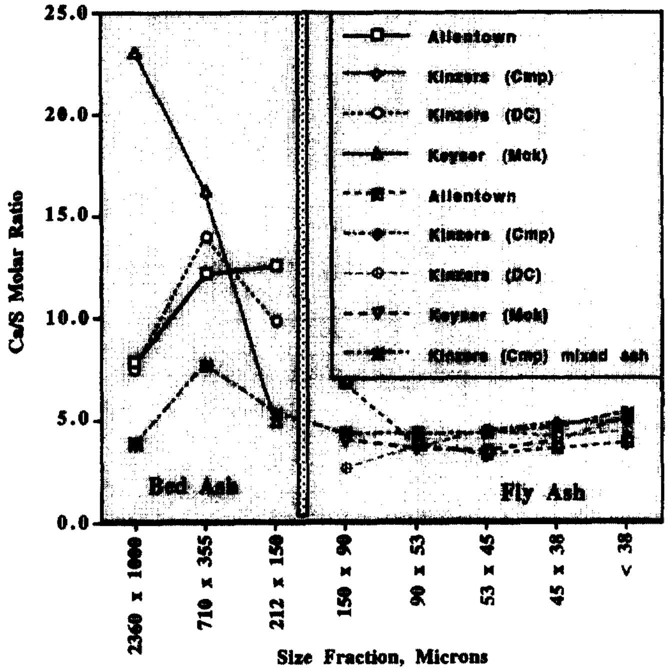

Fig. 26. Calcium to sulfur ratio of fly ash and bed ash samples from a 30 MW FBC power plant as a function of particle size. (Symbols and names in this figure correspond to sorbents whose properties are provided in reference 120.)

chars from the corresponding fresh coals. Relative ignition temperatures were lower and combustion efficiencies higher for weathered coals.[113]

Blends of anthracite and bituminous coals displayed better combustion behavior in a bench scale stoker simulator than the bituminous coals alone, due to reduced caking of the bed and enhanced air flow through the bed. Tempering the bed with water was more effective than manipulating the initial particle size distribution for decreasing the bulk density of the bed and improving combustion performance[114] (see Fig. 25). Reactivities of blends of high and low rank coals in a thermogravimetric analyzer and drop-tube reactor were predictable from the reactivities of the individual coals. The characteristic temperatures (particularly initial temperature) determined from their burning profiles correlated well with the combustion efficiencies obtained in the drop-tube reactor.[115]

8.5. *Fluidized-bed Combustion*

Fluidized-bed combustion (FBC) at both atmospheric and elevated pressures has received considerable attention from utilities and independent power producers because of the ability to remove SO_2 from the flue gas during combustion and to minimize NO_x production. Early work at EFRC concentrated on the influence of fuel properties on combustion performance.[116] Subsequent work on sorbent behavior established that each sorbent has an optimum temperature for sulfation, and that this temperature is residence time dependent.[117,118] At the laboratory scale, higher calcium utilizations were achieved by lower purity limestones due to the effect of impurities on structure development during calcination. The calcination rate dominated the overall reaction rate initially, followed by the sulfation rate once a significant amount of CaO had been generated. The higher the calcination rate, the better is the performance of the limestone.[119]

Sorbents with calcium carbonate contents ranging from 50–99.9% were effective in maintaining emissions compliance in a 30 MW(e) power plant.[118] Finer particle size fractions had lower Ca/S molar ratios than coarser sizes in the bed ash and recycle ash of the power plant[120] (see Fig. 26). For larger particles, the slow rate of SO_2 diffusion through the product layer limited the extent of sulfation. Hot stage scanning electron microscopy and microprobe analysis of the sulfur distribution in the particles produced in a TGA and a laboratory scale FBC reactor indicated that some sorbents developed thermally-induced fractures, while others with comparable $CaCO_3$ contents did not.[117] The TIFs promoted SO_2 diffusion into the particle and, as a consequence, the sulfation behavior of such sorbents was less particle size dependent than was that for the sorbents which did not develop TIFs.[120] Statistical methods were applied to predict sorbent performance in a large scale combustor based on laboratory scale data.[121] TGA and a laboratory scale FBC reactor data have also been compared.[122]

8.6. *Environmental Aspects*

8.6.1. *Sorbent injection*

The calcination behavior of pulverized calcium-based sorbents under high temperature, short residence time conditions was studied for applications involving the

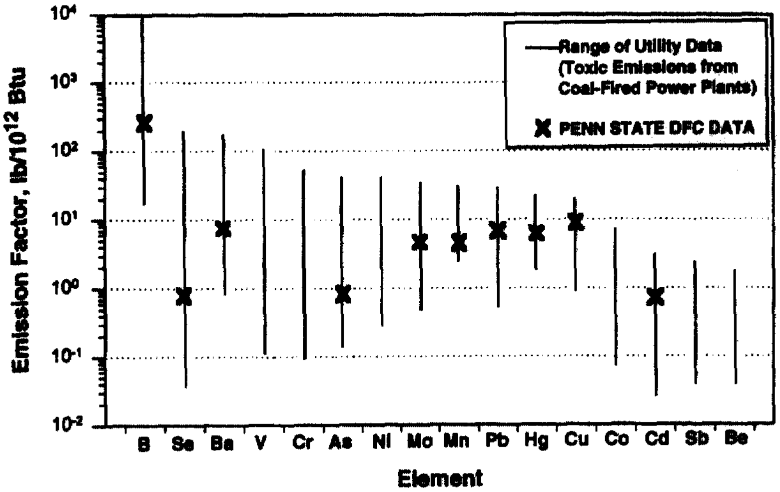

Fig. 27. Preliminary emission factors for Penn. State testing when firing Freeport seam coal in the down-fired combustor.

injection of dry sorbents into furnaces. It was found that under rapid heating conditions, fragmentation behavior was influenced by sorbent type, particle size and temperature. Magnesium carbonate content of a sorbent was found to have a strong influence on the fragmentation behavior.[123,124]

8.6.2. *Modelling of low NO_x burners*

Attempts were made to predict the combustion and emissions (particularly NO_x behavior of micronized coal in a retrofitted industrial boiler (5,300 kW) by the solution of the conservation equations of mass, momentum, and energy along with the appropriate constitutive equations, solved using the commercial CFD code, FLUENT. By modeling the burner in a two-dimensional, axi-symmetric geometry and the boiler in a three-dimensional geometry, and by careful inclusion of the properties of the internal recirculation zone, FLUENT accurately predicted the temperature and flow fields, and particle trajectories for micronized coal combustion in an industrial boiler.[125]

8.6.3. *Low-temperature catalytic reduction of NO_x*

In selective catalytic reduction, the NO_x concentration in the flue gas is reduced by reaction with ammonia in the presence of a catalyst. Tests conducted at the laboratory-scale have revealed that low temperature NO_x reduction of up to 90% is achievable, although selectivity to N_2 is not ideal and the catalyst produces some N_2O.

8.6.4. *Simultaneous SO_2 and NO_x reduction using biomass-based materials*

Biomass-based products are being developed for either co-firing with coal or as a liquid feedstock for combustion. A biomass-based liquid material (Bio-Lime), an emulsion of calcium and oil from the pyrolysis of biomass, has shown very promising results for simultaneous NO_x and SO_2 reduction. This product is introduced downstream of the burner. In a pilot-scale test program 90% SO_2 and 50% NO_x reductions were obtained simultaneously when firing high sulfur coal without combustion modifications for NO_x control. Finely dispersed calcium reacts with SO_2 efficiently, and hydrocarbon radicals from the pyrolysis of the oils reduce NO_x to N_2. Overall CO emissions were reduced by 20–30% compared to firing coal alone. The biomass-based products also reduced overall carbon emission.[126,127]

8.7. *Retrofitting Industrial Boilers*

The viability of future oil-to-coal boiler retrofits has been assessed, starting with determining the status of commercially-available CWSF burners and atomizers in the U.S. as the first step in retrofitting two package, oil-designed boilers at Penn State.[128] This was followed by the conversion of two package boilers, 1,000 and 15,000 lb steam/h, from oil to CWSF and pulverized coal.[108,129,130] The boilers were used to do the following: determine the effect of boiler operating parameters (i.e., atomization quality, fuel particle size, level of combustion air preheat temperature) on combustion performance;[131] automate the firing system, particularly with respect to start up and shutdown procedures but also to optimize boiler performance;[132] evaluate fuels;[133] determine the level of boiler derating ($< 15\%$); determine the maximum ash level (~5 wt.%) tolerable; and determine the ideal coal particle size distribution of about 18 μm (volumetric median diameter).

The system and operating knowledge (e.g., level of combustion air and CWSF temperature, proper flow meters, gauges, and piping geometries, mixer types and tank dimensions, coal silo dimensions, and proper coal transport equipment) gained from the demonstration boiler was used to design the retrofit of an oil-designed boiler located on a military base to fire dry, micronized coal and CWSF.[134]

8.8. *Future Directions*

The Center's current focus is on characterizing emissions from coal-fired boilers and developing strategies to reduce them. Emissions being addressed include SO_2, NO_x, fine particulate matter, trace elements, and volatile organic compounds. Activities include the following: demonstrating commercial, and developing new technologies for reducing SO_2 and NO_x emissions; developing a low-temperature SCR catalyst to operate at conventional baghouse temperature; evaluating simultaneous SO_2 and NO_x reductions using biomass-based materials; evaluating the use of ceramic filters for high-efficiency capture of fine particulate matter; and characterizing trace element (see Figure 27) and volatile organic compound emissions from coal-fired boilers. Studies on gasification of coal at high pressures are also underway.

9. THE HARWELL (AEA) COMBUSTION CENTRE

Philip Stopford, Oxfordshire, U.K.

9.1. *Introduction*

The Harwell Combustion Centre was formally established in 1984 to consolidate the expanding fundamental and applied research on laser diagnostics and computer modelling for combustion studies. Combustion research began in the mid-1970's when techniques originally developed for heat and mass transfer in nuclear plants were adapted for non-nuclear applications. New applications continue to be developed. With a highly qualified staff numbering 15-20 and an annual budget of about $1.5 million (U.S.$ equivalent), the Combustion Centre has contacts in many of the major technological centres through a range of international programmes. Characteristics of the Center are noted in Table 23.

The primary aims of the research are to improve boiler and furnace design and operation and to study the complex transient processes in internal combustion engines. The results are being used by research and development engineers in many branches of industry to improve the economy and emissions performance of their equipment. The Combustion Centre applies advanced diagnostics and mathematical modelling to both physical and chemical aspects of combustion. Advanced theoretical modelling simulates for example, turbulent flow, heat transfer, combustion in stationary and transient flows, and chemical processes such as hydrocarbon oxidation, auto-ignition and pollutant formation.

Staff members at the Combustion Centre have been developing non-intrusive, optically-based techniques for many years. Considerable expertise has been established by applying these techniques to a range of isothermal and combusting flows, and from a variety of other environments. These measurements are carried out using various techniques including laser-doppler anemometry (LDA) to measure velocities of both gas and fuel droplets or particles, laser scattering to measure fuel droplet and particle sizes, laser light sheet illumination (LSI) and particle image velocimetry (PIV) to study complex flow structures and coherent anti-stokes raman spectroscopy (CARS) and Rayleigh scattering to measure gas temperature. In addition, laser-induced fluorescence (LIF) and CARS are used to study species distributions. Other new techniques, such a degenerate four-wave mixing, are under development.

Programmes include individual contracts for third parties, government/industry collaborations and major governmental, national, and international programmes. Recent customers include Mitsui Babcock Energy Ltd., International Combustion Ltd., BP and PowerGen in the UK; and Foster-Wheeler, Southern Company Services (Georgia Power and Alabama Power) and Burns & Roe in the US.

In April 1994, the modeling activities of the Combustion Centre were amalgamated with the consultancy section of Computational Fluid Dynamics Services (CFDS) to form part of the new Process Engineering Software Group at Harwell under Dr. Steven Curl. CFDS is an international vendor of computational fluid dynamics software and software consultancy services. The principal CFD software is CFX 4 which is widely used with currently about 1,200 users throughout the world. Table 24 provides Centre data on personnel, funding, projects, and activities.

Table 23. General characteristics of the HCC

Title:	The Harwell (AEA) Combustion Centre
Location	Harwell Laboratory Building, Didcot, Oxfordshire, U.K.
Director(s)	P. Stopford, Modeling J. Norris, Experiment J. Sykes, Senior Consultant
Starting date	1984
Mission/objective	To develop and apply computer modeling and laser diagnostic techniques to industrial combustion plant
Focus	Boiler and furnace design and operation; in-cylinder internal combustion engines
Research areas	CFD modeling, laser diagnostics

Table 24. Data for the HCC

A. Number of personnel (1996)

Professional	10
Professorial	0
Postdoctoral	0
Graduate students	0
Undergraduate students	0
Staff/management	2
Other	0
TOTAL	12

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	1600
1995	1600
1996	1600

C. Budget sources (%) (1996)

Government	30
Domestic industry	50
University	0
Foreign	20
Income (patents, royalties, licenses, software, etc.)	0
Other	0
TOTAL	100

D. Space and equipment

1. Research space	3000 sq. ft.
2. Research equipment/instruments/ computers	$1 500 000

E. External participants/sponsors/advisors/members

Government	2
Industry	30
University	10
TOTAL	42

F. Research program (1996)

Number of fundamental projects	2
Number of applied projects	10
Number of proprietary projects	15
TOTAL	27

G. Center research projects/activities

	Minor				Major
Experimental data	1	2	3	4	**5**
Computer software	1	2	3	4	**5**
Inventions/patents	**1**	2	3	4	5
Project reports	1	2	3	**4**	5
Journal/book publications	1	**2**	3	4	5
Consulting services	1	2	3	4	**5**
Process/system concepts	1	**2**	3	4	5
Graduating students	**1**	2	3	4	5
Academic courses	1	2	**3**	4	5
Technology transfer	1	2	**3**	4	5

9.2. *Recent Projects*

9.2.1. *Burner Club (CBPE)*

The idea for a club to monitor burner performance and emissions first arose in September of 1989. After several stimulating meetings at Harwell with fuel suppliers, burner manufacturers, plant contractors and end users, and discussions with the Energy Efficiency Office (EEO), the Burner Club was launched successfully a year later. The emphasis was placed on gas-fired and oil-fired boilers and process heaters, because these covered the main interests of the first members, although it was appreciated that the scope could be expanded in the future.

The three year programme of work, outlined initially, was largely completed. One of the main difficulties turned out to be obtaining combustion plant data. The applications submitted by UK companies to Her Majesty's Inspectorate of Pollution (HMIP) for authorisation to operate large combustion plants did not (and still do not) contain the required detail, and so the Club started to commission its own emissions and performance monitoring. Another development, which was not anticipated fully, was the realisation that much work needed to be done on instrumentation, given the wide range of methods, performance and costs of instruments available commercially.

Early in 1994, it was decided to restructure the Club so that it would be easier for small and medium-sized companies to participate and, at the same time, broaden the scope to solid and waste fuels and to other plants. The main objectives are still as follows: (1) provide members with new and important information not obtainable otherwise, (2) expand the technical expertise and knowledge base available to members, and (3) extend the influence of the Club on legislators and industry.

9.2.2. *Heat Transfer and Fluid Flow Service (HTFS)*

HTFS was formed in 1968 to provide industry with leading edge, internationally accepted technology for the design and improvement of heat exchangers and related fluid flow equipment including furnaces and fired heaters. This technology is supported by HTFS's comprehensive research programme and is provided to industry as software, reports and manuals together with support and consultancy. HTFS currently has more than 200 member companies worldwide and annual expenditures approaching $4.5 million (U.S.$ equivalent) per annum.

The Furnaces and Fired Heaters area forms almost 15% of HTFS and is managed by J. Sykes, one of the proposers. The area covers turbulent flow modelling, burner aerodynamics, combustion processes in gas, oil and coal flames, pollutant formation, and radiative and convective heat transfer.

9.2.3. *Harwell Coal Combustion Programme (HCCP)*

Over the last few years, the Harwell Combustion Centre has made many significant advances in the development, demonstration and application of laser instrumentation and mathematical modelling to coal flames increasing in size from laboratory-scale to power station boilers. Two large Programmes on *Measurements and Scaling of Industrial Coal Flames* and *Flame Fluctuations and NOx Formation* funded by the UK Department of Energy were followed by another programme on *Industrial Coal Flames* funded by the Department of Trade and Industry as part of its *Clean Coal Programme*.

Much emphasis was placed on NOx chemistry. A detailed model, consisting of more than 230 reactions among 45 different species, was developed and validated using data from a well-stirred reactor. The detailed model was then used to estimate NO in a coal-fired power station boiler, the ratio of fuel-to-thermal NO being of particular interest. Work continued on developing a reduced scheme, by using equilibrium assumptions and 'lumped reactions' which was suitable for use with flow and combustion modelling codes such as AEA's CFX.

Harwell Combustion Centre is currently modelling test rigs and full-scale furnaces as part of a $4.5 million (U.S.$ equivalent) project to investigate the effects of coal quality on the production of NO_x. The industrial partners in this project are National Power, PowerGen, British Gas, Mitsui Babcock and International Combustion.

9.2.4. *Alabama Power/EPRI boiler modelling*

The consultancy section of CFDS Inc., in collaboration with the Combustion Centre, has recently developed a CFX model of a 500 MW_e, corner-fired furnace jointly for Alabama Power and the Electric Power Research Institute (EPRI) to help evaluate the relative value of various NO_x reduction strategies, such as overfire air and offset secondary air. The work included the modelling of the primary air and pulverised fuel (pf) flow upstream of the coal nozzle to determine the inlet conditions for the main furnace calculation. This work has recently been extended to the construction of a further six furnace models.

9.2.5. *NOEMI*

NOEMI was a collaborative research project between AEA Technology and two French organisations, Bertin and European Gas Turbines (EGT), with part-funding from the European Commission under the JOULE II Programme. The objective was to develop a validated numerical model of combustion and NOx formation in gas turbines used for power generation. With the 'rush' to generate electricity on a large scale from natural gas, the modification of gas turbines, originally designed for aeroplane propulsion, to satisfy emission controls for land-based use is of considerable commercial and environmental importance. The project officially in 1992 and took 30 months to complete at a total cost of about $1.2 million (U.S.$ equivalent). Chemical kinetics modelling was performed by the Modelling and Assessments Department of AEA Consultancy Services and the TECK model of Bertin was incorporated into AEA's three-dimensional computer code CFX 4 and tested for realistic three-dimensional cases by the Combustion Centre.

The objective was to develop and validate a reduced mechanism for HC combustion and NOx formation at high pressure. This formed the basis of a turbulent combustion model (TECK) which is an extension of the 'Eddy Break-up' model, currently used in CFX, to include chemical kinetics. This approach is adaptable to any chemistry scheme, applicable to both premixed and diffusion flames and computationally efficient.

Although NOEMI was focused on gas turbine applications, the new model will be of considerable value in all future work on turbulent combustion, particularly premixed combustion, explosions, fire and soot formation, and in all problems involving reacting flows where chemical processes are important.

9.2.6. *Multi-dimensional diagnostic imaging for combustion (MIDCOM)*

This now successfully completed collaborative project involved the development of experimental techniques for visualising and quantifying the two-dimensional distribution of fuel and its vapour formed by the spray from a diesel injector. Degenerate four-wave mixing was also developed and assessed as a potentially powerful multi-dimensional diagnostic tool, particularly for imaging NO_x in coal burning applications.

9.2.7. *Influence of fuel formation on particulate emission*

The Combustion Centre's contribution to this jointly funded project was to undertake laboratory-scale experimental studies to measure the formation of polycyclic, aromatic hydrocarbons and soot from well characterised test fuels under controlled conditions. Additionally, we developed a chemistry model that predicts the formation of soot and PAHs from the combustion of formulated diesel fuels. These tasks provided complementary data to that gathered by other partners from single and multi-cylinder engines running with the same test fuels.

10. THE INSTITUTE OF PROCESS ENGINEERING AND POWER PLANT TECHNOLOGY (IVD)

Klaus R. G. Hein
University of Stuttgart, Stuttgart, Germany

10.1. *Introduction*

In 1953, there were only limited possibilities to undertake research in the field of power plant technology.

Table 25. General characteristics of the IVD

Title	The Institute of Process Engineering and Power Plant Technology (IVD)
Location	University of Stuttgart, Stuttgart, Germany
Director(s)	Klaus R. G. Hein
Starting date	1953
Mission/objective	● combustion technology (predominantly solid fuels) ● air pollution and air quality control ● mathematical modeling of industrial combustion system and furnaces ● control and automatization of power plants
Focus	Conversion of energy, heat technology and control of conventional (fossil-fuel and renewable-fuel fired) power plants.
Research areas	Combustion technology, air pollution control, power generation and automatic control.

In those days, the decision was made to move the technical university institutes from Stuttgarts' city centre to its suburb of Vaihingen.

The concept of combined heat and power-production was adopted for the power supply of the university campus in Vaihingen. Accordingly, the combined heat and power station (CHP station) of Vaihingen was built in 1958/59. Since then, the head of the institute has also been director of the power station. Many IVD colleagues collaborated in operational and research projects at the CHP station. One of the consequences was that, by 1965, a digital process control computer was installed for the first time to optimize the operation of the power station.

Due to the rapid development of the university campus in Vaihingen, the power plant capacity was tripled within 10 years. The existence of the CHP station provided the possibility to establish many new institutes with equipment of high energy demand. These included the altitude test facility for turbo-aircraft engines, a test facility for turbines, wind tunnels, and combustion chambers.

After 1978, the CHP station was retrofitted and enlarged a second time by adding two gas turbines and a heat recovery boiler. Both had become necessary for

Table 26. Data for the IVD

A. Number of personnel (1996)

Professional	0
Professorial	3–5
Postdoctoral	0
Graduate students	30
Undergraduate students	60
Staff/management	15
Other	0
TOTAL	about 120

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	4500
1995	4700
1996	5000

C. Budget sources (%) (1996)

Government	35
Domestic industry	25
University	5
Foreign	10
Income (patents, royalties, licenses, software, etc.)	0
Other (European community)	25
TOTAL	100

D. Space and equipment

1. Research space	1100 m^2
2. Research equipment/instruments/ computers	$20 000 000

E. External participants/sponsors/advisors/members

Government	0
Industry	0
University	0
TOTAL	63

F. Research program (1996)

Number of fundamental projects	5
Number of applied projects	25
Number of proprietary projects	0
TOTAL	30

G. Center research projects/activities

	Minor Major
Experimental data	1 2 3 4 **5**
Computer software	1 2 3 4 **5**
Inventions/patents	1 **2** 3 4 5
Project reports	1 2 **3** 4 5
Journal/book publications	1 2 **3** 4 5
Consulting services	1 2 **3** 4 5
Process/system concepts	1 2 **3** 4 5
Graduating students	1 2 3 **4** 5
Academic courses	**1** 2 3 4 5
Technology transfer	1 2 **3** **4** 5

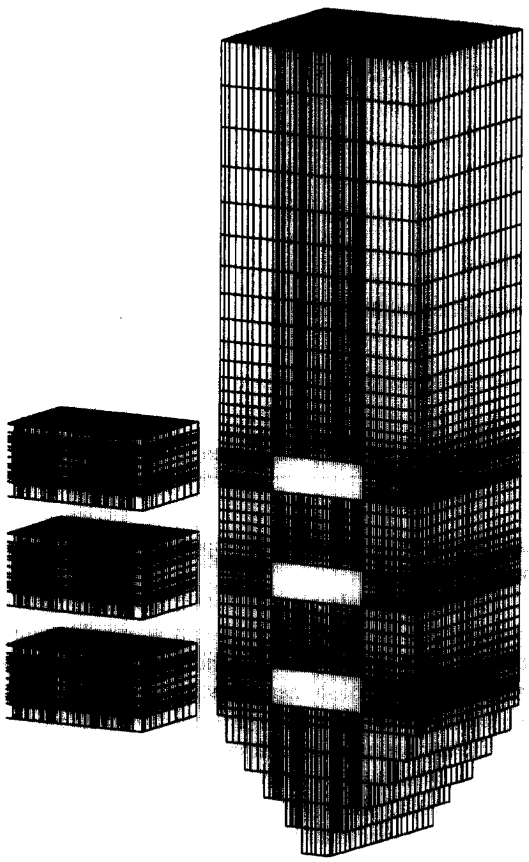

Fig. 28. Numerical grid of a steam generator combustion chamber.

environmental protection reasons and the university's increased energy demand. The renovated CHP station was inaugurated in 1989/90. In 1992, Klaus R.G. Hein took over the direction of the institute and the scientific management of the CHP station. General characteristics of the institute are noted in Table 25, while various data describing the institute are shown in Table 26.

10.2. *Research Program*

Research emphasis includes combustion technology (gas, oil, bituminous coals and lignites, biomass), air pollution and air quality control, mathematical modeling of industrial combustion systems and furnaces, and control and automatization of power plants. The IVD is a member of the Task Group for Air Pollution Control at the University of Stuttgart (ALS) and the Computer Science Union of Stuttgart.

10.2.1. *Major research facilities*

(1) 500 kW_{th} pulverized coal combustion chamber (KSVA) for bituminous coal and lignite/biomass and waste material; (2) 300 kW_{th} cyclone slag-tap furnace for coal comprising a high temperature material testing unit; (3) underfeed wood firing (175 kW_{th}); (4) electrically heated 20 kW_{th} entrained flow combustion chamber; (5) electrically heated entrained-flow pyrolysis reactor; (6) 20 kW_{th} fluidized-bed combustion chamber (stationary); (7) electrically heated pressurized, fluidized-bed reactor; (8) electrically heated, pressurized entrained-flow reactor (20 kW_{th}, 16 bar); (9) two-phase flow test rig; (10) a fully automatic movable measuring station for multi-component air quality investigations; (11) Tether balloon measuring system (O_3, NO_2, hydrocarbons and meteorological parameters); (12) Laser Doppler anemometry: 2 argon-ion laser (15W and 3W); (13) 14 automated data acquisition systems connected to the West European power system.

10.2.2. *Combustion technology*

The Combustion Technology Department is concerned with theoretical investigations of combustion processes in technical firing systems. The main focus is on developing mathematical models for industrial combustion systems. The practical experiments supporting the modelling efforts are carried out by the departments for process engineering and boiler technology, respectively. This guarantees, on the one hand, that the mathematical models can be verified and further developed by comparing them with the measured values, and, on the other, that the experiments are theoretically supported making it considerably easier to carry out the trials.

The mathematical models consider the processes during the combustion of technical fuels (e.g., gas, coal, and biomass (wood, miscanthus, straw)) as the following: (1) turbulent flow and turbulent mixing, both one- and two-phases; (2) the chemical reaction of the fuel and the associated heat release; and (3) the energy transfer from within the flame to the surrounding walls. This includes advanced models of turbulence, chemical reactions (fuel and pollutant components) and radiative heat exchange.

The main field of application is the simulation of industrial utility boilers with a three-dimensional furnace simulation program developed at the IVD. The geometrical dimensions of such furnaces, up to 25 m × 25 m × 90 m, make very great demands on the computational equipment so that methods have to be developed that allow an efficient discretization of the domain. Figure 28 presents a numerical grid of an industrial boiler furnace which was discretized using the technique of domain decomposition. This offers the possibility to attain the grid fineness adequate for various types of furnaces, even though locally limited, and thus to approach these domains by more detailed physical and numerical formulations. Numerical simulations have been performed for several bituminous coal-fired and lignite-fired power plants with different firing systems (tangential, corner, wall firing) and outputs up to 1800 MW_{th}. The example of Figure 29 shows the calculated distribution of the temperature at the bottom and the top burner level and at the furnace outlet of a 252 MW (thermal) CHP station.

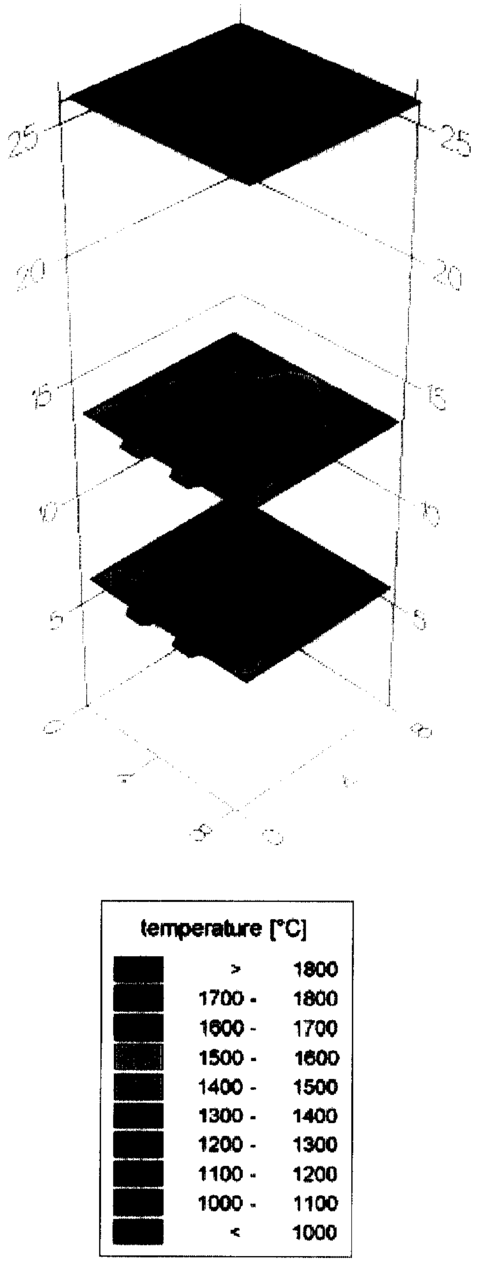

Fig. 29. Calculated temperature distribution.

10.2.3. *Boiler technology*

The Boiler Technology Department centres its research on experimental investigations for the development of environmentally compatible firing and power station systems. For this purpose, several experimental facilities for the use of solid fuels like bituminous coal, lignite, and biomass have been put up in the CHP station as follows: Atmospheric pressure combustion—(1) 20 kW combustion reactor, electrically heated; (2) 0.5 MW pulverized fuel furnace with milling devices; (3) 0.3 MW cyclone slag-tap firing; (4) 20 kW fluidized bed furnace; and (5) entrained flow reactor and fluidized bed pyrolysis reactor. Pressurized combustion—(1) entrained flow reactor ($20kW_{th}$, 16 bar, 1600°C) electrically heated; and (2) fluidized bed (20 kW_{th}, 16 bar), electrically heated.

The different testing facilities allow comparisons of various firing technologies for a specified fuel, thus establishing the most adequate technology. The emphasis of the research activities at the atmospheric pressure facilities is on investigating the burn-out behavior and the performance in service, as well as on developing emission reduction measures. Thus, air-staging and reburning turned out to be effective methods for decreasing NO_x emissions of pulverized coal-fired boilers. The 20 kW experimental facility is used for fundamental investigations of the dependencies on combustion engineering parameters like temperature, resident time, and stoichiometry. In the semi-industrial (0.5 MW_{th}) furnace, the combustion is run under similar conditions as on industrial scale. Here, besides conventional measurement techniques, modern laser measurement methods are used in order to understand the combustion procedures and pollutant formation mechanisms, and to supply data for the validation of mathematical models. The effectiveness of reburning could be proved at a 160 MW_e bituminous coal slag-tap firing within a joint research programme with a power station operator.

The impact of co-combustion of biological residual matter and renewable plants on combustion and emissions is established within the framework of a European research project using various experimental facilities.

Hot gas production by pyrolysis and filtration is being investigated in a small-scale plant. In this procedure, the coal or biomass gets devolatilized in a pyrolysis reactor at temperatures up to 1300°C, and, in a heated downstream filter, the residual char is separated from the pyrolysis gas. This pyrolysis gas is ideally suited for reducing nitrogen oxide emissions in reburning.

An increase in the efficiency of power stations, to reduce CO_2 emissions, can be achieved either by conventional steam processes with raised steam parameters or by combined gas turbine and steam turbine processes. In order to use solid fuels for such processes, they have to be gasified or combusted under pressure. For this reason, the fundamental dependencies are being established using two pressurized reactors, one with entrained flow and the other with fluidized bed. For the investigation of the externally fired gas turbine process with high-temperature heat exchanger, ceramic materials are tested under real conditions in collaboration with Stuttgart's Material Testing Institute.

10.2.4. *Process engineering*

The Process Engineering Department works on the following subjects: (1) advancement of application-oriented measuring techniques in particle-loaded combustion processes, (2) planning and design of fuel-burning systems and their system components, and (3) characteristics of fuels and combustion processes with regard to low-emission combustion. The mixing processes of the gas and particle phase(s) during combustion and pollutant formation are of essential importance. For a better understanding of the combustion processes and phenomena in two-phase flows, basic investigations of the flow are carried out in an isothermal, two-phase test rig. To this end, the flow fields of the particle and gas phases are established by means of the Laser-Doppler Anemometry (LDA). Supplementary investigations with the laser light sheet technique are carried out to visually demonstrate the processes inside a turbulent flow (comparable to a flame). The isothermal test bay is used in particular to investigate the effects that a high particle load and the particle size have on the flow processes. The design dust used for this are spherical glass particles.

Amplified investigations of two-phase effects in a flame are undertaken in the IVD 0.5 MW_{th} pulverized fuel combustion facility. The focus here is on establishing and/or estimating the particle slip velocities. The estimation of the slip velocities can be performed by separately measuring the flow fields of the fluid phase and the momentum behaviour of the coal, char and ash particles. This is done by comparing the flow fields of a pulverized coal flame with that of a corresponding natural gas flame. Both the investigations of the flow behaviour and the two-phase effects help to further develop mathematical turbulence models and flame models. The effects of formation and dissolution of streaks of fuel are also studied by means of the laser light sheet technique.

In collaboration with the Heidelberg University, the institute evaluates the application of the Laser-Induced Fluorescence (LIF) method to establish specific components in the flue gas. The special interest here is the alkali content. With the help of LDA, laser light sheet technique, and other optical measuring techniques (e.g., photography and video observation), investigations are undertaken on ignition and burn-out behaviour of fuel particles. In order to find out the influences of fuel quality, volatile content, and particle size, on the combustion behaviour (e.g., residence time of a particle fraction until ignition), the powdered fuel is fed to a turbulent jet gas flame.

Based on its many years of experience with facilities for the combustion of gaseous, liquid, solid, and pulverized fuels, the IVD prepares conceptual designs of complete utilities and/or system components for a low-pollution combustion of many different kinds of fuel.

10.2.5. *Air pollution and air quality control*

The Department of Air Pollution Prevention puts the main emphasis on source emission and control, as well as on air quality control. This research involves primarily the important fields of measurement technology for exhausts and for ambient air quality. In the field of emission investigations, the focal point which has developed in recent years is the formation and reduction of flue gas emissions in solid fuel combustion—wood and lignite—in small industrial and domestic stoves and furnaces . Taking the combustion principles used in these small-scale furnaces as a starting point, the department also deals with the treatment by incineration of residual material and waste products in recycling processes. A characteristic of the burn-out behaviour in such processes is that the burn out of organic matter is not continuous but happens in batch quantities, a feature which places special demands on the design and on the configuration of the fuel and air supply control. In these combustion processes, the products of incomplete combustion are major emission problems. The combustion of halogenated material adds the special problem of emissions of polychlorinated dioxins and furans. Investigations toward reduction of these compounds are carried out in cooperation with the Institute of Organic Chemistry at the University of Tübingen. In this context, another object of research is small-scale oil and gas firings, where the emissions of the greenhouse gases of CH_4 and N_2O are also investigated.

In the field of air quality, the investigations concern the distribution of air pollution over towns and rural areas. The vertical profiles measured by tethersonde balloons are completed by horizontal profile measurements taken with the remote-controlled airship 'Lotte' of the Institute for Statics and Dynamics of Aerospatial Constructions of the University of Stuttgart. These systems enable mass flows and mass balances of air pollutants to be established, for instance over towns.

The subjects currently dealt with are as follows: (1) emission assessment and control of small, industrial wood-fired furnaces (up to 1 MW thermal capacity) and in waste-wood incineration, (2) reduction of carbon monoxide and organic compound emissions from domestic wood and lignite-fired stoves, particularly fundamental investigations and combustion optimization, (3) emissions investigations on wood combustion in tropical regions of Africa (Nigeria), (4) optimization of the treatment by incineration of noble-metal-containing residual and waste materials and their emission control, (5) experimental determination of emission factors of domestic firings, especially of the greenhouse gases and trace element emissions of small-scale oil and gas firings, (6) on-board measurements on vehicles in motion and on-the-testing-stand (in collaboration with the Institute for Combustion Engines and Automobilism) and air quality investigations in the traffic of towns at home and abroad, (7) vertical distribution and the mass flow balances of air pollutants over towns and rural areas by means of tethersonde balloon and airship measurement systems, e.g. in the Turkish town of Izmir, and (8) long-distance transport of CO_2 and aerosols including measurements at two background measuring stations in the State of Baden-Wuerttemberg.

10.2.6. *Power generation and automatic control*

The department for Power Generation and Automatic Control deals with the application and testing of theoretical methods of the process dynamics and control engineering as well as the process data processing, mainly in the fields of 'instrumentation and control technology for power plants' and 'power system control.'

In the field of instrumentation and control technology for power plants, non-linear dynamic models with limited system order have been developed. In the same manner, real-time dynamic models have been provided and implemented such as for the power plant simulation and training centre of the VGB in Essen. Besides that static process models are the basis for the online balancing and error detection.

Building up on the non-linear dynamic unit models, extensive investigations on the usefulness and economy of spinning reserve power measures concerning the frequency-power control of power units are performed. In addition, an optimal multi-variable unit control has been developed and proved. For example in cases of load disturbances on the electrical network this optimal unit control enables the power plants to activate fast load changes within a wide load range thereby producing only low gradients in temperature, which lead to lower thermal stress in thick-walled pipes. Currently, a model-based real-time furnace control is being implemented. Such complex control algorithms can nowadays easily be implemented by means of digital control systems.

10.3. *Academic Program*

The IVD is responsible for student education in the field of conventional power plant technology at the University of Stuttgart. Over and above power plant technology and its fundamentals, associated topics are widely covered (e.g. energy supply of industrial plants, waste incineration technology, air pollution control, process management technology and network control). The student's project and diploma theses are an essential part of the practically oriented research work undertaken at the IVD. Research results, in turn, are integrated into the contents of the lectures.

11. THE INTERNATIONAL FLAME RESEARCH FOUNDATION

Roman Weber, Willem L. van de Kamp
and Peter A. Roberts
IJmuiden, The Netherlands

11.1. *Mission and Focus*

The International Flame Research Foundation—the IFRF—is a co-operative research and technical services organization, with its Research Station located within the industrial zone of Hoogovens Groep, at IJmuiden in the Netherlands. Its objectives are as follows: (1) to attain knowledge and experience in efficient and clean combustion, (2) to accumulate this knowledge within an international center of excellence, (3) to place this knowledge and experience at the disposal of the IFRF members for further development and industrial application. Table 27 provides a summary of key characteristics, while Table 28 provides data for IFRF.

11.2. *History*

11.2.1. *Establishment of the IFRF*

Convective heat transfer in furnaces was already well understood by the mid-1940's of this century. Methods of calculating radiative properties of non-luminous combustion products containing water vapor and carbon dioxide gradually became available. However, luminous radiation from sooty diffusion flames was hardly understood. The subject was of such importance that the three following establishments: the Royal Netherlands Steelworks Ltd., (Hoogovens—the Netherlands), British Iron

Table 27. General characteristics of IFRF*

Title	The International Flame Research Foundation
Location	IJmuiden, The Netherlands
Director(s)	W. L. van de Kamp, General Manager P. A. Roberts, Commercial Manager R. Weber, Technical Manager
Starting date	1955 (International Flame Research Foundation), before that, from 1948, the International Flame Radiation Association
Mission/objective	To attain knowledge and experience on efficient and clean combustion, to accumulate this knowledge within an international center of excellence; to communicate the knowledge for further development and industrial application
Focus	The combustion of fossil fuels and alternative fuels in a clean and efficient manner with emphasis on industrial implications
Research areas	Semi-industrial scale (2.5–4 MW) combustion of coal, oil, gas, alternative fuels including biomass, plastics, sewage sludges, detailed characterization of fuels, industrial testing and consultancy, combustion modeling (three-dimensional), advanced measurement techniques

* Recently, a book on the IFRF was published: Weber, R., *The Spirit of IJmuiden. Fifty years of the IFRF*: 1948–1998, IJmuiden, May 1998.

Table 28. Data for the IFRF

A. Number of personnel (1996)

Professional	19
Professorial	0
Postdoctoral	0
Graduate students/staff	(7)
Staff/management	3
Other	0
TOTAL	23/(30)

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	4600
1995	4200
1996	4200

C. Budget sources (%) (1996)

Government	27
Domestic industry	10
University	0
Foreign industry	44.5
Income (patents, royalties, licenses, software, etc.)	0.5
Other/members	18
TOTAL	100.0

D. Space and equipment

1. Research space	225 000 sq. ft.
2. Research equipment/instruments/ computers	$5 000 000

E. External participants/sponsors/advisors/members

Government	40
Industry	280
University	40
TOTAL	360

F. Research program (1996)

Number of fundamental projects	10
Number of applied projects	20
Number of proprietary projects	2–3
TOTAL	35

G. Center research projects/activities

	Minor Major
Experimental data	1 2 3 4 **5**
Computer software	1 2 3 **4** 5
Inventions/patents	1 2 **3** 4 5
Project reports	1 2 3 4 **5**
Journal/book publications	1 2 **3** 4 5
Consulting services	1 2 3 4 **5**
Process/system concepts	1 2 **3** 4 **5**
Graduating students	1 2 **3** 4 5
Academic courses	1 2 **3** 4 5
Technology transfer	1 2 3 4 **5**
Technical Services	1 2 3 4 **5**
Modeling calc., 3D	1 2 3 **4** **5**

and Steel Research Association (BISRA-UK), the Institut de Recherches de la Sidérurgie (IRSID-France), formed the International Flame Radiation Association (IFRA) in 1948, for carrying out research on radiation characteristics of large luminous flames used in the steel industry.[135] In 1947, the first trials were carried out in the Hoogovens experimental furnace. After establishing the IFRA, the furnace was dedicated to the international team of researchers, and the first comprehensive trials started in 1949 at the Research Station located in IJmuiden.

11.2.2. *The 1950s and 1960s*

The first publications dealt exclusively with subjects related to the luminous radiation and its role in determining furnace efficiency.[136] This initial period resulted in a number of designs for heat-flux meters, hemi-spherical and narrow-angle radiation pyrometers, and various suction pyrometers for temperature measurements. The Research Station adopted the Schmidt method for measurements of flame emissivity, and soon pioneering work showing variations of flame emissivity with the distance from the oil burner became available. It was established that 'the rise and fall of flame emissivity for an oil flame depend primarily on (a) the character of fuel-jet (droplet size, oil characteristics, initial momentum of the jet and character of the atomizing medium) (b) the rate and course of arrival of heat to, and radiation of heat from, the fuel-jet, (c) the rate and course of mixing of air and burnt gases.'[136]

Soon after the 1949 trials, it was established that the fuel type influenced the flame radiation in that a mixture of pitch and creosote-oil gave a higher radiative flux than fuel oil. This was further investigated in a number of trials by including not only heavier fuels but also lighter oils and coke-oven gas. Finally, the flame emissivity results were correlated with the C/H ratio.[137]

In the mid-fifties it was found that the rate of mixing determines the soot burning rates and, consequently, the flame emissivity. It was discovered[138,139] that one of the most effective ways of influencing mixing is by means of the jet momentum (spray momentum). In nearly all the oil trials up to 1960, the same burner/atomizer arrangement was used which produced a long and narrow flame. This type of flame was investigated thoroughly, theoretically and experimentally, both in models and at full-scale. It has been demonstrated that the mixing length of such a jet flame, if considered as a free jet, could be well described using the equivalent burner diameter concept of Thring and Newby.[140] It was shown that the flame length is inversely proportional to the square root of the jet momentum.

Substantial efforts were allocated to investigations of flames issued from pipe-in-pipe burners possessing a central fuel jet and an annular combustion air stream. The major conclusion was that these double concentric jets can be treated as single axial jets beyond a certain distance downstream the nozzle. The mixing length in such jets can be predicted as a function of the combined mass flows and combined momentum of the two jets.[141]

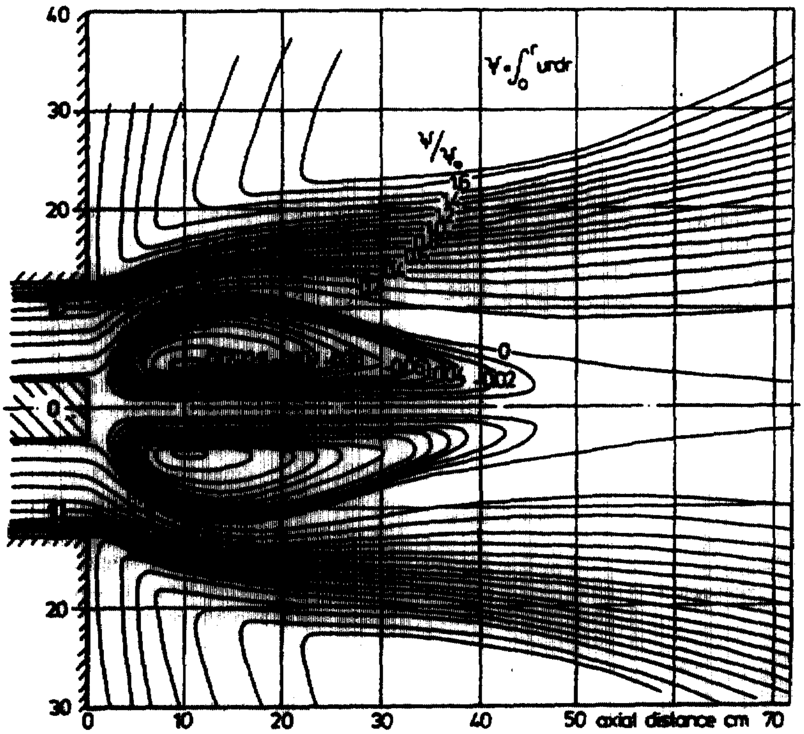

Fig. 30. Streamlines of the flow in the vortex region near the burner exit.[147]

In a series of trials, the effects related to the combustion air velocity, the oil spray angle, and the atomizing oil pressure were established. Stabilizer disks (bluff-bodies) of different sizes have also been tested to examine flame stability. A rotation has been added to the combustion air stream to examine its effect on the mixing.[142]

11.2.3. *The advent of coal combustion research*

In the mid-fifties, a coal-fired furnace was erected at IJmuiden. Five main trials on combustion of pulverized coal were conducted in this furnace from 1956 to 1960. The experience gained already on the pressure-atomized oil flames was relevant to the pulverized coal flames. However, difficulties were encountered in the application of the probe measurement techniques to the coal flames. The first experiments were dedicated to the development of the techniques for velocity, temperature, gas composition and radiation measurements. Double-concentric burners were used without swirl, and the main variables were the primary and secondary air velocities, the primary to secondary air mass flow rates, and the coal type. More stable, shorter, high emissivity flames were observed for bituminous coals and less stable, with longer and low emissivity flames for anthracite. The entrained hot combustion products make an important contribution to the heating of the pulverized fuel and thus to the flame stability.[143]

Throughout the sixties, the furnace trials were supported by theoretical studies. Of particular value were the aerodynamic studies aiming at establishing the laws to enable mixing conditions occurring in hot furnaces to be simulated in cold models. This work was inspired by two outstanding works.[140,144] The furnace measurements were directly related to the theoretical models[145] describing both the jet decay and formation of the momentum-driven (external) recirculation zone formed in the furnace.[146,147] The swirl number was introduced to characterize the degree of rotation and properties of a swirl induced, reverse flow zone formed in the vicinity of the burner, Fig. 30. The swirl number has been widely applied as a measure of the rotation of gaseous streams. The theoretical work on swirling flows resulted in Leuckel's moveable-block swirl generator,[148] a device for an easy generation and control of the inlet swirl in experimental burners. Over a number of years, a system for classification of swirling flames has gradually emerged. Among a number of flame types which were identified, the two distinct flame types, (named type-1 and type-2 flames) were extensively investigated.[149] Over the years, the IFRF has developed a flame classification system shown in Fig. 31. The first twenty years of Foundation work provided the basis for two books published in 1972.[150,151]

11.2.4. *The 1970s and 1980s*

In the seventies, coal combustion research activities emphasized mathematical modeling and pollutant minimization. The mathematical models, which were under development at the Imperial College, brought excitement to the combustion community and hopes were raised as to their predictive capabilities. At IJmuiden, a small theoretical group concentrated on development

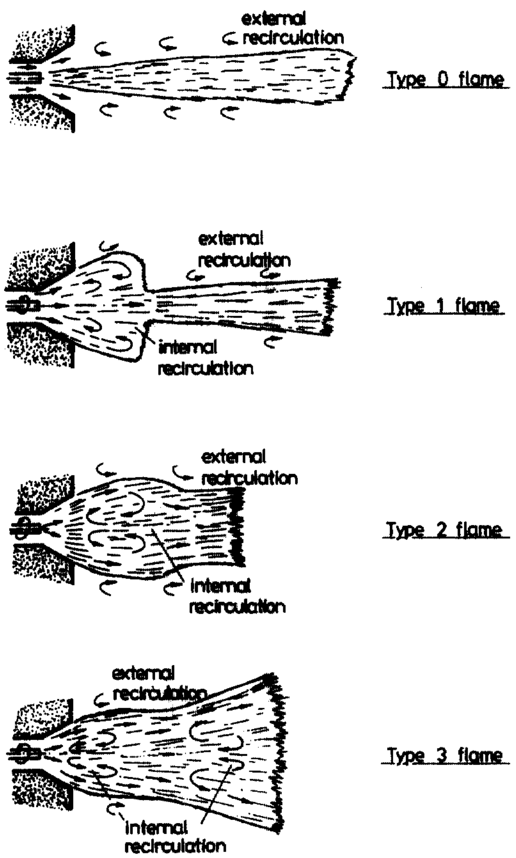

Fig. 31. The IFRF flame classification system.

of flux-methods for computing of radiative heat transfer. The radiation modeling work initiated in the early seventies[152] and completed in 1977,[153] has made a substantial contribution to the development of the flux methods for furnace and flame modeling. The experimental team produced comprehensive, in-flame data on natural gas and oil flames[154] as well as on non-swirling long flames of pulverized coal.[155] The collaboration of the Research Station with the power industry was particularly effective for low-NO_x and low-SO_x combustion of pulverized coal. The first prototype of the Externally Air Staged Low-NO_x Burner, Fig. 32, was tested in IJmuiden.[156] This low-NO_x burner concept was then perfected further in the power industry, and its commercialization took place at the end of the 1970's.[157] Four extra trials were carried out later to establish how to operate the burner for a variety of coals in order to secure low NO_x emissions and high char burnout.[158]

SO_x -emission regulations for coal-fired power plants were under intensive discussion in the mid-1970s. The issue was whether the proposed emission standards could be met by in-furnace sulfur capture (using calcium-based sorbents). In response to the technical demand,[159] the Research Station carried out several furnace trials[160] which led to the development of a new sulfur capture technology. In 1984, the technology was successfully implemented in a 700 MW_e power station boiler in France.[161] Further fundamental studies on calcination and sulfation[162] were carried out in a newly built plug flow reactor. Two trials, carried out in the mid-1980's,[163,164] determined a course of the burner development for the power industry. The trials led to the development of the Aerodynamically Air-Staged Burner, Fig. 33,[165] where the air staging was accomplished by fluid mechanics rather than through the external air ports. The simplicity of the burner allowed for generating both high- and low-NO_x flames by manipulating the coal injector position. Using this simple burner, and parallel mathematical modeling studies, the mechanistic explanation of the NO_x reduction by internal air staging was derived. The explanation utilizes knowledge of coal particle trajectories and their interaction with the swirl-induced, recirculation zone.[166] Further experiments established the effect of coal particle size and the coal injector design on the NO_x emissions of the burner.[167]

In the mid-1980s, fuel-staging or reburning was a relatively new technique for reduction of NO_x. A fundamental investigation[168] was undertaken to quantify the effect of various process parameters on NO_x and Total Volatile Fixed Nitrogen (TVFN). NO_x reduction was best at a reburn zone temperature of 1400°C and a secondary stoichiometry in the range 0.82 to 0.9. Residence times greater than 0.3s at 1400°C were necessary to attain NO_x levels of less than 100 ppm. A furnace trial[169] then gave much higher NO_x emissions than from the fundamental investigation. The Foundation was among the first research establishments which pointed out the mixing limitations of the reburning process.[170] Growing need for coal data yielded six coal characterization experiments carried out in an isothermal entrained flow reactor.[171]

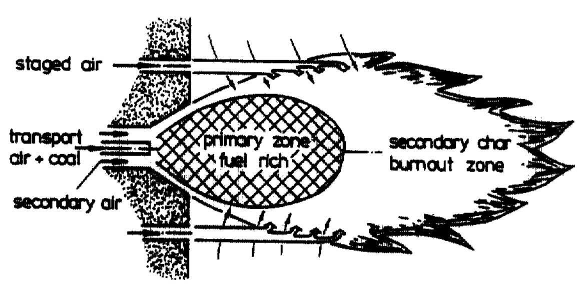

Fig. 32. Externally Air-Staged Burner.

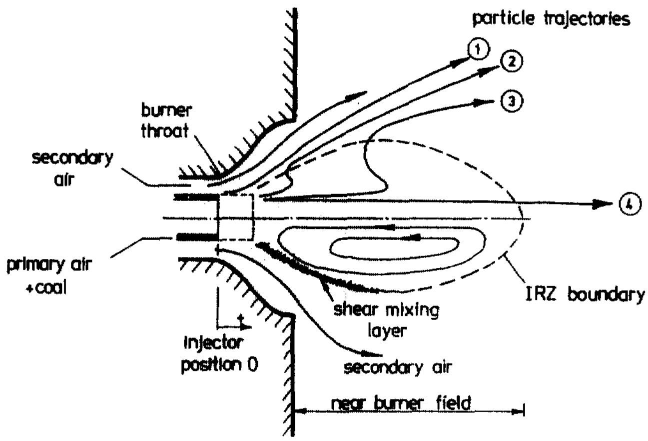

Fig. 33. Particle trajectories in the Aerodynamically Air -Staged Burner.[165]

11.3. *Administrative Structure and Practice*

11.3.1. *The IFRF membership*

The IFRF Membership Network consists mainly of industrial concerns based in power generation, petroleum refining, iron and steel, cement, glass, and chemical manufacturing industries. The membership also includes companies and research organizations active in the fields of fuel production, fuel utilization, and combustion equipment manufacturing. Appropriate departments of many universities are associated to the network as organizations or through independent membership. The basic organization of the IFRF Membership Network is managed through National Committees for Flame Research. The National Committees are based in fourteen countries around the world. In addition to associated groups and individual participants in other countries, the IFRF Membership Network extends through over twenty-one countries situated in Europe, America, Central and East Asia, and Australia. The IFRF is governed by the Joint Committee, consisting of the chairmen of the National Committees, and a number of technical experts nominated by the Joint Committee. The body meets twice a year to review the technical and financial status of the organization.

11.3.2. *Information transfer*

The basic policy on dissemination of the technical information generated at IJmuiden is initially to provide the funding parties and later the IFRF members with the information generated. Transfer of knowledge on technical advances and trials takes place through regular mailing of the research reports and through verbal presentations made at numerous IFRF meetings. Publications in the open literature reflect only a fraction of the research activities. The National Committees organize regular meetings and Flame Days at which progress in technical activities of the Research Station is scrutinized. Furthermore, topic-oriented meetings are frequently organized to allow for technical exchange between the IJmuiden's staff and the members. Both execution and technical planning of major projects are monitored by groups of technical experts nominated by the members. Every three years, the Members' Conference is organized to summarize triennial work and to plan. The Foundation traditionally engages a young, international, scientific and engineering staff. Also the IFRF offers the possibility for young engineers to complete their graduate studies at IJmuiden.

11.4. *Facilities and Equipment*

Experimental research facilities include the following: (1) the single-burner boiler simulator (2 × 2 × 6 m, 2–4 MW_t); (2) the cement kiln flame zone simulator (0.8 m dia. × 10.5 m, 1.5–2.5 MW_t); (3) the basic research simulator (2 × 2 × 4.3 m, 0.5–2 MW_t); (4) the solid fuels characterization isothermal entrained flow reactor (0.15 m dia. × 4 m); (5) isothermal rig for studying flow field and mixing in boilers and furnaces; and (6) the solid fuels preparation plant (6 MW_t coal). A variety of measurement techniques, as follows, are also applied to flame studies: (1) standard IFRF diagnostic probes and combustion gas sampling for measurements of O_2, CO,CO_2, unburned hydrocarbons, SO_2, NO, NO_2, N_2O, HCN and NH_3;[172] (2) solid sampling for measurements of char burnout, concentration of solids, particulates, and soot; (3) suction pyrometers; (4) wall thermocouples; (5) ellipsoidal radiometers; (6) narrow-angle radiometers;[173,174] (7) Laser-Doppler Velocimetry; (8) a special high-temperature gas sampling probes; (9) Laser Flow Visualization Sheet Technique (Mie Scattering);[175] and Phase Doppler Particle Analyzer.[176] The mathematical modeling facilities include work stations and special sub-models for predicting NO_x emissions and char burnout,[177,178] natural gas combustion,[179] coke-oven gas combustion, and the flux and Discrete Transfer Methods for radiative heat transfer.

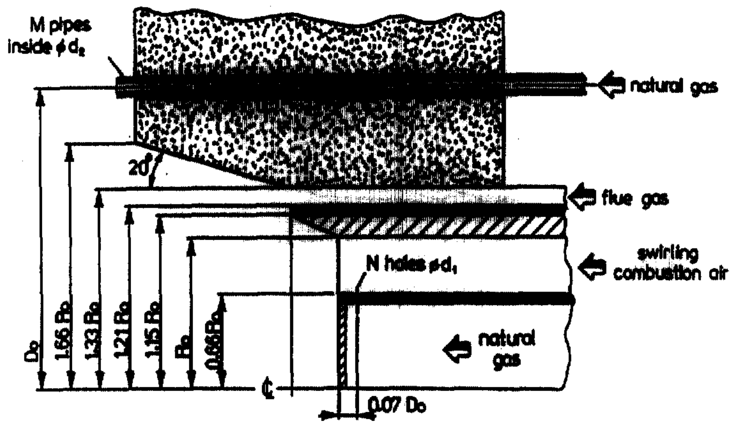

Fig. 34. The Scaling 400 natural gas burner.[181]

11.5. *Research Program and Results*

Laboratory scale and semi-industrial scale experiments play an important role in development of burners and combustion systems. Results obtained on small and semi-industrial scale burners can be extrapolated to the full industrial scale when scaling rules are used to account for the differences in thermal input range. At present, these scaling rules are still not completely understood. A typical scenario that is often encountered is that a low-NO_x burner, when installed in a furnace different to that on which it was originally tested, has produced differing NO_x emissions. This is predominantly due to unforeseen alterations to either in-furnace fluid flow or heat transfer. The IFRF has allocated substantial efforts to derive the required knowledge by carrying out interrelated projects on scaling of natural gas and pulverized coal flames.

11.5.1. *Scaling of natural gas flames*

The Scaling 400 study,[180,181] has spanned the thermal input range from 30 kW to 12 MW. Figure 34 shows a

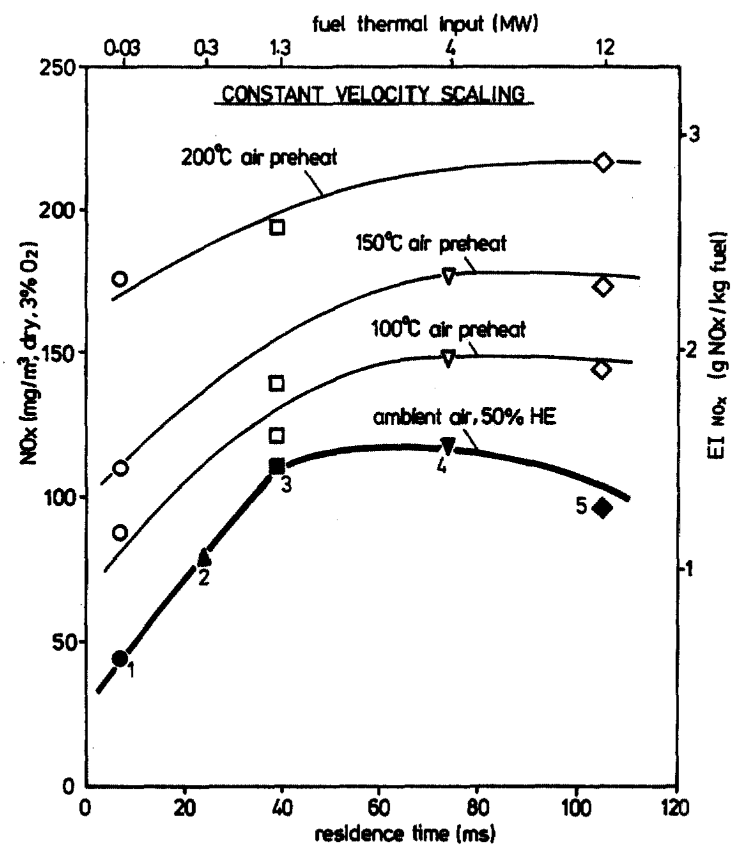

Fig. 35. NO_x emissions of Scaling 400 natural gas flames.[182]

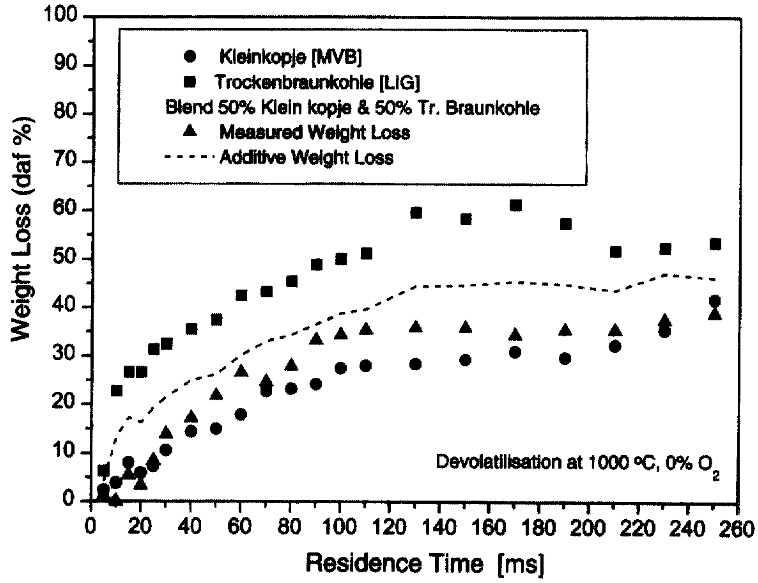

Fig. 36. Devolatilization of two parent coals and their 50/50 blend.[184]

generic, natural gas burner used throughout the project. The 30 kW and 300 kW versions of the burner were used in laboratory-scale experiments while 1.3 MW and 4 MW versions were tested at semi-industrial scale. The industrial scale verification was carried out at 12 MW thermal input. Emission data for nominal (design) load flames are plotted in Fig. 35[182] as a function of thermal input ($Q^{0.5}$ scale is used) and flame residence time (linear scale). The baseline points (marked 1–5) correspond to ambient combustion air temperature and 50% heat extraction. Very low NO_x emissions (below 30 mg/ Nm^3, at 3% O_2) were obtained at the 12 MW industrial test when the natural gas was injected using spuds located on the periphery of the burner. Furthermore, these low emissions do not increase with the air preheat when the staging ratio approaches 100%.

11.5.2. *Scaling of swirl-stabilized pulverized coal flames*

The IFRF has undertaken a comprehensive study on methodology of scaling low-NO_x burners. An aero-dynamically air-staged burner was used in the thermal

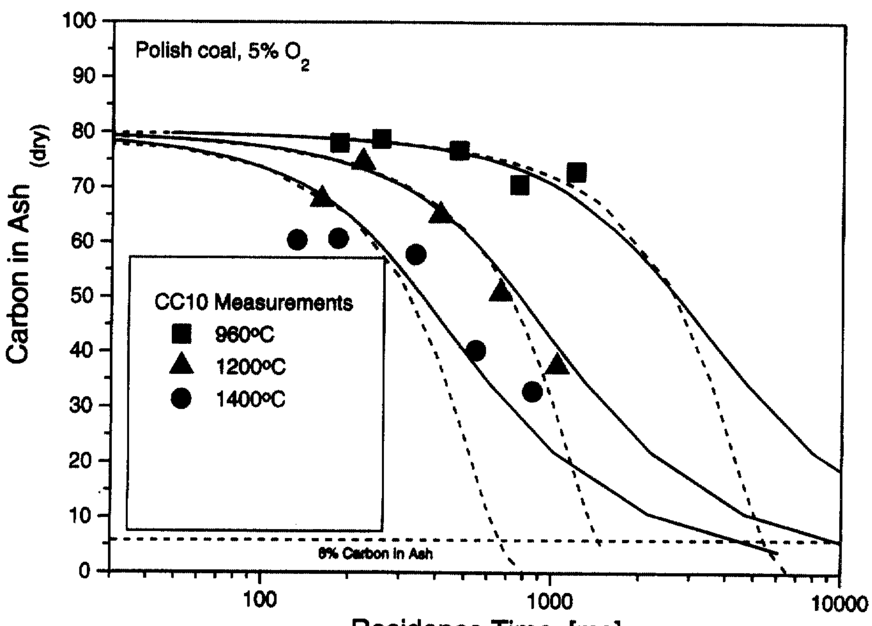

Fig. 37. Char combustion curves. ■ ▲ ● measurements;[184] ——— char burnout model of Ref. 184; – – – char burnout model of Ref. 185.

Table 29. IFRF coal database

Coal	Rank	Coal	Rank	Coal	Rank
ANR	HVB	Great White Tip	LVB	Peak Downs	LVB
Byron Creek	LVB	Heinrich Robert	MVB	Pittsburgh #8	HVB
Coal Valley	HVB	Hem Heath	HVB	Rietspruit	MVB
Daw Mill	HVB	High Vale	UB	Rhein Preussen	HVB
Drayton	HVB	Hugo	HVB	Polish Coal	HVB
Eastside	HVB	Ibbenbüren	ANT	Saskatchewan	LIG
El Cerrejon	HVB	Illawarra	HVB	Scotts Branch	HVB
Elk Creek	HVB	Klein Kopie	MVB	Smoky River	LVB
Esskohle	LVB	Middelburg	MVB	Trockenbraunkohle	LIG
Fettkohle	LVB	Milner	HVB	Fifteen coal blends	—
Göttelborn	HVB	Ontario Hydro	HVB		

LVB, low-volatile blend; MVB, medium-volatile blend; HVB, high-volatile blend.

input range 0.9–12 MW. NO_x emissions vary with the burner size (thermal input) for fixed residence time and velocity scaling. One of the main findings of the scaling program is the importance of the coal particles' penetration distance into the swirl-induced recirculation zone in scaling.[183]

11.5.3. *Coal characterization*

Work here characterizes devolatilization and char burn-out of coals over a range of conditions representative of pulverized coal combustion. These studies provide the rate of devolatilization and the high temperature yield of volatiles, Fig. 36. The char combustion rates, Fig. 37, are determined for a number of temperatures and oxygen concentrations. Under various devolatilization and char combustion conditions, the retention of the original coal nitrogen in the char is measured. This information is relevant for combustion equipment manufacturers and utility users. Low and medium volatile coals showed lower char combustion rates compared to the high volatile coals. At high temperatures, the chars generated from highly volatile coals burn near the bulk diffusion limit. The char combustion of the low and medium volatile coals indicate substantial pore diffusion limitations. Furthermore, the rate of burnout is shown to decrease during combustion, and it is not clear whether changes in pore structure and surface area or coal-related chemical and catalytic effects cause these effects, especially in the last 10% of burnout. These coal characterization (routine) experiments provide coal-specific submodels for devolatilization and char combustion which are incorporated into the IFRF software package for mathematical modeling of coal combustion systems. Table 29 lists the coals incorporated into the IFRF coal data base.[184,185]

11.5.4. *Burners for wall-fired and tangential boilers*

An internally fuel-staged burner (IFSB) concept was recently developed.[186] The NO_x formed in the primary zone is destroyed with the CH_i radicals present in the reburn zone. The primary and reburn fuel injection systems are incorporated within the burner itself. The tertiary burnout air, however, is physically segregated from the primary and the reburn zone and injected downstream in the furnace. The NO_x reduction potential of the IFSB was investigated for a set of reburn fuels consisting of natural gas, coke oven gas, Göttelborn coal, Coal Valley coal and heavy fuel oil.[187] The primary

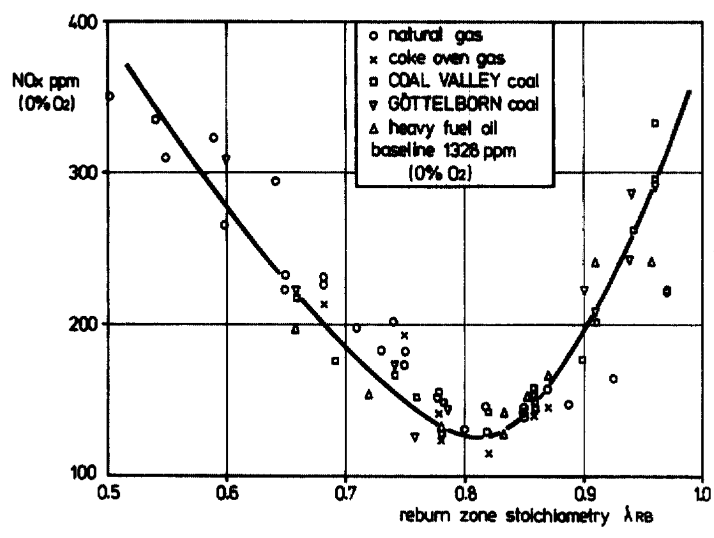

Fig. 38. Effect of reburn-zone stoichiometry on NO_x emissions.[187]

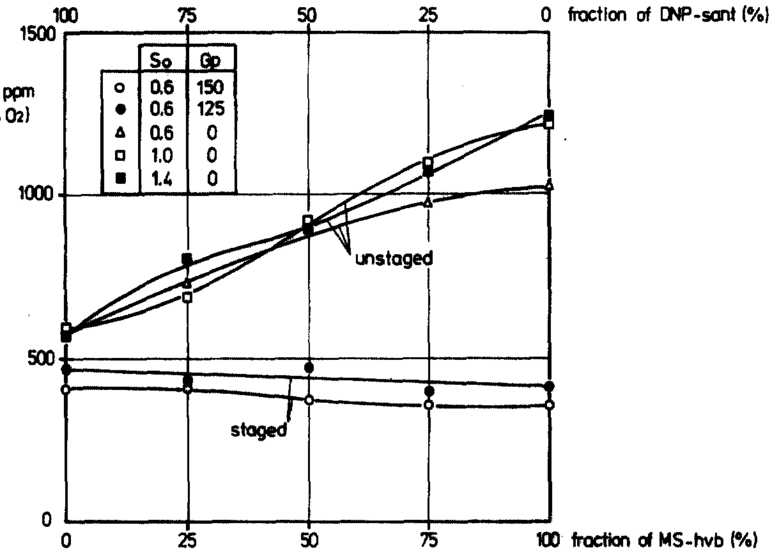

Fig. 39. Effect of blends on NO_x emissions of the AASB.[188] MS-high volatile bituminous coal; DNP-semi anthracite; S_0—swirl number, G_p—coal gun position.

flame was generated by high volatile Göttelborn coal. Injection of the reburn fuel through the swirl induced, internal recirculation zone showed that NO_x emissions can be reduced from 1300 ppm under unoptimized, baseline conditions down to 150 ppm by burner-fuel-staging. These minimum NO_x levels were obtained with reburn fuel fractions between 20 and 30%, with a reburn zone stoichiometry in the range 0.75–0.9. These results were obtained irrespective of reburn fuel type, Fig. 38. A single tangentially-fired boiler (TFB) burner cell was also tested using furnace No. 1. This burner consisted of an aerodynamically air-staged burner equipped with two jet flame coal injectors of variable vane angles and separate ports for tertiary air injection. Results were not as dramatic as those for the wall-fired burners.

11.5.5. *Firing of coal blends*

Single coals are seldom fired in utility boilers. The following are three main criteria for selection of coals for utility boilers: the price, the sulfur content, and the slagging/fouling potential. The effects of coal blends on performance of internally, air-staged burners was examined in a furnace trial.[188] In the first phase, a semi-antracite and a high-volatile bituminous coal were blended and fired. In the second phase, low-volatile and high-volatile bituminous coals were used. Nominal blending ratios were 75/25, 50/50, and 25/75 on a percentage thermal input basis. For unstaged firing, NO_x levels increased linearly with the fraction of high volatile coal, Figure 39. All results were correlated with the volatile nitrogen content of the parent coals and their blends. In the unstaged flame, it was estimated that about 55% of the volatile nitrogen and 15% char nitrogen were converted to NO_x. For the staged flames, NO_x emissions were very similar for all parent coals and blends. Results also indicated that the higher reactivity coal in a blend is preferentially burnt at the expense of the lower reactivity coal.

11.5.6. *Utilization of turbine exhaust gas*

The plausibility of the burner design for combustion of coal with turbine exhaust gases (TEG) has been explored with furnace No. 1 in the aerodynamically air-staged burner. A simulated turbine exhaust gas was used as the main comburent as well as a transport medium for the pulverized coal. With high-volatile coals, a stable combustion was possible for main and transport TEG oxygen levels down to 10%. At low TEG oxygen levels (11–15%), the NO_x emissions were substantially lower (150–400 ppm) than under unoptimized baseline conditions (1000 ppm). Burnout was reduced at lower TEG oxygen levels and was observed to be extremely coal-type dependent.

11.5.7. *Cofiring of pulverized coal with biomass and municipal wastes*

Extensive tests have been conducted on the cofiring of pulverised coal with straw and waste paper. The main parameters affecting the NO_x and SO_x emissions and burnout were the cofiring ratio, coal type, and flame type.[189] The investigation into the cofiring of pulverised coal with municipal sewage sludge has demonstrated that the sewage can be milled and fired successfully as a pulverized fuel, fired unmixed with bituminous coal, or cofired as a blend with pulverized coal in varying proportions. Substantial NO_x emission reductions (ca. 60–80%) were obtained by optimization of the fuel injection mode and by air and fuel-staging. Operational difficulties such as slagging and fouling may result from the high ash content of the sewage.

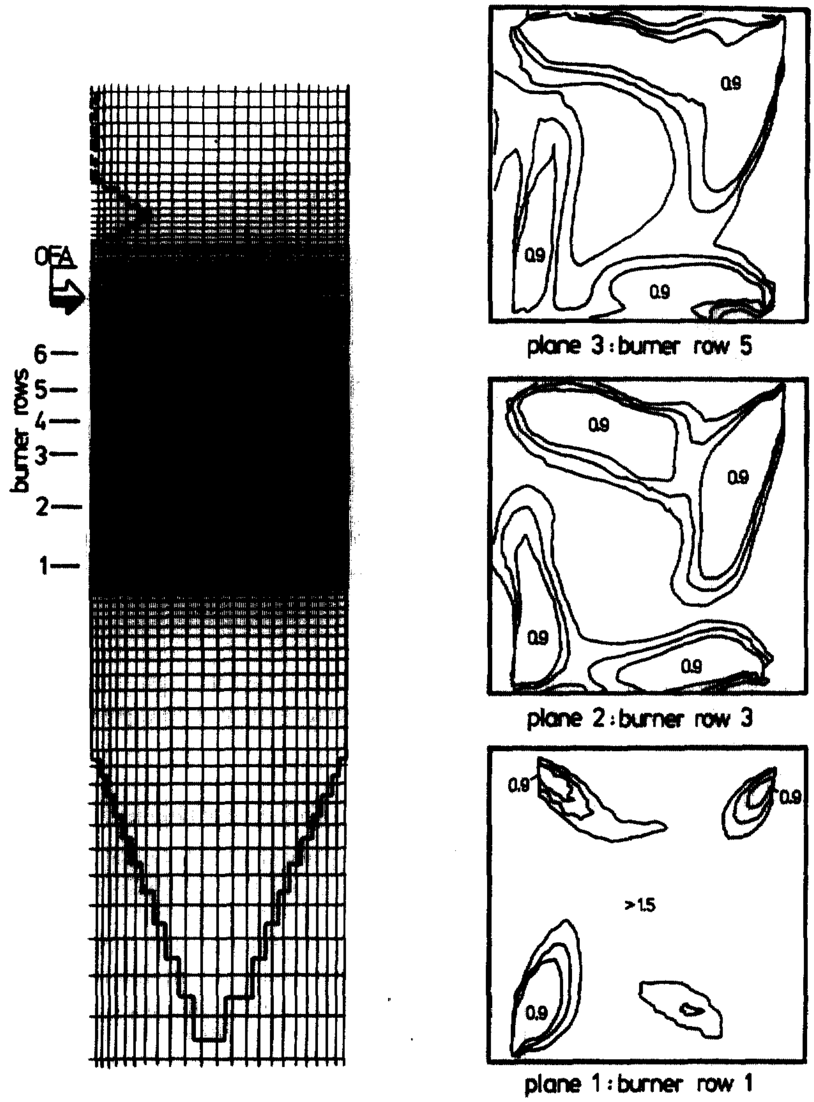

Fig. 40. Predictions of the local stoichiometry variation in a tangentially fired boiler.[194] The boiler is equipped with PM burners of Mitshubishi Heavy Industries Ltd.

11.5.8. *Cement kiln work*

The IFRF has been conducting experimental research programmes for a consortium—CemFlame—of cement manufacturing companies.[190] The objectives were to improve the understanding of cement kiln flames, and to determine the effect of burner design on thermal efficiency and NO_x formation. In this programme, strong effects of particle size distribution and/or volatile matter content on the NO_x emission level were observed. An engineering guideline was derived which correlated the NO_x emission level with flame ignition distance.

11.5.9. *Work for the iron and steel industry*

The IFRF has co-operated over the years with Hoogovens Groep B.V. in research related to the reduction/eradication of coke utilization in iron-making. The first major trials at IJmuiden in this area concerned pulverized coal injection in blast furnaces.[191] A blast furnace coal injection system simulator was set-up at the IFRF, and several coals were fired and the rates of combustion compared. Results assisted in selection of coals preceding the successful installation of a coal injection system. IFRF also conducted a number of pilot scale tests on direct reduction of iron ore in a cyclone converter furnace.[192] The IFRF also carried out trials for Hoogovens on a palletizing plant burner to improve the modeling of flames produced from natural gas and coke-oven gas as fired in iron and steelworks burners.[193]

11.5.10 *Natural gas firing for glass-melting furnaces*

Glass-melting furnaces produce high levels of thermal NO_x, typically in the range 900 to 2800 ppm (at 3% O_2).

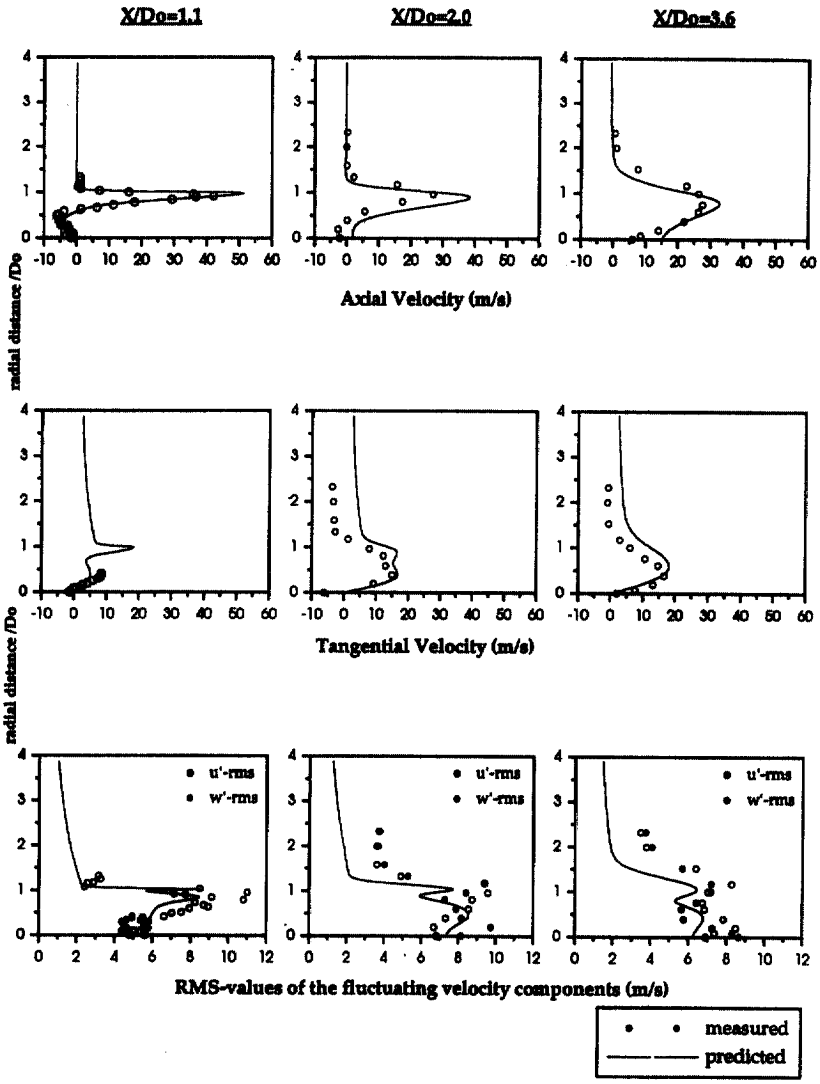

Fig. 41. Measured and predicted flow-filed of a 12 MW flame of pulverized coal. x—distance from the furnace front wall; D_0—burner outlet quarl diameter.

Tests were conducted in a semi-industrial scale glass tank simulator fired at 0.5 MW thermal input with combustion air preheated to 1100°C. The basic strategy for NO_x reduction was optimization of mixing between the natural gas jet and the combustion air stream. Over the whole range of conditions investigated, NO_x levels varied from 200 and 2500 ppm (0% O_2), depending on the mixing conditions. Corresponding fuel efficiencies were in the range 0.51 to 0.57.

11.5.11. *Mathematical models for simulation of combustion systems*

IFRF has developed and applied various mathematical models for predicting performance of combustion systems. The mathematical models are frequently applied in scaling of the semi-industrial results to full industrial applications. These in-flame measured data have been collected in small-scale (up to 300 kW) flames as well as industrial flames up to 12 MW thermal input. Figure 40 shows predictions of a tangentially-fired, pulverized coal boiler, in which the over-fired air is able to minimize the emissions of carbon monoxide.[194]

Figure 41 shows an example of single flame predictions for a 12 MW flame compared with the measured in-flame data. Relatively accurate predictions can be achieved with respect to temperature, gas species and velocities of the 'standard' high-NO_x flames. For such flames, the developed NO_x post-processor[178] performs adequately. However, predicting properties of staged, low-NO_x flames is more complex. Due to fluid mechanics of the near-burner zone and increased importance of the NO_x reburning chemistry.

11.6. *Future Directions*

The combustion systems of the future will be more complex with a multiplicity of fuel types and injection points. Comburent preparation and injection location may also be similarly complex. This, more accurate three-dimensional modeling of the total combustion chamber will become more and more essential, with improvement of phenomenological understanding of the processes and the continued generation of model validation data.

The required knowledge base must cover natural gas, steel plant gases and refinery gases, oils and slurries, biomass fuels, and coal blends. The comburents should include air, enriched air, oxygen, and furnace/engine exhaust gases of low oxygen concentration. Specifics on equipment design for combustion of particular fuels and their combinations (co-firing and blending) should be established together with characteristics of emissions and heat transfer. Nitrogen oxides, sulfur oxides, carbon monoxide, and unburned hydrocarbons will remain principal gaseous pollutants, while particulates and soot principal solid pollutants. The appropriate knowledge on emissions of air toxins, PAH and heavy metals is required. Appropriate fundamental and semi-industrial scale experiments are to be planned with an involvement of academia, industry, and the IFRF. Engineering procedures for designing flames must encompass fluid mechanics, heat transfer, and pollution characteristics applicable to a wide thermal input range. The Research Station will continue development of fuel-specific software for flame and total combustion chamber predictions. The policy of rigorous validation of the predictions against in-flame data of industrial flames must be maintained. The Members are to be provided with both software and the in-flame data. The IFRF coal data base should be continuously updated and enlarged with data on blends.

Acknowledgments — The original basis of the Foundation's funding was the iron and steel industry, specifically IRSID, BISRA, and KNHS, the European Coal, Steel Community (ECSC). The IFRF cooperates with the Environmental Protection Agency (USA) (EPA), Netherlands Ministries of Economic Affairs (EZ), Environment Protection (VOMIL), Netherlands Energy Development Corporation (NEOM), Canadian Natural Resources (CANMET), International Energy Agency, BMBT, NOVEM, The British Department of Trade and Industry, Gas Research Institute (USA), John Zink Company, British Gas, the University of Michigan, Energy and Environmental Research Corporation (EERC), the Sandia National Laboratories, the European Commission DG XII (EC), Gaz de France, Nederlandse Gasunie, Osaka Gas, SNAM, Tokyo Gas, Blue Circle Industries, Castle Cement, ENCI/CBR, Ciments Francais, FCT, Fincem, Heracles, Holderbank, Italcementi, KHD, Lafarge Coppee Researches, Pillard Feuerungen, Unicem, VDZ, AGA, Air Liquide, Hoogovens, Groep, Linde, and Nippon Sanso. The work summarized has been undertaken over a period approaching 50 years by a large number of investigators, many of whom may not be named in this section, or its references. Furthermore, their efforts would not have been possible without the work of an even larger number of support staff. The authors would like to thank their colleagues past and present for providing them with such a body of work to describe.

12. THE LIEKKI COMBUSTION AND GASIFICATION RESEARCH PROGRAM

Mikko Hupa and Jukka Matinlinna
Åbo Akademi University, Turku, Finland

12.1. *Introduction*

The objective of the Combustion and Gasification Research Program LIEKKI is to develop environmentally sound energy production techniques that are based

Table 30. General characteristics of the LIEKKI program

Title	The LIEKKI Combustion and Gasification Research Program (cordinated by the Åbo Akademi University, Turku, Finland)
Location	Åbo Akademi University, Combustion Chemistry Research Group, Turku, Finland
Director(s)	Mikko Hupa, Director, Professor
Starting date	1988
Mission/objective	Support of the equipment manufacturers and power plant operators in Finland in their development efforts for environmentally sound and more efficient energy production technology that is based on combustion or gasification. To maintain and develop long-term competence of the research groups in the universities and national laboratories in Finland in the area of combustion and gasification.
Focus	Combustion/gasification and emission formation/destruction related research relevant to ● fluidized-bed combustion; ● pressurized fluidized-bed combustion; ● pressurized fluidized-bed gasification; ● black liquor combustion; ● diesel-engine-based power plants; ● co-firing of refuse-derived fuels with conventional fuels.
Research areas	● modeling of the furnace processes; ● the chemistry of gaseous emission components; ● ash, aerosols and the behavior of particles; ● new combustion and gasification technologies; ● black liquor; ● conventional combustion technology and wastes.

Table 31. Data for the LIEKKE program

A. Number of personnel (1996)
(graduate students are those preparing their licentiate or doctoral, and undergraduate students are those preparing masters' theses)

Professional	16
Professorial	70
Postdoctoral	10
Graduate students	37
Undergraduate students	15
Staff/management	10
Other (visiting participants)	0
TOTAL	158

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	11 600
1995	13 150
1996	7410

C. Budget sources (%) (1996)

Government	39
Domestic industry	53
University	7
Foreign	1
Income (patents, royalties, licenses, software, etc.)	0
Other	0
TOTAL	100

D. Space and equipment

Activities in a number fof laboratories, detailed information not available

E. External participants/sponsors/advisors/members

Government	2
Industry	11
University	6
TOTAL	19

F. Research program (1996)

Number of fundamental projects	25
Number of applied projects	14
Number of proprietary projects	18
TOTAL	57

G. Center research projects/activities

	Minor Major
Experimental data	1 2 3 4 **5**
Computer software	1 2 **3** 4 5
Inventions/patents	1 **2** 3 4 5
Project reports	1 2 **3** 4 5
Journal/book publications	1 2 3 **4** 5
Consulting services	1 2 **3** 4 5
Process/system concepts	1 **2** 3 4 5
Graduating students	1 2 3 **4** 5
Academic courses	1 **2** 3 4 5
Technology transfer	1 2 3 **4** 5

on combustion and/or gasification. The research supports equipment manufacturers in Finland as they develop and improve their top export products, such as the fluidized bed boilers, black liquor recovery boilers, and heavy diesel power plants. The research is also heavily focused on new technologies not yet on the market, these with higher efficiency of electricity production and, simultaneously, significantly simpler emission control systems. The most important concepts here include combustors or gasifiers based on fluidized bed technology at elevated pressures. In 1996, the LIEKKI program includes 57 research projects and it connects some 150 scientists and research engineers in the universities and research centers of Finland. The overall annual budget of the program has been around 10 million U.S.$, co-funded by the industry and the government agency TEKES (Technology Development Centre) in Finland. The program is coordinated by Åbo Akademi University in Turku, Finland.

The Combustion Research Program LIEKKI was initiated by the Finnish Ministry of Trade and Industry in 1987. This five-year program (1987–1992) included altogether 91 projects, whose total costs amounted to 25 million U.S.$. The program received excellent recognition both from evaluations made by the companies involved and also by an international evaluation team. Consequently, the program was continued with a second phase (1993–1998). This second phase has a somewhat broader focus than the first phase, as research related to gasification processes was included in the program. Altogether, 90 projects have been completed in the second phase, and at present the program includes 49 projects under way. Tables 30 and 31 provide a summary of LIEKKI characteristics and data. This section gives a short overview of the LIEKKI activities, the main focus being in the second phase of the program.

12.2. *Objectives*

The objectives of the research in the LIEKKI program are to enhance and support the development of energy conversion technology based on combustion and/or

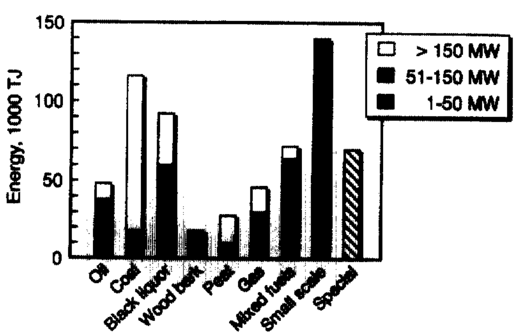

Fig. 42. Fuel use in different types of boilers in Finland.

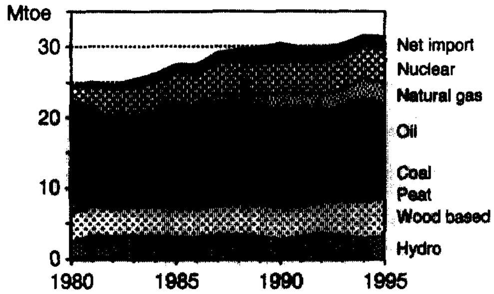

Fig. 43. Primary energy production in Finland.

gasification in Finland. Finland has much experience toward the suitability of different combustion techniques and fuels both at industrial and municipal boilers (see Figs 42 and 43). Exports of combustion technology products from Finland presently total close to 1 billion U.S.$. In the following, the applications of combustion and gasification which are of interest in the LIEKKI research activities are briefly discussed. The three first items refer to existing products, the next two to products under development.

12.2.1. *Applications for existing products*

Fluidized-bed boilers (FBC), especially the circulating, fluidized-bed (CFBC) systems are major export products. There are more than 200 CFBC units in operation, with a total power exceeding 20,000 MW_e (see Figure 44). More than half of these boilers are designed in Finland. Present development of the FBC is focused on improvement of the in-furnace emission control, on the use of various low-grade and waste-derived fuels, and on simplifying the overall design of the furnace and cyclone.

Black liquor recovery boiler (BLRB) is another important Finnish products. Black liquor is the most important by-product in the pulp manufacturing process. It contains roughly half of the wood raw material (lignin) and the pulp cooking chemicals (sodium and sulfur). In a BLRB, both the energy and the chemicals are recovered in an advanced furnace process. In Finland, black liquor is also an important factor in the overall energy mix (see Figure 42). Present development needs are related to

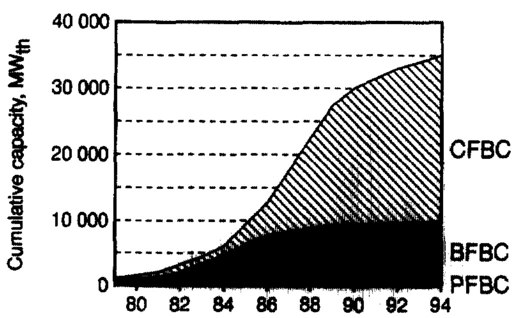

Fig. 44. Cumulative capacity of fluidized bed boilers worldwide.

further emission control and to the behavior of foreign, non-process elements, such as chlorine and potassium, in the BLRB process.

Diesel power plants of the total power of more than 1000 MW_e were exported from Finland in the year 1995 alone. The development of these heavy engines has been extremely rapid during the latest years, and the main focus has been in optimizing the combustion process for minimum NO_x emissions and maximum power output. Also, the suitability of various heavy fuel oil grades has been the subject at several research projects.

12.2.2. *Support of new product development*

Pressurized fluidized bed combustors (PFBC) for solid fuels in simple, combined-cycle power plants are being developed in many countries, and the first full-scale units have been introduced on the market (see Fig. 44). In Finland, pressurized combustion in a circulating fluidized bed has been the main concept, and many research projects in the LIEKKI program have dealt with details of this technology. Sulfur capture under pressure, fuel nitrogen behavior, ceramic filters, and alkali vaporization, are the focus of this research.

Pressurized, fluidized-bed gasifier (PFBG) of some sort is believed to be an essential part of future, combined-cycle processes. Both the concept based on complete gasification in one step and the concept of partial gasification followed by a separate combustor for the char residue have been of interest in the LIEKKI program. The research has included studies on fuel nitrogen conversion, tar formation, ash behavior, sulfur capture, and alkali metal vaporization under pressurized gasification conditions. Besides the applications mentioned above, the LIEKKI research has also included retrofit emission control in existing conventional power plants, and also studies on co-firing of various refuse-derived fuels (RDF), together with 'conventional' fuels in existing boilers.

12.3. *Research Areas*

The LIEKKI program has been divided into six research activity areas. The activities include both applied projects by participating companies, and more fundamental, long-term research by the university groups and the national laboratories. The participating organizations are listed in Fig. 45.

12.3.1. *Modeling of combustion, burners and furnaces*

A very essential tool in the development work of combustion processes is mathematical modeling to describe the combustion conditions and to calculate such quantities as the gas flow, temperature distribution, gas species concentrations, and heat flows. Such models are in actual use at many manufacturing companies, but there are still major development needs. At present, LIEKKI research includes 11 research projects improving the modeling tools for especially fluidized bed

• Ahlstrom Corporation	• Åbo Akademi University
• Borealis Polymers Oy	• Helsinki University of Technology
• Enso-Gutzeit Oy	• Tampere University of Technology
• Enviropower Inc.	• University of Jyväskylä
• Foster Wheeler Energia Oy	• University of Kuopio
• IVO Group Oy	• University of Oulu
• Kvaerner Pulping Oy	• VTT Chemical Technology
• Neste Corporation	• VTT Energy
• Wartsila Diesel NSD Corp.	
• Technology Development Center (Tekes)	

Fig. 45. Participating organizations in LIEKKI.

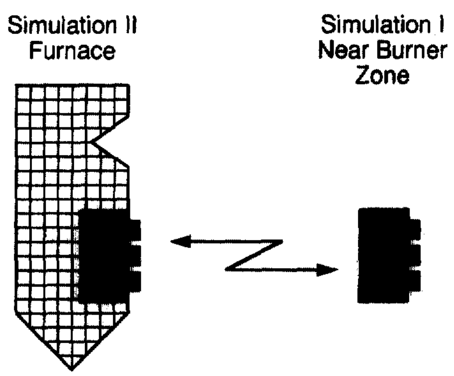

Fig. 46. Multidomain simulation of large pf-coal fired furnaces (LIEKKI-projects L2-Y01 and L2-Y36).

combustors, but also for large pulverized-fuel furnaces. Figure 46 shows the municipal grid of a comprehensive three dimensional model for large, multi-burner furnaces, using the so-called multi-domain technique. This model treats the burners separately and then combines them in an overall furnace calculation, thus allowing for detailed calculations in the near-field area of the burner, where most of the combustion and, in particular, most of the NO_x chemistry takes place.

12.3.2. *Chemistry of gaseous emission components*

Modern combustion technology controls the formation of pollutants within the furnace. The LIEKKI program strongly focuses on better understanding of the emission formation and destruction chemistry under various conditions. At present, 9 projects are under way. A special focus here is to study the influence of pressure on the mechanisms that cause emissions. Figure 47 shows a schematic of the most important reaction routes along which the fuel-bound nitrogen in coal is gradually converted to nitrogen oxides in a fluidized bed combustor. This scheme is a result of a great number of studies using data from laboratory-scale and full-scale FBC combustors and advanced chemical kinetic modeling. The figure shows, besides the nitric oxide, the main routes to nitrous oxide N_2O. Nitrous oxide

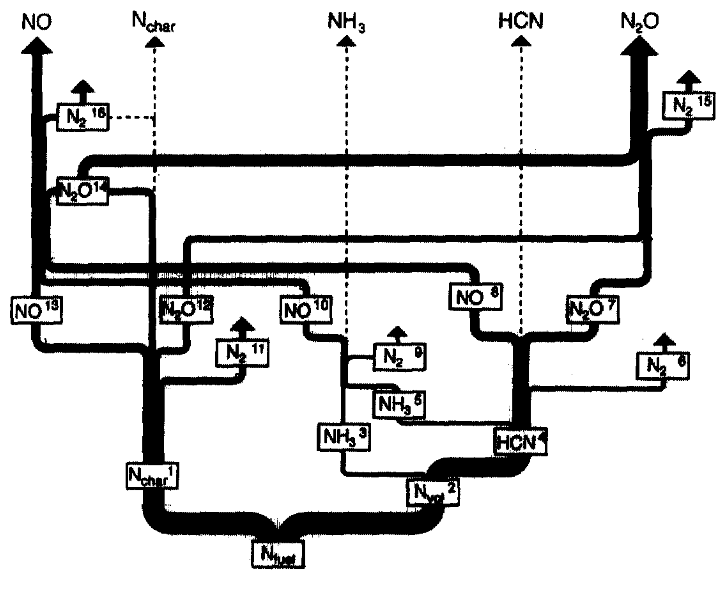

Fig. 47. Fuel nitrogen conversion to nitrogen oxides in a FBC burning coal (LIEKKI-project L2-207).

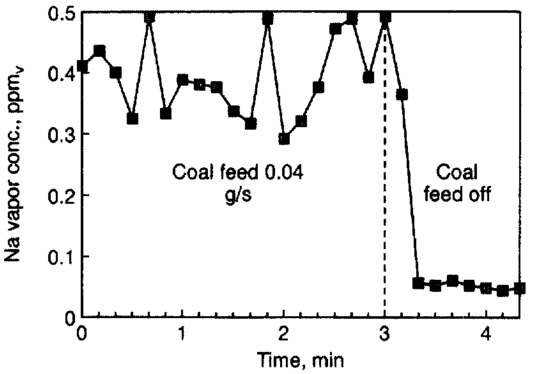

Fig. 48. Concentration of vaporized sodium during combustion of coal particles in an entrained flow reactor at a pressure of 10 bar. Oxygen concentration 20 %, gas temperature 800°C, particle size ca. 100 micrometer, measured average particle temperature 1310°C (LIEKKI-project L2-312 and LIEKKI-project L2-310).

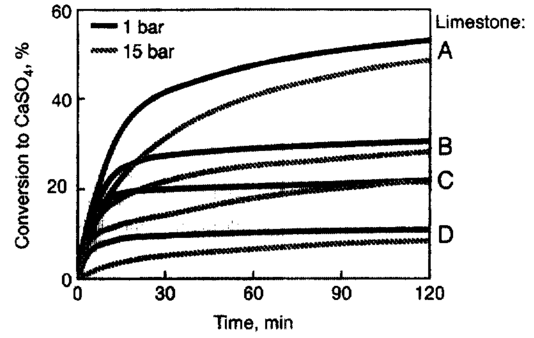

Fig. 50. Sulfur dioxide capture by four lime-stones at both atmospheric pressure (dark symbols) and at 15 bar (open symbols). Gas composition: 0.3% SO_2, 4% O_2, 20% CO_2, balance N_2 (LIEKKI-project L2-305).

formation is a topical challenge for FBC development work, and several projects in LIEKKI have dealt with this issue.

12.3.3. *Particle behavior, ash and aerosols*

Understanding the behavior of fuel particles or droplets is essential when new combustion processes are considered. Also, the behavior of the fuel ash may be of crucial importance for some applications. If uncontrolled, the ash may cause significant fouling of the heat exchange surfaces and so-called bed sintering in FBC systems. New laboratory techniques, together with advanced chemistry and aerosol behavior models, are adding significantly to our knowledge in this area. In LIEKKI, all projects dealing with particle or particle-gas behavior are located in the same review group, thus facilitating the exchange of methodological information among various experts in sulfur capture, aerosol measurements, and high temperature chemistry. Currently, 13 projects deal with issues of particles, ash, and aerosols.

Figure 48 shows an example of *in-situ* measurements of vaporized sodium during pressurized combustion of coal particles in an entrained-flow laboratory combustor. The sampling and analysis system is based on *in-situ* plasma emission of the gas sample, with simultaneous optical detection of the sodium. The system detects very low sodium concentrations and reacts rapidly to changes. Sulfur capture by limestone in PFBC and PFBG proceeds very differently from atmospheric pressure fluidized beds. Figure 49 shows that the calcium carbonate $CaCO_3$ will always calcine to calcium oxide, CaO, in atmospheric pressure systems, and it is this calcium oxide that captures the sulfur dioxide, forming calcium sulfate. At elevated pressures, the calcium carbonate will not form oxide, and the capture reaction takes place directly with the calcium carbonate. It was surprisingly shown that the capture reaction at elevated pressures was more effective than the reaction at atmospheric pressures (see Fig. 50).

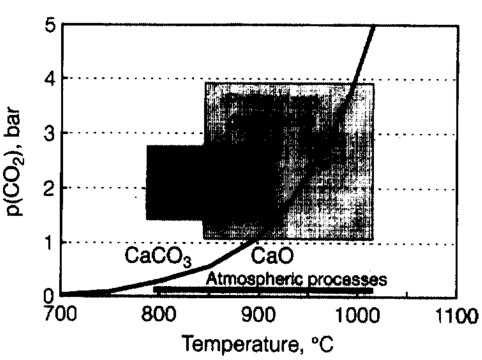

Fig. 49. Calcium carbonate decomposition in fluidized bed combustion and gasification systems (LIEKKI-project L2-305).

12.3.4. *New technologies and black liquor*

LIEKKI has included a number of projects supporting new gasification or combustion systems. Many of these projects have been partially confidential company projects, but some parts have been reported, to identify the nature of this research. Figure 51 shows a schematic of the pressurized, fluidized-bed gasification pilot plant at the national laboratory VTT (Technical Research Centre of Finland) in Espoo. This pilot plant has a small thermal input of some 300 kW_t, but it has produced useful measurement data. Figure 52 shows an example of the gas product lower heating value for feed stocks ranging from bituminous coal to wood and straw. In biomass gasification, more than 50 % of the heating value of the gas comes from light hydrocarbon gases and tars while, in coal gasification, the tars and all hydrocarbons, except methane, are almost completely decomposed.

Combustion behavior and emission control of black liquor includes 8 projects, while incineration of various selected waste fractions, especially together with prime fuels, is the focus of four projects.

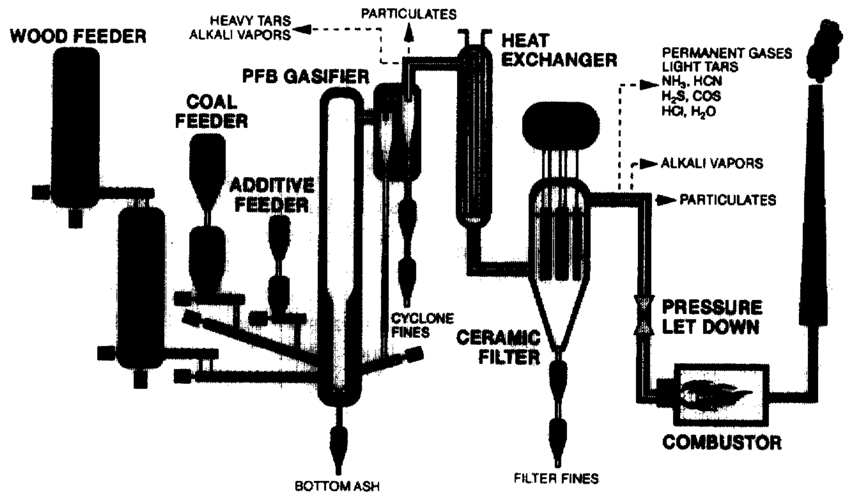

Fig. 51. Schematic diagram of the pressurized fluidized bed gasifier test rig at VTT in Espoo, Finland (LIEKKI-projects L2-404 and L2-405).

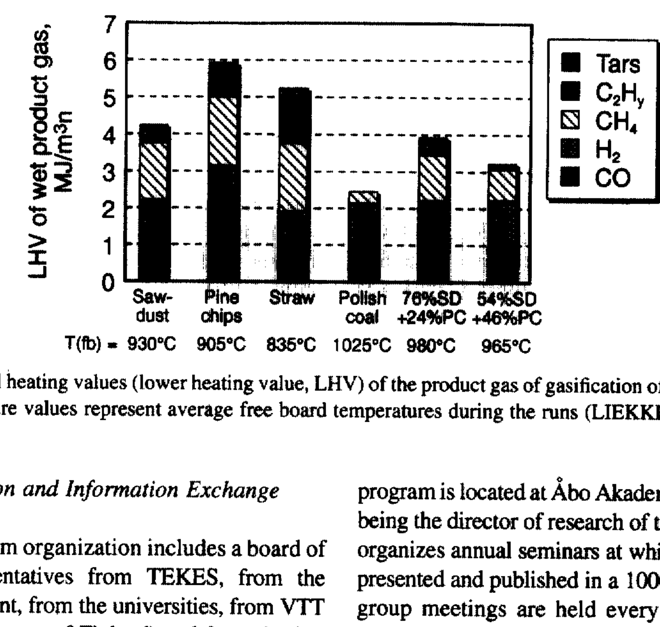

Fig. 52. Typical heating values (lower heating value, LHV) of the product gas of gasification of some feed stocks. The temperature values represent average free board temperatures during the runs (LIEKKI-project L2-404).

12.4. *Organization and Information Exchange*

The LIEKKI program organization includes a board of directors with representatives from TEKES, from the Ministry of Environment, from the universities, from VTT (Technical Research Centre of Finland) and from the following companies: Ahlstrom Corporation, Foster Wheeler Energia Oy, IVO Group (IVO Power Engineering), Kvaerner Pulping Oy, and Wartsila Diesel NSD Corp. The program funding is shown in Fig. 53. The coordination of the program is located at Åbo Akademi, Professor Mikko Hupa being the director of research of the program. The program organizes annual seminars at which all project reviews are presented and published in a 1000-page yearbook. Review group meetings are held every fall. For internal information, LIEKKI publishes two newsletters each year.

LIEKKI results have already been published in 21 prominent, international journals. Altogether, 12 doctoral theses have been published in association with the LIEKKI activities.

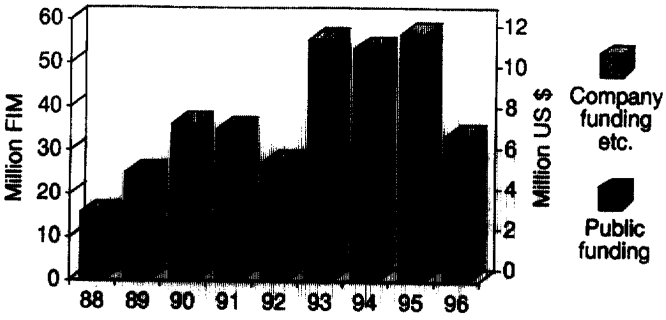

Fig. 53. Funding of the LIEKKI program since its beginning in 1988.

13. THE NATIONAL COAL COMBUSTION LABORATORY

Chuguang Zheng, Jidong Lu, Huaichun Zhou and Xuefeng Shi
Huazhong University of Science and Technology, Wuhan, P. R. China

13.1. *Introduction*

The annual amount of coal produced and consumed in China is the largest in the world and China is among the few countries which use coal as their main primary energy resource. In 1994, the percents of coal, petroleum, natural gas and hydroelectricity in the total primary energy base in China were approximately 74.6%, 17.6%, 2.0% and 5.8% respectively. It can be predicted that the use of coal as the main primary energy resource in China will not change dramatically in the future.[195]

The total utilization efficiency of energy is only 30% in China, 10-20% lower than that in developed countries. The energy consumption was 414 g-fuel/KWh in 1994 and 412 g/KWh in 1995 respectively, which were 50-80 g/KWh higher than that of advanced levels in the world. Besides that, the ratio of coal processed before utilization is very low and washed coals make up only 20 percent of the total coal consumption.

The utilization of coal by direct combustion is causing serious air pollution in China. It is estimated that the main pollutant matters in the atmosphere emitted from coal combustion, such as dust, SO_2, NO_x, and CO comprise 96 percent of the total pollutants from fuel combustion. The amount of CO_2 emitted in China is about 600 million tons, which makes up about 9.4 percent in the world. China also faces a serious challenge in efficient and clean utilization of coal. Thus, the mission of our laboratory is to carry out R & D in coal utilization with high efficiency and low pollution, to focus on the essential research of reaction kinetics, aerodynamics, pollution formation mechanisms in coal combustion, and to develop new coal combustion technology with potential of application.

13.1.1. *History*

The predecessor of the National Coal Combustion Laboratory is the Combustion Research Institute of Huazhong Institute of Technology (now Huazhong University of Science and Technology), founded in 1978. They were engaged in studying of coal combustion technology and fluidized-bed technology. After being evaluated by a team of experts, the Combustion Research Institute of Huazhong Institute of Technology was granted to be expanded and become NCCL by the State Planning Commission and the State Education Commission in June, 1988. After three years of preparation, the laboratory was inspected and accepted by the State Planning Commission and opened in 1991.

13.1.2. *Characteristics*

NCCL is characterized by two aspects, the essential research and the development of low-grade coal combustion technology. The essential research in NCCL emphasizes pyrolysis, ignition of coal, combustion kinetics of low-grade coal, flame-stabilization mechanisms for low-grade coal combustion in utility boilers, correlation of turbulent fluctuations in coal combustion processes, computer simulation of coal combustion processes, formation mechanisms of pollutants during coal combustion, aerodynamics in coal combustion, combustion visualization, diagnosis and optimal control expert systems for large-scale pc-fired utility boilers.

Combustion technologies for low-grade coals, such as bluff-body combustion stabilizers, were developed and have made important contributions for the safety and economic utilization of low-grade coals in power plants. Design of 10T/h and 75T/h fluidized-bed, coal-fired boilers and high temperature hot-gas furnaces, and the development of monitoring and control systems of thermal engineering processes in power plants have been undertaken.

Table 32. General characteristics of the NCCL

Title	The National Coal Combustion Laboratory
Location	Huazhong University of Science and Technology, Wuhan, People's Republic of China
Directors	Chuguang Zheng, Director Jidong Lu, Associate Director Huaichun Zhou, Associate Director Xuefeng Shi, Associate Director
Starting date	June 1988
Mission/objective	Research and development in coal combustion with high efficiency and low pollution
Focus	Fundamental research of reaction kinetics, aerodynamics and pollutant formation mechanisms in coal combustion, and development of new coal combustion technology with bright perspectives of application.
Research areas	Mechanisms, kinetics, aerodynamics, pollutant formation and heat and mass transfer in coal combustion processes, mathematical models, numerical simulation, diagnosis and optimal control of coal combustion processes

Table 33. Data for the NCCL

A. Number of personnel (1996)

Professional	14
Professorial	15
Postdoctoral	3
Graduate students	46
Undergraduate students	50
Staff/management	2
Other	0
TOTAL	130

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	412
1995	454
1996	724

C. Budget sources (%) (1996)

Government	55
Domestic industry	42
University	0
Foreign	2
Income (patents, royalties, licenses, software, etc.)	1
Other	0
TOTAL	100

D. Space and equipment

1. Research space	4.5 sq. metres
2. Research equipment/instruments/ computers	$1 500 000

E. External participants/sponsors/advisors/members

Government	2
Industry	1
University	15
TOTAL	18

F. Research program (1996)

Number of fundamental projects	17
Number of applied projects	18
Number of proprietary projects	0
TOTAL	35

G. Center research projects/activities

	Minor Major
Experimental data	1 2 3 4 **5**
Computer software	1 2 3 **4** 5
Inventions/patents	1 2 3 **4** 5
Project reports	1 **2** 3 4 5
Journal/book publications	1 2 **3** 4 5
Consulting services	1 2 3 **4** 5
Process/system concepts	1 **2** 3 4 5
Graduating students	1 2 3 4 **5**
Academic courses	1 2 **3** 4 5
Technology transfer	1 2 3 **4** 5

13.1.3. *Administrative structure and practice*

The NCCL is headed by a director and three associate directors (see Table 32). The researchers are organized into research groups, the coal property group, the pollutant emission and control group, the numerical simulation of coal combustion processes group, the burner and combustion system R&D group, the combustion diagnosis and optimal control group, and the fluidized-bed coal combustion group.

There is also an academic advisory committee which consists of about 30 professionals from various countries. The chairman is Kefa Cen, an academician of the Chinese Academy of Engineering from Zhejiang University. The committee guides the research work of NCCL, and examines project application from public to NCCL.

13.1.4. *Resources*

The staff of NCCL includes 20 researchers, 7 technicians and 2 secretaries. Among them there are 8 professors, 7 associate professors and 12 lecturers and engineers. Two post-doctorates, 17 Ph. D. candidates, 29 M. S. candidates and 60 undergraduates also work in NCCL (see Table 33).

NCCL takes up an area of 10,000 sq. m., with a research space of 4500 sq. m. Since 1979, a more integrated experimental apparatus system for research work on coal combustion has been established, including a drop-tube furnace, a one-dimensional furnace, cold-state and hot-state experimental burner rigs, experimental rigs for flow characteristics in furnaces, one four-corner tangentially-fired furnace, a hydrodynamic test rig and a hot-state test rig of bubbling bed, cold and hot-state circulating fluidized-bed test rigs, and test rigs of flow pattern in burners and furnaces. Large-scale scientific instruments in NCCL include a laser holographic system for measurements of shape, size, concentration and 3-D velocity, a 3-D particle dynamic analyzer for measurements of size, 3-D velocity components and concentration of particles, a GC/IRD/MSD system for measurements of trace elements of 10^{-13} in gas or liquid samples below 350, a proximate analyzer for measuring water, volatile matter, fixed carbon and ash contents in coal and other fuels, an instrument for measuring carbon, hydrogen and nitrogen contents in fuels, a caloric value analyzer, an ash fusibility determinator, an accelerated surface area and porosimetry system, and a trace differential thermobalance.

13.2. *Research Program*

The research work in NCCL ranges widely over coal combustion areas, from mechanisms and kinetics of coal combustion, aerodynamics and heat and mass transfer in combustion processes, combustion with low-pollution and flue-gas treatment, mathematical models, numerical simulation, diagnosis and optimal control of coal combustion processes, to application technology for coal combustion. From 1981 to 1985, the laboratory accomplished two projects of the State's Sixth Five-Year Plan on a bluff-body coal stabilizer and its stability mechanism. From 1986 to 1990, the laboratory also contracted to do several projects of the State's Seventh Five-Year Plan on coal properties, coal burners and flow characteristics in furnaces of home-made large-scale utility units, and on feasibility and design of a 130 T/h fluidized-bed boiler, firing low-grade anthracites. From 1991 to 1995, NCCL contracted to do six projects of the State's Eighth Five-Year Plan on the burnout process of coal, large-scale pulverized-coal burners and flow characteristics in furnaces, a slag cooler and the formation and emission of N_2O and NO in a 220 T/h circulating, fluidized-bed boiler.

NCCL has 2 to 3 projects supported by the National Natural Science Foundation of China every year. These projects include research on stabilizers for coal combustion, formation and reduction of N_2O, SO_2 and NO, turbulence properties of coal combustion processes, diagnosis and optimization of combustion systems, optical and radiative properties of coal suspension combustion medium, micro-structures of coal and their influences on combustion, analysis and intensifying of coal combustion stability, and combustion visualization in pc-fired furnaces. A project on fundamental research of highly efficient and low-pollutant combustion of coal and petroleum, is the only engineering project in the State's Key Fundamental Research Projects in the State Eighth Five-Year Plan (1992–1996). Its two sub-projects have been undertaken by NCCL, one on structural properties and combustion stability of coal, the other on formation and properties of toxic heavy metals and N_2O in coal combustion.

In the past ten years, many projects have been authorized from different state commissions and provincial governments. The funds from the state and provincial governments are about half of the total funding obtained by NCCL. With the reform and open policy and the development of the market economy in China, the electrical industry pays more and more attention to the transformation of traditional technology and application of new technology. NCCL often participates in many projects in cooperation with industry, and the funds obtained make up 60 percent of the total at the present. The cooperation with the industry has accelerated both the transformation of research results to profits, and the essential research.

Since 1991, about 30 projects have been opened to the public by NCCL in order to sustain other institutes in China, such as Zhejiang University, Shanghai Jiaotong University, and Harbin Institute of Technology, to carry out the research on efficient and clean coal combustion. We took the advantages of the multi-disciplines of our university to do research work, and invited the experts from Physics Department to participate in the investigation on reactive flow processes, researchers from Chemistry Department to join in the research on chemical reaction kinetics and pollutant formation in coal combustion, and the scholars from Mathematical Department to engage in the study of mathematical modeling of combustion processes.

13.3. *Key Research Results*

13.3.1. *Coal combustion technology*

In order to solve ignition and combustion problems caused by low-grade coal, a bluff-body burner technique was introduced by NCCL.[196] The hot-state experiments on experimental furnaces showed that this bluff-body burner can increase the combustion speed of anthracite and low-grade bituminous coals, and promote the ignition processes.[197] Furthermore, the ratio of primary air flow can be increased properly, which will be helpful to the combustion of anthracite coal.[198] Numerical simulation of the turbulent, separated flow of the bluff-body burner[199] and the combustion processes[200] showed that[195] this turbulent, separated flow behind the bluff-body burner can enhance the heat and mass transfer processes at the early stage of coal ignition.[201] The hot flue-gas engaged by the inner recirculating flow provides a stable heat source for ignition,[196] the turbulence intensity occurring in the marginal zones of the recirculating flow is four to six times higher than those in the free jet flow, and[197] the local enrichment of pulverized coal in the marginal zone of the recirculating flow also accelerates the ignition process of pulverized coal. The bluff-body has been applied to utility boilers widely, and has achieved good results.

On the basis of the bluff-body burner, a cavity bluff-body burner has been developed.[202,203] Research results show that the cavity can increase the length and mass recirculating flow rate in the recirculation zone behind the bluff-body.[202] The average velocity and fluctuation of velocity and other turbulence parameters at the outlet of this burner have been measured with a three-dimensional particle dynamic analyzer. The results indicate that the particle number density, the particle volume flux, turbulence intensity and flame temperature are all higher in the recirculation zone than in other zones, and these factors form the basis of stabilizing low-grade coal combustion.[203] Already, this burner has been applied in many 50 MW_e, 100 MW_e, and 200 MW_e utility boilers, and generally the lowest load level of stable combustion has been decreased by 20–30%, and the combustion efficiency has been improved.

13.3.2. *Coal combustion characteristics*

Coal pyrolysis and char reactivity. Slow pyrolysis characteristics of pulverized coal were studied by using the thermal analysis method in conjunction with gas chromatography. A two-stage kinetic model for pyrolysis reaction has been proposed. The model was applied successfully in explaining the experimental data of rapid pyrolysis in a drop-tube furnace.[204] The time-temperature history and residence time of coal particles in the drop-tube furnaces were obtained, both by a detailed numerical model of the flow and particle in the reactor and by direct measurements. Based on the calculated particle temperature, a functional group, reaction-based, coal pyrolysis model was used to predict the overall reaction and volatile species evolution in the drop-tube furnace.[205]

A volatiles evolution characteristics index and combustion characteristics index from DTGA have been proposed. They can be used for determining ignition and burnout of different coals.[206] Volatiles evolution and residual volatiles combustion mechanisms for suspended combustion of single coal particles were also studied. The reactivity of char changed during combustion. A new concept of instantaneous reactivity of char was proposed, to facilitate the studying of char reactivity of practical, pulverized coal flames.[207] Physical relationships between intrinsic ash and combustible material in coal were also studied. High ash content was shown to affect the combustion process, and observations were consistent with a shrinking core model. It was concluded that the ash layer was an important factor affecting the combustion rate. The effective coefficient of diffusivity of the ash layer was of the order of oxygen molecular diffusivity.[208]

Surface area and pore structure of eight coals with different ranks and their chars with different ratios of burnout were studied, and a simple, shapeless pore structure model (SPM), was proposed to distinguish between physical and chemical effects. Shapless pores include macro-pores by which oxygen diffusion is controlled and micro-pores by which chemical combustion is controlled. SPM avoided the complexities and variations of pore structures and difficulties in mathematical modeling. The reliability of SPM was evaluated by comparing with the pore tree model of Simons[209] and experiment results of Smith.[210] The effects of ash content, particle size, porosity, pore area, temperature, and oxygen pressure on char ignition and burnout were analyzed by using SPM.[211]

Combustion characteristics of blended coals. The experimental investigations were carried out with a thermobalance analyzer, a drop-tube furnace, a combustion test furnace, and an ash fusion temperature autoanalyzer. Mineral phases at different temperatures and combustion atmospheres were determined by X-ray diffraction analysis. A three-stage kinetic model was established to predict the devolatilization of blended coal. An equivalent volatiles content was used to describe the ignition behavior. A burnout index, taking account of early and later stages in combustion processes, was proposed to determine the burnout efficiency.[212] The maximum value of NO_x generated from blended coal combustion depends on the relative nitrogen content, blend ratio, and oxygen concentration. The emission of NO_x in the late combustion process will increase in oxidizing atmospheres.[213] The ash fusion temperatures for various percentages of two different coal blends illustrate the non-arithmetic averaging. The blend coals may have a higher or a lower ash fusibility temperature than either of the component coals. A grey clustering method was used to assess the slagging potential of blended coals.[214] The phase transition and reaction of the minerals in different coals with each other at high temperature in blended coals are the main factors affecting the fusibility and slagging of blends.[215] An overall fuzzy judgement model, taking account of ignition, burnout, slagging, and NO_x formation, was developed to predict the optimal blend ratios.[216]

Coal combustion stability. A quantitative index CSI, Combustion Stability Index, was proposed to assess its relative combustion stability of any coal-fired combustion system with high nonlinearity. CSI takes the absolute value of maximum disturbance ratio of fuel mass flowrate (keeping a constant oxygen mass flowrate) which can be overcome by the stable combustion process. Zero and unity values of CSI refer to the lowest and highest combustion stability, respectively. The dynamic simulation on a tangentially-fired utility furnace shows that CSI can predict correctly the variations of combustion stability with load level and coal types.[217] Experimental studies on a kind of bluff-body pulverized coal (pc) burner shows that it has a CST higher than the normal straight flow burner by 0.375.[218] This index can be used to assess quantitatively the relative stability between different combustion systems such as pc-fired combustion systems with straight flow burners or swirl burners, or fluidized-bed combustion systems.

Color characterization of pc combustion flames. The relative spectral intensity under three concentration conditions (1.22, 0.88, 0.68 kg coal/kg air) within the wavelength range of 100–1000 nm has been detected by a monochrometer for a bituminous coal in a single-burner, pc-fired experimental furnace. Then, the chromaticity coordinates (x, y) of the flame under these three concentrations have been calculated according to CIE 1931 standard colorimetric system theory, and they are (0.3452, 0.3772), (0.3244, 0.3753) and (0.2516, 0.3062), respectively. It can be seen that as the coal concentration decreases, the chromaticity coordinates of the flame will decrease too, and it is especially sensitive to fuel-lean flames. A simple device to monitor the chromaticity coordinates of pc flames was designed without a monochrometer with a relative error of less than 5%, and the device can be used to monitor the fuel-air ratio in boilers.[219]

13.3.3. *Formation and control of pollutants*

Toxic heavy metals. The distribution of toxic heavy metal elements of typical coals in China has been studied, and the toxic heavy metal elements were divided into two categories through Solari's model and regression analysis. One is that of affinity with the inorganic matter, such as As, Cd, Cu, Pb, Ni, and the other of affinity with organic matter, such as Be or Ge. From research on experimental facilities and large-scale utility furnaces, the distribution of trace elements in ash particles is associated with coal type, combustion conditions, and coal particle fineness. Those elements combined with sulfides, such as Cd, Pb, Cu, or Ni, are easy to enrich in fine-ash particles. The enrichment occurs more easily in high-temperature, reductive environments than in low-temperature, oxygenic environments. Chemical desulfurization of coal, flotation methods with different ph, and injection of solid sorbents into furnaces all proved to be efficient in reduction of emissions of toxic heavy metal elements.[270]

de-SO_x and de-NO_x in pulverized coal-fired furnaces. Research has been conducted on activation of sorbents for de-SO_x and de-NO_x by injection of sorbent into furnaces.[271] Alcohol, exhaust liquid from paper-mills, and pulverized-coal flyash have been studied to activate Ca-based sorbents for de-SO_x. The results showed that when the alcohol concentration is 30%, the surface area of a Ca-based sorbent is the largest, with activation a maximum. The addition of a proper amount of pc flyash is beneficial to the transformations from SO_2 to SO_3 and CaO to $CaSO_4$, and improvement of SO_2 removal through catalytic effects.

The main factors influencing de-SO_x and de-NO_x by injection of sorbents into furnaces, such as temperature, Ca/S, fineness of sorbent, coal type, and excess air coefficient, have been examined. The results showed that the SO_2 removal ratio is the highest when the temperature approaches 1100°C, and NO_x will increases as the temperature increases. As Ca/S increases, the SO_2 removal ratio increases, but the SO_2 removal ratio decreases, and the utilization ratio of Ca decreases. The smaller the sorbent particle and the larger the surface area capacity, the higher the SO_2 removal ratio becomes. If the diameter of sorbent is reduced, the SO_2 removal ratio will decrease. The SO_2 removal ratio and the Ca utilization ratio for high-S coal are all higher than those for low-S coal. The influence of coal type on emissions of NO_x is associated with its volatile matter content. For high-volatile-matter coal, the injection of CaO has catalytic effects on NO_x formation, increasing NO_x levels.

Formation and destruction of N_2O. The mechanisms of formation and destruction of N_2O, including both homogeneous and heterogeneous reactions,[222] emissions of nitrogenous oxides, analytical techniques of N_2O, and the effect of de-NO_x on N_2O were studied during coal combustion in bubbling fluidized bed and circulating fluidized bed. The grey system theory was first applied to the study on the influence of various factors on N_2O emissions. It was discovered that CH_4 is the factor helping the conversion of HCN to NH_3, and the reaction between NO and coal-char in the presence of oxygen contributes the most to the formation of N_2O.[223] Experiments demonstrated that some NO was converted into N_2O during NO reduction with pulsed corona discharge. The measures of comprehensive control of $N_2O/SO_x/NO_x$ such as after-burning, co-combustion of coal and biomass, staged combustion, etc. were also studied.

13.3.4. *Mathematical modeling of coal combustion processes*

Turbulent reacting flow. Interactions of turbulent flow and combustion are complex phenomena, especially for the random fluctuation of velocity and other scalars. For example, ignoring the density fluctuation and its correlation terms will cause significant errors in prediction of pollutant production of turbulent combustion. A comprehensive experimental and theoretical study was conducted on the density fluctuations of nonisothermal, turbulent flow. The density fluctuation correlation terms, including the density-scalars fluctuation correlation terms and the density-velocity fluctuation correlation terms were introduced into the modeling of a turbulent flame.[224]

The PDF simulation method may accurately account the correlation of turbulent transport and chemical reaction rates in simulation of turbulent combustion and pollutant production. The combined velocity and thermal chemistry parameters in the PDF transport model were developed and applied. To improve the calculating efficiency of PDF methods on complex reactive flows, a reduced reaction mechanism was also developed.[225] The Lattice Gas Method, which arose in 1980's and gained great worldwide interest, is a new method to simulate the complex flows by directly simulating the collision of 'particles' in a fluid. The Lattice-Boltsman method successfully simulates complex flows such as the Karmon vortex. This is a potential approach to investigate combustion phenomena in pulverized coal fires.[226,227]

The discrete arithmetic scheme. For tangentially-fired furnaces, false diffusion from numerical inaccuracies will occur when the flow is oblique to the grid lines. It causes serious errors in the predictions of tangentially-fired furnaces. To decrease the false diffusion error, a new discrete arithmetic scheme, named the '27-points' differencing scheme, was developed and compared with 'upwind', 'hybrid', and 'quick' differencing schemes. All of these schemes were used to simulate a constrained jet and a lab-scale tangential furnace to compare solutions with experimental data. Overall, the '27-points' approximation emerged as the most satisfactory for simulating tangential furnaces.[228]

13.3.5. *Ash deposition, radiative heat transfer and combustion visualization*

Fume formation and ash deposition. The formation of fumes depends not only on the characteristics of coal but also on the operating conditions (temperature, atmosphere, sizes of coal particles). By burning the coal under different temperatures and atmospheres, the evolution of mineral matter from coal was observed. The results coincided with the results gained by simulating the typical process of minerals evaporation in coal combustion by means of an analog thermochemical equilibrium program. The depositing property of coal ashes under different operation conditions has good correlation with the quantity of evaporated iron and alkali compounds during coal combustion. While under the same conditions, the deposition tendency is proportional to the evaporation of iron and alkali compounds (K and Na).[229]

Radiative properties. Based on Mie theory, a thorough experimental and numerical investigation was conducted on the radiative properties of particulate products of pulverized coal combustion. Special attention was given to the unburned char. The dielectric equation was used to gain the mean optical properties of porous char. The structure and radiative properties of unburned char particles was modeled. It is found that the absorption of particles is enhanced during the initial burning stage and declines sharply near burnout. Monte Carlo and Hottel Zone methods were developed to simulate the radiative heat transfer in furnaces. Efforts are being made to modify the programs to account for the effects of heterogeneous, anistropic, radiative properties of particles.[230]

Visualization of combustion temperature distribution. A simple method to monitor two- dimensional combustion temperature distribution has been proposed for combustion environments containing pulverized coal particles in large-scale utility furnaces. In this method, a monochromatic flame image is detected by an image-processing technique from furnaces and, at the same time, a reference temperature is measured by a two-color pyrometer at the image-formation direction. Then, a two-dimensional temperature distribution can be deduced from the monochromatic image and the reference temperature.[231] Using this measurement method, experiments were conducted on flame measurements in a pulverized-coal-fired, laboratory-scale furnace and a 670 T/h utility boiler. The data-processing results showed that combustion temperature measured by this method is closely related to the operational parameters and the states of boilers, and can provide some direct evidences to diagnose the combustion processes in furnaces.[232]

A mathematical equation between the two-dimensional, grey-scale image and the three-dimensional temperature distribution in furnaces has been derived. Then, using the temperature measured by the two-color pyrometer as a reference temperature, the calibration of the radiative energy against the grey scale of the images has been obtained. Through mounting a group of c cameras around the combustion space measured together with the same number of two-color pyrometers for each camera, a reconstruction method of the three-dimensional temperature distribution for utility boiler furnaces based on radiative image processing and numerical simulation on combustion processes has been proposed. The potential of three-dimensional temperature distribution reconstruction for comprehensive visualization of combustion processes in utility coal-fired furnaces is large.[233]

Two-loop combustion control. Full-furnace flame TV equipment and a computer image capturing and processing system are adopted to capture the flame radiative images representative of the radiative energy level in furnaces. The average grey-scale of the images is taken as an intermediate controlled parameter and, together with the steam pressure parameter, a new two-loop combustion control strategy was established for utility boilers. Through in-situ measurements, the parameters of the model are determined preliminarily. Simulation results show that this control system can effectively overcome the influence of the fuel disturbance on steam pressure, and the efficiency of combustion control will be improved.[234]

13.3.6. *Coal combustion mechanisms and technologies in fluidized beds*

Heat transfer. The bias of heat transfer surface area in design of fluidized bed boilers is always too large. To deal with this problem, the heat transfer process in fluidized beds has been studied systematically, and a new mechanistic model, accounting for the heat transfer modes of conduction, convection and radiation, has been proposed based on the large number of experiments. The model is the first comprehensive model which can apply to wide ranges of particle size and operating temperatures. In this model, new definitions on conductive and convective components are given, and the quantitative variations of the fraction of each component are given in different particle size and temperature ranges.[235] A new scheme describing heat transfer regions is shown with the Archimedes number, representing the fluidizing property of particles, and Planck number, reflecting the radiative importance of conduction and radiation. Nine characteristic regions are defined according to the change of dominant heat transfer modes, which are useful in the optimum design and normal operation of fluidized bed equipment.[236]

Combustion technology. In order to use low-grade coals in China, FBC technology has been extensively investigated and developed in NCCL. A fluidized-bed combustion boiler of 35 T/h for burning mudstone with heating value of 3300 kJ/kg has been put into operation. A circulating, fluidized-bed boiler of 10 T/h steam flow developed by NCCL was put on-line in 1992.[237] A Π-shaped circulating, fluidized-bed boiler of 35 T/h, with downward exhaust gas cyclone separator developed by NCCL, went into operation in 1994.[238] Fluidized-bed hot-gas furnaces developed by NCCL have been extensively employed by several hundred cement plants to dry raw material. Some fundamental investigations on aerodynamics, heat transfer, and emissions control of SO_x, NO_x and N_2O in fluidized-bed combustors have been done.[239] The study of large-scale circulating fluidized-bed boiler of 125 MW_e and the retrofitting of aged pulverized coal-fired boiler into circulating fluidized-bed boiler are being conducted. Aerodynamics, heat transfer, and emissions control in fluidized-bed combustors continue to be studied in NCCL.

13.4. *Directions*

New research directions for NCCL are as follows: (1) Nonlinearities in coal combustion; (2) Low-cost, clean combustion technology for coal-fired utility boilers; (3) Combustion visualization and optimal control in coal-fired furnaces; (4) Fume formation and ash deposition in coal combustion.

14. THE STATE KEY LABORATORY OF EFFICIENT AND CLEAN COMBUSTION OF COAL

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14.1. *Introduction*

Recent advances in combustion of coal at the State Key Laboratory of Efficient and Clean Combustion of Coal (SKLECCC) are noted. The research of SKLECCC covers several areas on coal combustion. Four programs have been presented herein (see Table 34). The first program is pulverized coal combustion. It includes stabilizing flame with combustors, numerical simulation of pulverized coal combustion, and studying characteristics of coal. The next is combustion of fluidized beds. The third program is pollution control, specifically, the research on desulfurization and de-NO_x. The fourth program is coal gasification in steam fluidized beds.

An integrated research program on coal combustion being conducted by the State Key Laboratory of Efficient and Clean Combustion of Coal (SKLECCC) has been presented in this section. Many recent research results have been published in journals of conference proceedings. Some published results were written in Chinese, making it difficult to interact with researchers who do not read Chinese.

SKLECCC is located at Tsinghua University, Beijing, China. About 27 faculty, including 13 full professors, and 150 graduate students are working in this laboratory (see Table 35). In addition, there is an experimental base, with a 20T/h power plant and about 30 staff members. The main research areas include modeling of solid-gas flow and combustion, controlling of pollution in coal combustion, developing CFBC boilers, cogeneration of steam and town gas by CFBC, and measurement techniques in coal combustion. The most important mission of the SKLECCC is research and development of technologies for efficient and clean combustion of coal. Some selected recent research programs are presented in the following sections.

14.2. *Research Results*

14.2.1. *Pulverized coal combustion*

Ignition and Stability. Most power plants in China use pulverized coal boilers. In these plants, different kinds of coal, from lignites, bituminous coals, sub-anthracites to anthracites, are often used even in the same boiler due to difficulty of transportation. About 18% of the total amount of coals fired are difficult to ignite. Therefore, improving flame stability is very important. SKLECCC has conducted research on stabilizing flames in pulverized coal combustors for many years. Xuchang Xu *et al.*[240] have presented 'the three-high zone' theory, a new principle of pulverized coal flame stabilization. According to this theory, the multi-functional, tangential pulverized coal burner with the boat-shaped stabilizer, shown in Fig. 54 has been developed. Due to the special flow pattern in the burner and the furnace, the artificial formation of some local regions benefits ignition of the pulverized coal–air mixture continuously and keeps the flame stabilized. In these special regions, when the primary air across the boat-shaped flame stabilizer is installed inside the burner nozzle, a very short recirculating zone is formed, and half of the zone is located in the nozzle, with the balance in the furnace, outside of the nozzle. The gas temperature in the central recirculating zone is not high enough to ignite the pulverized coal, being only 100–260°C. Although, the zone is short, and the jet issued from the primary air

Table 34. General characteristics of the SKLECCC

Title	The State Key Laboratory of Efficient and Clean Combustion of Coal
Location	Tsingjua University, Beijing, People's Republic of China
Director(s)	Changhe Chen, Director Yan Li, Associate Director Xilin Wang, Associate Director
Starting date	April 1992
Mission/objective	To research and develop the advanced new technologies of coal combustion and pollution control
Focus	Efficient and clean combustion of coal
Research areas	Development of CFBC boilers of medium size, cogeneration of steam and town gas with CFBC, general model of devolatization of coals, dispersion of coal particles, control of the pollution from coal combustion, low pollution burner for pulverized-coal firing, modeling of solid and gas two-phase flow and combustion, measurement technologies in coal combustion

Table 35. Data for the SKLECCC

A. Number of personnel (1996)

Professional	17
Professorial	13
Postdoctoral	3
Graduate students	71
Undergraduate students	53
Staff/management	3
Other	0
TOTAL	160

B. Fiscal year budget (U.S.$ thousands equivalent)

1994	338.3
1995	361.4
1996	385.5

C. Budget sources (%) (1996)

Government	57
Domestic industry	34
University	1
Foreign	7
Income (patents, royalties, licenses, software, etc.)	2
Other	0
TOTAL	100

D. Space and equipment

1. Research space	27 790 sq. ft.
2. Research equipment/instruments/ computers	$1 370 000

E. External participants/sponsors/advisors/members

Government	2
Industry	28
University	15
TOTAL	45

F. Research program (1996)

Number of fundamental projects	33
Number of applied projects	10
Number of proprietary projects	0
TOTAL	43

G. Center research projects/activities

	Minor Major
Experimental data	1 2 3 4 **5**
Computer software	1 2 3 **4** 5
Inventions/patents	1 2 3 **4** 5
Project reports	1 2 **3** 4 5
Journal/book publications	1 2 3 4 **5**
Consulting services	1 2 **3** 4 5
Process/system concepts	1 **2** 3 4 5
Graduating students	1 2 3 4 **5**
Academic courses	1 2 **3** 4 5
Technology transfer	1 2 3 4 **5**

nozzle forms the apparent wasp-waist shaped flow. The pulverized coal particles are separated from the jet and concentrated on the outside boundary of the wasp-waist part of the jet. In this local region, the pulverized coal concentration is higher, reaching 1–3 kg/(kg air); the gas temperature is high, and the oxygen concentration is appropriately high. The region is therefore called a 'three-high zone,' in which the pulverized coal can be ignited continuously and the flame is well sustained. It is evident by experiments and numerical simulation, the 'three-high zone' principle of pulverized coal flame stabilization is successful in developing new types of

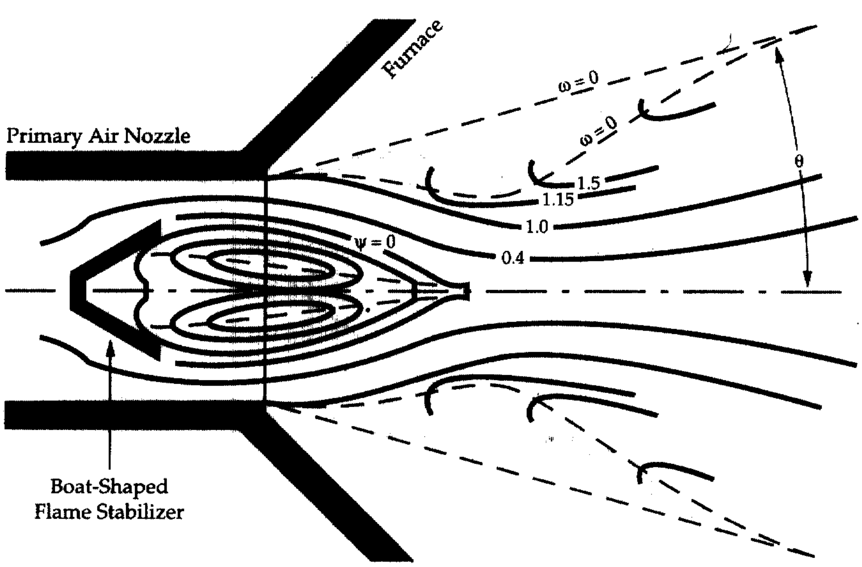

Fig. 54. The flow pattern in the local high concentration region of the multi-functional tangential pulverized coal burner.

pulverized coal burners. The 'three-high zone' can also reduce NO_x formation in the combustion process, because it implies a kind of multi-staged pulverized coal combustion. For example, by using the tangential burner with the boat-shaped flame stabilizer, in the igniting zone, the concentration of pulverized coal is higher. The ignited, pulverized coal particles quickly leave this coal-concentrated zone and mix completely with the primary air from the same nozzle in the downstream region, subsequently, it will mix with the secondary air from other nozzles.

Combustion Modeling. SKLECCC has given increasing attention to the modeling of gas- particle flows and coal combustion in combustors and furnaces. Different comprehensive models and computer codes have been developed. A two-fluid model, with both k–G model and algebraic stress model, has been developed. It combines with an algebraic stress model of particle turbulence to simulate turbulent, gas-particle flows in a tangentially, coal-fired furnace.[241,242] The detailed information of gas-particle velocity and particle concentration in computed domains, which cannot be obtained by using either the trajectory model (difficult to give particle concentration maps) or the no-slip model (unable to give the two-phase velocity field), can be obtained. The model can well predict the effects of swirl and turbulent diffusion on the gas-particle mixing. Considering both turbulent particle diffusion and particle history effects due to reaction and heat transfer, a continuum-trajectory (Lagrangean–Eulerian) model of reacting particle phase[241,242] and a pure, two-fluid model are used. To predict particle number density and velocity distribution, both models use Eulerian particle number density and momentum equations as

$$\frac{\partial}{\partial t}(n_p) + \frac{\partial}{\partial x_j}(n_p v_{pj}) = -\frac{\partial}{\partial x_j}\overline{(n' v_{pj})} \qquad (14.1)$$

$$\frac{\partial}{\partial t}(n_p v_{pi}) + \frac{\partial}{\partial x_j}(n_p v_{pj} v_{pi})$$
$$= n_p g_i + n_p(v_i - v_{pi})(1/\tau_{rp} + \dot{m}_p/m_p)$$
$$-\frac{\partial}{\partial x_j}(n_p\overline{v_{pi}v_{pj}} + v_{pi}\overline{n_p v_{pj}} + v_{pj}\overline{n_p v_{pi}} + n_p\overline{v_{pi}v_{pj}}) \qquad (14.2)$$

with details and term definitions in ref. 241.

Combustion characteristics. Measurement and correlation of pulverized coal combustion characteristics is another research area in SKLECCC. A method for determining kinetic parameters of char oxidation has been developed. In this method, the activation energy, E, is independent of coal properties and only varies with the temperature of char particles, while the frequency factor of char oxidation, $k_{o,ch}$, is dependent on coal properties during its burning in air. The activation energy for carbon and char burning in air is a constant, 180 (kJ/mol). The frequency factor of char burning in air, $k_{o,ch}$, is

$$k_{o,ch} = 4.018(Fz + 27)^{1.808} \times 10^{-22}$$
$$\times [1 - (0.863 + 0.7082Fb + 0.2150Fb^2 + 0.0267Fb^3$$
$$+ 0.00107Fb^4) \times \exp(-Fb)] \qquad (14.3)$$

where Fz and Fb can be written in polynomial expressions. The details can be found in Fu *et al.*[243] and Fu and Zeng.[244]

14.2.2. *Circulating fluidized-bed combustors*

A mathematical model of single char particle combustion in circulating fluidized-bed combustors (CFBC) has been presented.[245] From this model, the

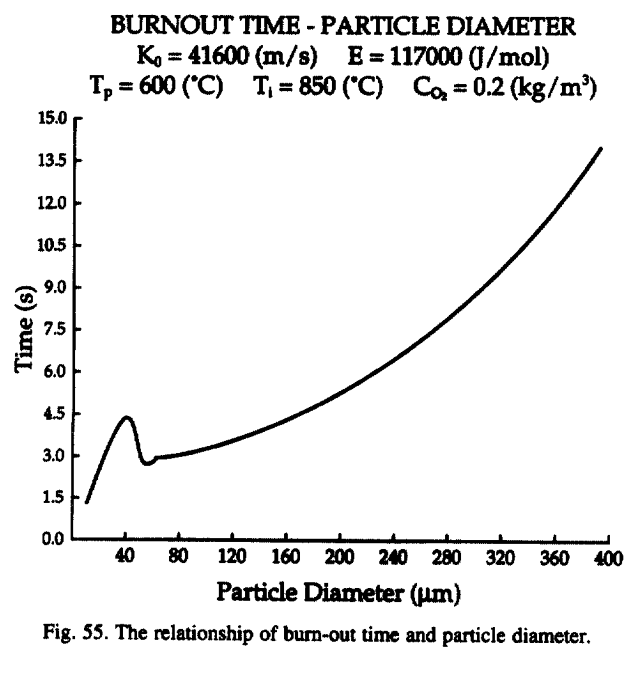

Fig. 55. The relationship of burn-out time and particle diameter.

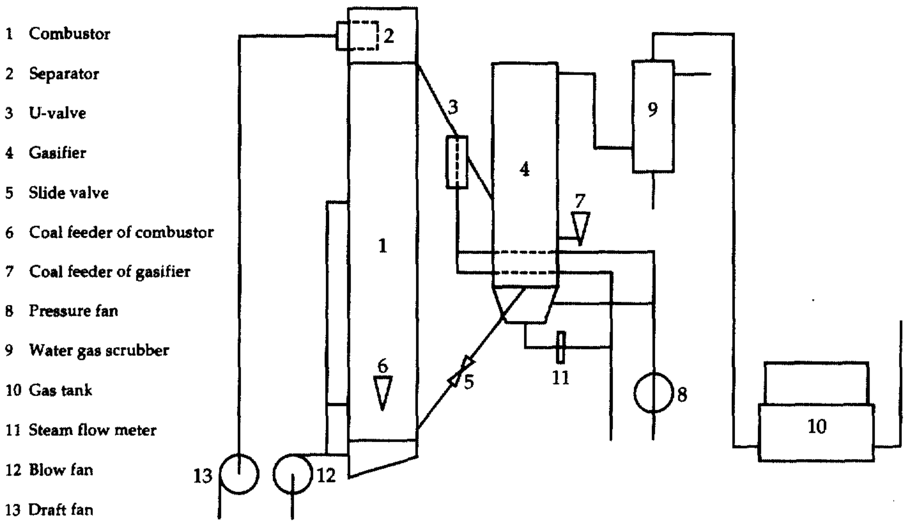

Fig. 56. The block diagram of tri-cogeneration of gas, heat, and power.

distribution of carbon content of char particles for operating condition of a CFBC has a peak value versus their diameters, shown in Fig. 55. This model also shows that the char particles 40–50 m in diameter are the most difficult to burn out.

Researchers of SKLECCC have done many experiments on separators for CFBC's separators. A new square-shaped separator has been developed. It has the advantages of easy manufacturing and reasonably good collection efficiency. The improved, square-shaped separator has the similar properties to the cyclone and the efficiency of the fine particles has been increased. Both numerical and experimental investigations on this kind of separator have been conducted.[246]

14.2.3. *Pollution control*

In China, about 87% of SO_x and 67% of NO_x pollution come from coal combustion. About 76% of the total is from coal. It is predicted that this percentage will not change in the next twenty years. With the rapid development of China's economy, the pollution control of coal combustion will become more and more critical. SKLECCC has paid substantial attention to the low SO_x and NO_x combustion techniques. Right now, a project, funded by China's government, of reducing SO_x and NO_x is on-going. A large-scale testing system to reduce SO_x concentrations in the flue-gas for a 20 T/h power plant is in the design stage for subsequent manufacture. From the experiments in the lab, it is estimated that the de-SO_x efficiency of the large-scale testing demonstration could be 85% with Ca/S = 1.5. Two of its advantages are the low primary cost and low operating cost.

14.2.4. *Tri-cogeneration of gas, heat and power*

China is facing the shortage of gas for domestic needs. Millions of families and restaurants still use coal for cooking and heating. It leads to serious energy waste and environmental pollution. The researchers at SKLECCC have been engaged in a project of tri-cogeneration of gas, heat and power with CFBC for several years.[247] The diagram of the process is in Fig. 56. In this process, large amounts of hot, circulating solid materials from a CFBC boiler are elutirated and entrained into a horizontal cyclone, which is also a part of the boiler, where they are separated and transported to a gasifier. In the gasifier, the hot materials, fluidized by superheated steam, are used as heat carrier and mixed with coal feed, rapidly increasing the temperature of the coal. The coal is pyrolysed, and a small portion of carbon in char is gasified by the mixture of the steam and pyrolysis gas. After purification, the gaseous product of pyrolysis and gasification can be used as town-gas with medium heating value. The unreacted char, together with the circulating solids, driven by gravity and the pressure difference between the gasifier and the combustor, flows downwards into the combustor through a slide valve. The remaining combustible materials in the char and the circulating solids as well as the coal fed directly to the combustor for load adjustment, burn to generate steam for power generation and heat supply. In 1992, a pilot-scale test system was built at Tsingjua University. Many results were obtained from this system. A demonstration project with steam capacity of 35t/h at 5.3 Mpa and 703K is being constructed and may be in operation next year.

15. DISCUSSION

15.1. *Centers' Characteristics*

Thirteen centers doing work in coal combustion from eight nations participated in this publication of the seventeen that were contacted. Table 36 provides a tabular comparative summary of information from the thirteen participating centers Included are centers approaching a half-century of productive work (e.g.,

Table 36. Comparative summary of participating center characteristics

Center/location	Years	Focus areas[1]	Personnel total	1996 Budget (U.S.$ millions)	% from government	Budget direction	Members	Projects	Major activities[2]	Fuels of increasing Interest
ACERC/Provo, Utah, U.S.A.	11	A,B,C,D,E	140	4.8	58	Declining	63	34	A,B,E,H,J	Natural gas, solid wastes
CRCS/Lisbon, Portugal	11	A,B,C,G,K	52	1.75	32	Increasing	4	15	B,D,H,I	Natural gas, solid wastes, mixed fuels
CRC-NTPGLRC/ Victoria, Australia	4	D,E,F,G	112	4.9	40	Increasing	14	42	A,B,E,G,H,I,J	Low-rank coal
CRC-BCU/Newcastle, Australia	1	H,D,N,J,I	54	4.9	33	Increasing	13	25	A,D,E,H,J	Black coal
CCET (CSIRO)/North Ryde, Australia	50	B,D,E,H,G,I	220	12.9	60	Steady	—	120	A,G,J,K	Natural gas, biomass
EERC/Grand Forks, North Dakota, U.S.A.	48	A,B,D,E,F,J,N	260	24.6	77	Increasing	93	207	A,D,F,G	—
EI/University Park, PA, U.S.A.	47	A,D,N	75	4.6	82	Increasing	43	27	A,D,E,F,H	Coal, water slurries, micronized coal
CC/Oxfordshire, UK	13	A,D,E,G	12	1.6	30	Steady	42	27	A,B,D,F	Fossil fuels
IVD/ Stuttgart Germany	44	A,B,C,D,K	120	5	15	Steady	—	30	—	High-rank coal, biomass
IFRF/IJmuiden, the Netherlands	42	A,D,E,J,M	30	4.2	27	Steady/ Declining	360	35	A,D,F,J model calc.	Coal, biomass, coke, gas. fuels
LIEKKI/Turku, Finland	10	D,L,M,N	29	1.9	45	Declining	13	32	A,E,H,I,L	Biomass, black liquor
NCCL/Wuhan, People's Republic of China	9	B,D,E,J	130	0.7	55	Increasing	18	35	A,B,C,F, H,J	Low-grade coal, wastes, mixed fuels
SKLECCC/Beijing, People's Republic of China	5	B,D,F	239	0.4	57	Steady	45	43	A,B,C,E, H,J	Biomass, coal
TOTAL	292		1473	72.3	—		708	615		
RANGE	1–50		12–260	0.4–24.6	15–82		4–360	15–207		
AVERAGE	22		113	5.6	47		54	47		

[1]A, fossil fuels; B, coal; C, waste materials; D, environmental; E, efficiency; F, low-rank coal; G, power generation; H, high-rank coal; I, metallurgical; J, industrial testing; K, control; L, black liquor; M, biomass/solid wastes; N, gasification, advanced technologies.

[2]A, experimental data; B, computer software; C, inventions/patents; D, reports; E, journal/book publications; F, consulting serivices; G, process/system concepts; H, graduating students; I, academic courses; J, technology transfer.

Table 37. Budget ranges

Annual budget ($ millions)	No. of centres	Average no/ of personnel	Average no. of members	Average no. of projects
<2	5	92	24	30
4–5	6	89	99	32
>12	2	240	93	163

CSIRO, EERC, EFRC, IVD, and IFRF), and those with less than about a half decade of experience (CRC(2), NCCL, SKLECCC). Centers range substantially in size as well, from over two-hundred personnel and $10 million annual budget (e.g., CSIRO, EERC), to less than 30 personnel (IFRF, LIEKKE, AEA), and for five centers, less than a $2 million annual budget. There is not a strong correlation between annual budget and participating personnel, participating members, or numbers of projects. However, participating personnel are not necessarily full-time and those from academically-related organizations and often involve students who work part-time.

The centers divide conveniently by budget range as shown in Table 37. On average, each center expends about $5 million per year, interacts with about 50 participating member organizations, and conducts about 50 projects. Budgets for three of the centers are declining, four are steady, and six are increasing. It must be recognized that economics in the represented nations can differ substantially. It is clear that China (PRC) can engage larger numbers of participants with smaller expenditures.

Table 38 provides a summary of fossil fuel production and consumption for the nations or regions where the participating centers are located.[248] This collection of countries produces nearly 2/3 of the world's coal production, and consumes over half of it, being net coal exporters. At the same time, the collection of countries produces far less of the world's oil and gas, and consumes much more than they produce, particularly oil for the U.S. and Western Europe. It should be noted that there is a strong element of international research in seven of the participating centers (ranging form 2% to 51% of annual expenditures) who do research for foreign organizations. The collective research output from all of the centers is an international contribution, with most of the work thought to be in the public domain.

15.2. *Total Impact*

As a collection, these 13 centers expend $72 million per year, conduct over 600 research projects, involving nearly 1500 researchers, and interact with over 700 organizations (some of whom must have been counted more than once, by participating in more than one center).

Numbers of publications (reports, journals, conferences, monographs, and books) were not identified for all centers, but based on partial data, an average of 50–100 publications per year is estimated for each center, suggesting about 1000 publications annually. The sections above illustrate some of the recent technical accomplishments for each center.

15.3. *Research Emphasis*

This review has only considered centers with a substantial research effort in coal combustion. However, as noted in Table 36, eight of the centers conduct significant research in other fossil fuels (oil, gas, slurries) and waste or biomass materials (wood, black liquor,

Table 38. Production and consumption of fossil fuels among the nations and regions where participating centers are located[249]

		% of world production (1995)		
Nation/region	Participating centers	Coal	Oil	Gas
A. Fossil fuel production				
U.S.A.	3	20.6	10.5	24.4
China	2	28.1	4.9	0.8
Australia	3	5.0	—	1.2
Western Europe	5	11.3	4.0[1]	11.0
Total	13	65.0	>19.4	37.4
B. Fossil fuel consumption				
U.S.	3	18.5	26.1	26.9
China	2	27.5	4.7	—
Australia	3	2.1	—	—
Western Europe	5	7.7	12.4	13.3
Total	13	55.8	>43.2	>40.2

[1]U.K.

municipal wastes). The five centers that have dominant emphasis on coal are the three centers in Australia and the two centers in China. All of the centers have a strong component of environmental research and most are concerned with questions of efficiency. Conventional power generation is a major driving force, but waste remediation and advanced conversion technologies (e.g., gasification) are of interest to several of the centers.

All of the centers also have a strong experimental test component, with testing typically at several scales. A smaller number of centers (e.g. ACERC, AEA, CRCS) develop and distribute combustion code software while all of the centers apply advanced computerized combustion codes to various combustion problems to at least some extent. All but one of the centers rated technology transfer to industrial participants as a high or very high priority. Only three of the centers (i.e., CRC-NTPGFLRC, CSIRO, EERC) noted high priority on specific process/systems development.

15.4. *Academic Activities*

All but one of the centers (i.e., AEA) make use of students at some level, though CSIRO involves only post-doctoral associates. The other eleven report substantial academic involvement with over 650 graduate and undergraduate students participating in center research, an average of about 60 students per center. Six of the centers indicate medium to high activity in academic courses, which most commonly are offered through the regular program of the University with whom the center associates.

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1. Abbreviations

CAAA Clean Air Act Amendment
CANMET Canadian Centre for Mineral and Energy Technology
CCTC Clean Coal Technology Coalition
EIA Energy Information Administration
RISØ Danish National Laboratory

2. Abbreviations

ACERC Advanced Combustion Engineering Research Center
BYU Brigham Young University
CARS Coherent Anti-Stokes Raman Spectroscopy
CFD Computational Fluid Dynamics
CPD Chemical Percolation, Devolatilization
DOE Department of Energy
ERC Engineering Research Center
FTIR Fourier Transform Infrared Radiation
GC Gas Chromatography
HiPPS High Performance Power System
LDA Laser-Doppler Anemometry
LEBS Low Emission Boiler Systems
METC Morgantown Energy Technology Center
MS Mass Spectroscopy
NASA National Aeronautics and Space Administration
NMR Nuclear Magnetic Resonance
NSF National Science Foundation
NYSEG New York State Electric and Gas Co.
PCGC-3 Pulverized Coal Gasification and Combustion Code—Three-Dimensional
PCSV Particle Counter-Size Velocimeter
PDPA Phase Doppler Particle Analyzer
PETC Pittsburgh Energy Technology Center
PLIF Planar Laser Induced Fluorescence
SNCR Selective, Non-Catalytic Reduction
U of U The University of Utah

3. Abbreviations

BRITE Basic Research in Individual Technologies for Europe
CFD Computational Fluid Dynamics
CIENCIA National Program for Scientific Infrastructures
CRCS Center of Heat and Mass Transfer in Radiating and Combustion Systems
DEM Department of Mechanical Engineering Technologies
EDP Portugese Electricity Generating Board
ENEL Italian Electricity Generating Board
ESPRIT European Strategic Programme for Research and Development in Information
Technology
ICSTM Imperial College of Science Technology and Medicine
IrRADIARE Research and Development in Engineering and Environment
IST Instituto Superior Técnico
JOULE Joint Opportunities for Unconventional or Long Term Energy Supply
LASEF Laboratory of Advanced Sensors for Fluid Flow
LASIQ-CNT Laboratory of Environment and Industrial Combustion Systems-Center of New Technologies
LDA Laser Doppler Anemometer
PEDIP National Program for the Development of Industry
THERMIE Projects for the Promotion of Energy Technologies

4. Abbreviations

APFBC Advanced Pressurised Fluid Bed Combustion
AEA AEA Technology, United Kingdom
CFB Circulating Fluid Bed
CFBC Circulating Fluid Bed Combustion
CFD Computational Fluid Dynamics
CFX4 A specific CFD commercial code
CRC Cooperative Research Centre
CSIRO Commonwealth Scientific and Industrial Research Organisation
HRL Limited An Australian Company

HT High Temperature
HTD Hydrothermal Dewatering
IGCC Integrated Gasification Combined Cycle
PDTF Pressurized Drop Tube Furnace
PFBC Pressurised Fluid Bed Combustion
R & D Research and Development
SFBD Steam Fluid Bed Drier
UK United Kingdom

5. Abbreviations

ACIRL Australian Coal Industry Research Laboratories
CCSEM Computer-Controlled Scanning Electron Microscopy
CRA-ATD Queensland Department of Mines and Energy Technological Resources Pty. Ltd.
CRC Cooperative Research Centre
CRE Coal Research Establishment, United Kingdom
IGCC Integrated Gasification with Combined Cycle
MRI Magnetic Resonance Imaging
NMR Nuclear Magnetic Imaging
NSW New South Wales
PCI Pulverised Coal Injection
PF Pulverised Fuel
PFBC Pressurised Fluidised Bed Combustion
TMA Thermochemical Analysis
UNSW University of New South Wales

6. Abbreviations

DCET Division of Coal and Energy Technology
CSIRO Commonwealth Scientific and Industrial Research Organization
NMR Nuclear Magnetic Resonance
PF Pulverized Fuel
R & D Research and Development
SIROQUANT X-Ray Diffraction Software

7. Abbreviations

DOE Department of Energy
EERC Energy & Environmental Research Center
ERDA Energy Research and Development Administration
JSRP Jointly Sponsored Research Program
UND University of North Dakota

8. Abbreviations

CFD Computation Fluid Dynamics
CWSF Coal-Water Slurry Fuel
EFRC Energy and Fuels Research Center
FBC Fluidized-Bed Combustion
kW Kilowatt
MW(e) Megawatt, electric
SCR Selective Catalytic Reduction
TGA Thermogravimetric Analysis
TIF Thermally Induced Fracture
W.C. Water Column

9. Abbreviations

BP British Petroleum
CARS Coherent Anti-Stokes Raman Spectroscopy
CBPE Burner Club
CFD Computational Fluid Dynamics
CFDS Computational Fluid Dynamics Services
CFX4 Fluid Dynamics Software Package
EEO Energy Efficiency Office
EGT European Gas Turbines
EPRI Electric Power Research Institute
HCCP Harwell Coal Combustion Programme
HMIP Her Majesty's Inspectorate of Pollution
HTFS Heat Transfer and Fluid Flow Service
LDA Laser Doppler Anemometry
LIF Laser Induced Fluorescence
LSI Light Sheet Illumination
MIDCOM Multi-Dimensional (Diagnostic Imaging for Combustion)
NOEMI Nitrogen Oxide Emissions Model Implementation
PAH Polyaromatic Hydrocarbons
PIV Particle Image Velocimetry
TECK Chemical Kinetics Software
U.K. United Kingdom

10. Abbreviations

ALS Task Group of Air Pollution Prevention at the University of Stuttgart
CHP Combined Heat and Power
IVD Institute of Process Engineering and Power Plant Technology
KSVA Pulverized Coal Combustion Test Facility
kW_{th} Kilowatt, thermal
LDA Laser-Doppler Anemometry
LIF Laser-Induced Fluorescence
MW_{th} Megawatt, thermal
VGB Technical Association of Large Power Plant Operators

11. Abbreviations

BISRA-UK British Iron and Steel Research Association, United Kingdom
CANMET Canadian Natural Resources
CBO Char Burnout
CC Char Combustion
DAF Dry, Ash-free
EC European Commission
ECSC European Coal, Steel Community
EERC Energy and Environmental Research Corporation
EI Emissions index
EPA Environmental Protection Agency
EZ Netherlands Ministries of Economic Affairs
HE Heat Extration
hvb High Volatile Bituminous
IFRA International Flame Radiation Association
IFRF International Flame Research Foundation
IFSB Internally Fuel-Staged Burner
IRSID-France Institut de Recherches de la Sidérurgie
kW_{th} Kilowatt, thermal
LIG Lignite
MW_{th} Megawatt, thermal
MVB Medium Volatile Bituminous
NEOM Netherlands Energy Development Corporation
OFA Over-fire Air

PAH Polyaromatic Hydrocarbons
SANT Semi-Anthracite
TEG Turbine Exhaust Gases
TFB Tangentially-fired Boiler
TVFN Total Volatile Fixed Nitrogen
VOMIL Environment Protection

12. Abbreviations
BLRB Black Liquor Recovery Boiler
BFBC Bubbling Fluidized Bed Combustor
CFBC Circulating Fluidized Bed Combustor
FBC Fluidized Bed Combustor
IVO IVO Group (IVO Power Engineerging)
LIEKKI Combustion and Gasification Research Center in Finland
LHV Lower Heating Value
PFBC Pressurized Fluidized Bed Combustors
PFBG Pressurized Fluidized Bed Gasifier
RDF Refuse-Derived Fuels
TEKES Technology Development Centre
VTT Technical Research Centre of Finland

13. Abbreviations
CIE Comission Internationale de L'Eclairage
CSI Combustion Stability Index
DTGA Differential Thermogravimetric Analysis
FBC Fluidized Bed Combustor
NCCL National Coal Combustion Laboratory
PDA Particle Dynamic Analyzer
PDF Probability Density Function
SPM Shapeless Pore Model

14. Abbreviations
CFBC Circulating Fluidized Bed Combustors
SKLECCC State Key Laboratory of Efficient and Clean Combustion of Coal

15. Abbreviations
AEA AEA Technology, United Kingdom
CRCS Center of Heat and Mass Transfer in radiating and Combustion Systems
CRC Cooperative Research Centre for Black Coal Utilisation
CRC Cooperative Research Centre for New Technologies for Power Generation from Low Rank Coal
CSIRO Commonwealth Scientific Industrial Research Organisation
EERC Energy and Environmental Research Center
EFRC Energy and Fuels Research Center
IFRF International Flame Research Foundation
IVD Institute of Process Engineering and Power Plant Technology
LIEKKI Combustion and Gasification Research Center in Finland
NCCL National Coal Combustion Laboratory
PRC People's Republic of China
SKLECCC State Key Laboratory of Efficient and Clean Combustion of Coal

1. REFERENCES

1. EIA, 'Annual Energy Review,' Report No. DOE/EIA 0384 (95), Energy Information Administration, U.S. Department of Energy, Washington D.C., 20585 (1995).
2. Smoot, L.D., 'The role of combustion research in the fossil energy industry,' *Energy and Fuels* **7**, 689–699 (1993).
3. Bernthal, F.M., National Critical Technologies Panel, U.S. Dept. of Commerce, PB93- 213742, Washington, D.C. (January 1993).
4. Gibbons, J.H. and David Jr., E.E., 'New opportunities for engineering in the Clinton Administration,' National Technical University Interactive Satellite Telecast, Colorado (September 21, 1993).
5. CCTC Newsbrief, Clean Coal Technology Coalition, Washington, D.C. (June 1994).
6. Lamarre, L., 'Worldwide activity in IGCC,' *EPRI Journal*, Electric Power Research Institute, Palo Alto, California, p. 6 (July/August 1994).
7. Craft III, J.W., Oliver, J.J. and Spencer, D.F., Clean Coal Technology for Sustainable Development, The National Coal Council, U.S. DOE, Arlington, Virginia (February 1994).
8. Jones, T., Coal Technology Transfer: Motivation and Markets, IEA Coal Research PER/10, London, England (1994).
9. Smoot, L.D., Fletcher, T.H. and Pershing, D.P., ACERC Annual Report, Vol. 1, Brigham Young University, Provo, Utah (February 15, 1994).

2. REFERENCES

10. Smoot, L.D. (Ed), *Fundamentals of Coal Combustion*, Elsevier, The Netherlands (1993).
11. Smoot, L.D., 'A decade of combustion research,' *Progr. Energy Combust. Sci.*, **23**, 203–232 (1997).
12. Smith, K.L., Smoot, L.D., Fletcher, T.H. and Pugmire, R.J., *The Structure and Reaction Processes of Coal*, Plenum Press, New York (1994).
13. Fletcher, T.H., Kerstein, A.R., Pugmire, R.J. and Grant, D.M., 'Chemical percolation model for devolatilization. 3. Direct use of ^{13}CNMR data to predict effects of coal type,' *Energy and Fuels* 6, 414–431 (1992).
14. Reade, W.C., Morris, K.W. and Hecker, W.C., 'Modeling the effects of burnout on high-temperature char oxidation,' *Coal Sci. Tech.* **24**, 639–649 (1995).
15. Benson, S.A., Jones, M.L. and Harb, J.N., 'Ash formation and deposition' (Chapter 4), in: L.D. Smoot (Ed), *Fundamentals of Coal Combustion*, Elsevier (1993).
16. Harb, J.N., Zygarlicke, C.J. and Richards, G.H., 'The effect of particle composition and temperature on the deposition of two western coals in a laminar drop-tube furnace,' *J. Inst. Energy* **66**, 91 (1993).
17. Richards, G.H., 'Investigation of mechanisms for the formation of fly ash and ash deposits from two powder river basin coals,' Ph.D. Dissertation, Brigham Young University, Provo, Utah (1994).
18. Richards, G.H., Slater, P.N. and Harb, J.N., 'Simulation of ash deposit growth in a pulverized coal-fired pilot scale reactor,' *Energy and Fuels* 7, 774–781 (1993).
19. Spinti, J., Pershing, D., Brouwer, J. and Heap, M., 'The influence of near burner combustion modifications on NO_x formation from an all-axial multi-fuel burner,' *Combustion Science and Technology*, **126**, 1–21 (1997).
20. Owens, W.D., Silcox, G.D., Lighty, J.S., Deng, X.X., Pershing, D.W., Cundy, V.A., Leger C.B. and Jakway, A.J., 'Thermal analysis of rotary kiln incineration: Comparison of theory and experiment,' *Combust. Flame* **86**, 101–114 (1991).
21. Denison, M.K. and Webb, B.W., 'k-distributions and

weighted-sum-of-gray-gases: A hybrid model,' *Heat Transfer* **2**, 19–24 (1994).
22. McMurtry, P.A. and Queiroz, M., 'Turbulent reacting flows,' in: L.D. Smoot (Ed), *Fundamentals of Coal Combustion*, Elsevier, The Netherlands, 511–566 (1993).
23. Hill, S.C. and Smoot, L.D., 'A comprehensive three-dimensional model for simulation of combustion systems: PCGC-3,' *Energy and Fuels* 7, 874–883 (1993).
24. Eaton, A.M., Smoot, L.D., Hill, S.C., Eatough, C.N., 'A review and evaluation of comprehensive fossil-fuel combustion models,' *Progr. Energy Combust. Sci.*, in review (1997).
25. Brewster, B.S., Cannon, S.M. and Kramer, S.K., 'Combustion modeling for advanced turbine systems,' *Prog. Energy Combust. Sci.*, in press (1998).
26. Bonin, M.P. and McQuay, M., 'A parametric evaluation of particle-phase dynamics in an industrial pulverized-coal-fired boiler,' *Fuel*, **75**, 195–206 (1996).
27. Boyack, K.W. and Hedman, P.O., 'Dual-Stokes CARS system for simultaneous measurement of temperature and multiple species in turbulent flames,' *Twenty-Third Symposium (International) on Combustion*; The Combustion Institute, Pittsburgh, PA, 1893–1899 (1990). See also Boyack, K.W., 'A study of turbulent non-premixed jet flames of CO/N_2 using CARS spectroscopy,' Doctoral Dissertation, Brigham Young University, Provo, Utah (April 1990).
28. Schmidt, S.E. and Hedman, P.O., 'CARS temperature and LDA velocity measurements in a turbulent, swirling premixed propane/air fueled model gas turbine combustor,' ASME Paper 95-GT-64, International Gas Turbine and Aero Engine Congress and Exposition, Houston, TX (June 5–8, 1995).
29. Smoot, L.D., 'The role of combustion research in the fossil energy industry,' *Energy and Fuels* 7, 689–699 (1993).

3. REFERENCES

30. Azevedo, J.L.T., 'Physical modeling and numerical simulation of solid fuel combustion systems,' Ph.D. Thesis, Instituto Superior Técnico (in Portuguese) (1994).
31. Azevedo, J.L.T. and Pereira, J.C.F., 'Flow patterns around and inside a bubble growing in a gas-fluidised bed,' *Chem. Eng. Sci.* **46**, 155 (1991).
32. Azevedo, J.L.T., Carvalho, M.G.S., Durão, D.F.G., 'Mathematic modeling of coal-fired fluidised bed combustors,' *Combust. Flame* **77**, 91 (1989).
33. Azevedo, J.L.T., Carvalho, M.G. and Foster, P., 'Modeling wood combustion in a fluidised bed,' *5th European Conference Biomass for Energy and Industry*, Grassi, G., Gosse, G. e Santos, G. (Eds), pp. 2.575–2.579, Elsevier Applied Science, London (1989).
34. Águas, M.P.N., Azevedo, J.L.T. and Carvalho, M.G., 'Modeling the heat transfer in a FBC,' *Heat and Technology* **10**, 107 (1992).
35. Saraiva, P.C., Azevedo, J.L.T. and Carvalho, M.G., 'Mathematical simulation of a circulating fluidised bed combustor,' *Combust. Sci. and Tech.* **93**, 223 (1993).
36. Saraiva, P.C., Azevedo, J.L.T. and Carvalho, M.G., 'Modeling combustion, NO_x emissions and SO_2 retention in a CAFBC,' *12th Int. Conf. on Fluidised Bed Combustion*, Lynn N. Rubow (Ed), pp. 375–380, ASME, San Diego (1993).
37. Azevedo, J.L.T. and Pereira, J.C.F., 'Calculation of free and confined gas-multiple size particles swirling jets,' *Turbulence Modification in Multiphase Flows*, E.E. Michaelidis, T.Fukano and A. Serizawa (Eds), pp. 111–117, ASME, Portland (1991).
38. Azevedo, J.L.T. and Carvalho, M.G., 'Modeling combustion and fuel-NO_x in pulverised coal flames,' *6th Workshop on Two-Phase Flow Predictions*, M. Sommerfeld (Ed), LSTM, Erlangen, pp. 313–323 (1992).
39. Azevedo, J.L.T. and Carvalho, M.G., 'Numerical modeling: The effect of using flue gas recirculation in pulverised coal combustion,' *2nd Int. Conf. on Combustion Technologies for a Clean Environment*, M.G. Carvalho, W.A. Fiveland, F.C. Lockwood and C. Papadopoulos (Eds), IST, Lisbon, pp. 9.22–27 (1993).
40. Coelho, P.J. and Carvalho, M.G., 'Numerical prediction of an oil-fired water tube boiler,' *Eng. Comput.* **7**, 227 (1990).
41. Costa, M., Azevedo, J.L.T. and Carvalho, M.G., 'Combustion characteristics of a front- wall fired pulverised coal 300 MW_e utility boiler,' Submitted to *Combust. Science and Technology* (1997).
42. Carvalho, M.G., Coelho, P.J., Moreira, A.L.N., Silva, A.M.C. and Silva T.F., 'Comparison of measurements and predictions of wall heat flux and gas composition in an oil-fired utility boiler,' *25th Symp. (Int.) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 227–234 (1994).
43. Coelho, P.J. and Carvalho, M.G., 'Evaluation of a three-dimensional mathematical model of a power station boiler,' *Journal of Engineering for Gas Turbines and Power* **118**, 887 (1996).
44. Coimbra, C.F.M., Azevedo, J.L.T. and Carvalho, M.G., '3-D Numerical model for predicting NO_x emissions from a pulverised coal industrial boiler,' *Fuel* **73**, 1128 (1994).
45. Coelho, L.R., Azevedo, J.L.T. and Carvalho, M.G., 'Numerical simulation and comparison of NO_x emissions from a low NO_x front wall fired boiler for different operating conditions,' *3rd Int. Symp. on Coal Combustion*, X. Xu and L. Zhou (Eds), Science Press, Beijing, pp. 617–624 (1995).
46. Azevedo, J.L.T., Coelho, L.M.R. and Carvalho, M.G., 'Numerical simulation of a pulverised coal fired boiler using flue gas recirculation and oxygen injection,' *Crocus 1994*, The Combustion Institute, Napoli, pp. II-17 (1994).
47. Carvalho, M.G., Azevedo, J.L.T., Coelho, L.R. and Branco, A.J., 'Numerical prediction of the impact of retrofitting RFG/O_2 technology for CO_2 enhancement on a full size front wall fired utility boiler,' Chapter 4 of final report of JOU-0220, Ed., G. Allen, Derby (1996).
48. Dinho, P., Coelho, L.R., Azevedo, J.L.T. and Carvalho, M.G., 'Modeling radiation in pulverised coal combustion,' *Heat Transfer in Radiating and Combusting Systems* 2, Eurotherm (1994).
49. Azevedo, J.L.T., Carnall, F. and Carvalho, M.G., 'Heat transfer assessment of a boiler convection section,' *New Developments in Heat Exchangers*, N. Afgan, M.G. Carvalho, A. Bar-Cohen, D. Butterworth and W. Roetzel (Eds), Gordon and Breach, Amsterdam, The Netherlands, pp. 117–129 (1996).

4. REFERENCES

50. Brockway, D.J. and Higgins, R.S., 'Brown coal sampling, analysis and composition,' Chapter 5, *The Science of Victorian Brown Coal*, RA Durie (Ed), Butterworth Heinemann, Oxford (1991).
51. Brockway, D.J., Ottrey, A.L. and Higgins, R.S., 'Inorganic constituents,' Chapter 11, *The Science of Victorian Brown Coal*, R.A. Durie (Ed), Butterworth Heinemann, Oxford (1991).
52. Bongers, G.D., Jackson, W.R. and Woskoboenko, F., 'High pressure steam drying of brown coal,' *Eighth International Coal Science Conference*, Oviedo, Spain (September 10–15, 1995).
53. Racovalis, L., Hobday, M., Hodges, S. and Hovelling, A., 'Analysis of organics in wastewater from coal processing,' *Proceedings, Third Annual RACI Research and*

Development Topics in Analytical Chemistry Conference, University of Newcastle (December 4–6, 1995).

54. Ouyang, S., Yeasmin, H. and Mathews, J.F., 'A new experimental system for measurement of coal devolatilisation, gasification and combustion kinetics under high pressure,' *Proceedings, Sixth Japan–Australia Joint Technical Meeting on Coal*, Hokkaido National Industrial Research Institute, Sapporo, Japan (June 1996).
55. Schluter, G.B., Zhang, D-k and Agnew, J.B., 'The combustion rate of a South Australian lignite in a fluidised bed,' *Proceedings, Australian Symposium on Combustion and the Fourth Australian Flame Days*, Paper No B3-2, Adelaide (November 9–10, 1995).
56. Meyyappan, M. and Perry, J.H., 'Numerical modelling of coal-water slurry combustion,' *Proceedings, Australian Symposium on Combustion and the Fourth Australian Flame Days*, Adelaide (November 9–10, 1995).
57. Griffin, P.G., Goch, D.C., Chadwick, B.L., Campisi, A. and Morrison, R.J.S., 'Reduction of undesirable gaseous species in the gasification process stream: Vapour phase sodium species, H_2S and NO_x,' *Proceedings, Australian Symposium on Combustion and the Fourth Australian Flame Days*, Adelaide (November 9–10, 1995).
58. Mackay, G.H., Mullins, P.J. and Riley, K.W., 'Loss of inorganics during the devolatilisation of Victorian Brown Coals,' *25th Symposium (International) on Combustion*, University of California, Irvine (July 31- August 5, 1994).
59. Schiuter, G.B., Linjewile, T.M., Zhang, D-k and Agnew, J.B., 'The influence of carbon type and oxygen concentration on the CO/CO_2 product ratio during combustion in an incipiently fluidised bed,' *Proceedings of CHEMECA '94*, Perth, Vol. 1, pp. 443–449 (September 1994).
60. Zhang, D-k, Schluter, G.B., Linjewile, T.M. and Agnew, J.B., 'Measurement of the CO/CO_2 product ratio from single particle combustion in an incipiently fluidised bed and char reactivity,' *Proceeding, The Third ASEAN—Pacific International Symposium on Combustion and Energy Utilisation*, pp. 366–371, Hong Kong (December 1995).
61. Agnew, J.B., Schluter, G.B. and Zhang, D-k, 'Gasification and combustion of low-rank coals in fluidised beds,' *World Chem. Eng. Congress*, San Diego (July 1996).
62. Ross, D., 'Investigation into the devolatilisation, decomposition and combustion of volatile matter during fluidised bed gasification of low-rank coal,' *Cooperative Research Centre for New Technologies for Power Generation from Low-Rank Coal*, Report No 97006, Melbourne, Australia (1997).
63. Meyyappan, M., Witt, P.J., Perry, J.H. and Bulach, V., 'Numerical simulation of a tangentially fired multi-burner coal fired furnace,' *Second CFDC International User Conference*, Pittsburgh, USA (September 5–9, 1994).
64. Witt, P.J. and Perry, J.H., 'Application of multiphase modelling to the hydrodynamics in circulating fluidised beds,' *2nd CFDS International User Conference*, Pittsburgh, USA (December 5–9, 1994).
65. Witt, P.J. and Perry, J.H., 'Prediction of the hydrodynamic behaviour and outlet gas composition of a fluidised bed coal fired gasifier,' *Proceedings, Australian Symposium on Combustion and the Fourth Australian Flame Days*, Adelaide (November 9–10, 1995).
66. Chadwick, B.L. and Morrison, R.J.S., 'Monte-Carlo simulation of radiation trapping and quenching of photofragment fluorescence after 193 nm photolysis of NaCl,' *Journal of the Chemical Society, Faraday Transactions* **91**, pp. 1931–1934 (1995).
67. Chadwick, B.L., Morrison, R.J.S. and Domazetis, G., 'Multiwavelength monitoring of photofragment fluorescence after 193 nm photolysis of NaCl and NaOH: Application to measuring the sodium species released from coal at high temperatures,' *Analytical Chemistry* **67**, pp. 710–716 (1995).
68. Chadwick, B.L., Ashman, R.A., Campisi, A., Crofts, G.J., Godfrey, P.D., Griffin, P.G., Ottrey, A.L. and Morrison, R.J.S., 'Development of techniques for monitoring gas-phase sodium species formed during coal combustion and gasification,' *Proceedings, 1995 International Chemical Congress of Pacific Basin Societies*, Honolulu, Hawaii (1995).
69. Manzoori, A.R. and Agarwal, P.K., 'The role of inorganic matter in coal in the formation of agglomerates in circulating fluid bed combustors,' *Fuel* **72**, 1069–1076 (1993).
70. Manzoori, A.R. and Agarwal, P.K., 'Agglomeration and defluidization under simulated circulating fluidized bed combustion conditions,' *Fuel* **73**, 563–568 (1994).
71. Nguyen, Q.D. and Miah, A.S., 'A review on the rheology and rheological measurement of molten coal ash,' *Cooperative Research Centre for New Technologies for Power Generation from Low-Rank Coal*, Report No 96031, Melbourne, Australia (1996).
72. Achim, D., Easton, A.K., Perry, J.H. and Schwarz, P.M., 'Mathematical modelling of erosion in a fluidised bed,' *Proceedings, Twelfth Australian Fluid Mechanics Conference*, The University of Sydney, pp. 489–492 (December 10–15, 1995).
73. Bhattacharya, S.P. and McIntosh, M.J., 'Evaluation of advanced power cycles for use with low-rank coals,' Cooperative Research Centre for New Technologies for Power Generation from Low-Rank Coal, Report No 97005, Melbourne, Australia (1997).
74. Zhang, D.K., Agnew, J.B. and Manzoori, A.R., 'Fluid bed gasification of Australian low- rank coal,' *Proceedings of the 5th Japan-Australia Joint Technical Meeting on Coal*, Adelaide (June 1995).
75. Manzoori, A.R. and Williams, R.G., 'Utilisation of low-grade, low-rank coal using circulating fluidised bed combustion technology,' *Proceedings, Australian Symposium on Combustion and the Fourth Australian Flame Days*, Adelaide (November 9–10, 1995).

5. REFERENCES

76. Alfredson, P.G., 'The Cooperative Research Centre for Black Coal Utilisation,' *Chemeca 95 Conference*, Adelaide (September 1995).
77. Alfredson, P.G., 'The Australian Cooperative Research Centre for Black Coal Utilisation—Potential for reduced greenhouse gas emissions through improved efficiencies,' *IEA Greenhouse Conference*, London (August 1995).
78. Dale, L.S., 'Modes of occurrence of trace elements in coal and significance in combustion,' Technical session of Executive Committee meeting of IEA COAL Combustion Sciences Agreement - Annex 1, CANMET, Ottawa (June 10, 1996).
79. Elliott, L., Wang, S.M., Wall, T.F., Novak, F., Lucas, J., Hurst, H., Patterson, J. and Happ, J., 'Dissolution of lime into synthetic coal ash slags,' *Melt Chemistry Symposium Proceedings*, G.K. Williams, CRC for Extractive Metallurgy, Ed. S. Wright, pp. 151–158 (1996).
80. Elliott, L., Wang, S.M., Wall, T.F., Novak, F., Lucas, J., Hurst, H., Patterson, J. and Happ, J., 'Dissolution of lime into synthetic coal ash slags,' American Chemical Society, Division of Fuel Chemistry, Preprints of Papers, *211th ACS National Meeting*, New Orleans, pp. 41(2), 647–651 (1996).
81. Gupta, S., Wall, T.F., Creelman, R.A. and Gupta, R., 'Ash fusion temperatures and the transformations of coal ash particles to slag,' American Chemical Society, Division of Fuel Chemistry, Preprints of Papers, *211th ACS National Meeting*, New Orleans, pp. 41(2), 647–651 (1996).
82. Harris, D.J., Smith, I.W., Nixon, B.T., Prokopiuk, A.J., Cahill, P.H., Beath, A.C. and Wall, T.F., 'Laboratory evaluation of Australian coals for advanced power generation technologies: Gasification yield and conversion

efficiency,' *Australian Symposium on Combustion Proceedings*, Australian and NZ Section of the Combustion Institute (1995).

83. Hart, J.A., 'Clean coal technology for the future: Preparing the way for Australian Black Coal,' *1996 Australian Coal Conference*, Gold Coast, Queensland (May 1996).
84. Hart, J.A., 'Achieving low environmental impact from coal production and utilisation,' *Second APEC Coal Flow Seminar*, Shanghai (December 1995).
85. Hart, J.A., 'Performance of clean coal technologies with Australian Black Coals,' *Asia Coal 96 Conference*, Singapore (March 1996).
86. Hart, J.A., 'Progress report on the Cooperative Research Centre for Black Coal Utilisation,' *Sixth Japan-Australia Joint Technical Meeting on Coal*, Sapporo (June 1996).
87. Li, Y.H., Lu, G.Q. and Rudolph, V., 'NO_x and N_2O reduction kinetics over coal char in fluidised bed combustion,' *Chemical Engineering Science*, in press (1996).
88. Lu, G.Q., 'A kinetic model of NO carbon reaction for NO_x reduction,' *Proceedings of Australian Symposium on Combustion*, C1: 19–24, Gawler, Adelaide (November 9–10, 1996).
89. Wall, T.F., Coin, C., Creelman, R.A., Lowe, A., Gupta, R.P. and Gupta, S., 'Coal ash fusion temperatures—new characterisation techniques and associations with phase equilibria, ash deposit properties and radiative transfer in coal fired plant - Current understanding and new developments,' *Engineering Foundation Conference on Applications of Advanced Technology to Ash-Related Problems Proceedings*, Waterville Valley, New Hampshire, in press (1995).
90. Wall, T.F., Paulson, CJ., Boyd, R., Truelove, J.S., Johnson, T.R. and Waraker, K., 'Developments in thermal coal utilisation in the power generation and steel industries - Implications for international coal trade and collaborative research,' *11th IFRF Members Conference Proceedings*, International Flame Research Foundation, Ijmuiden, The Netherlands (1995).
91. Wang, S., Lu, G.Q. and Tang, H.S., 'Prospects of carbon dioxide utilisation as a source of carbon,' *Proceedings of Chemeca '95*, Adelaide, (Ed. K.D. King), Vol. 2, pp. 42–47 (1995).
92. Wall, T.F., Coin, C., Creelman, R.A., Lowe, A., Gupta, R.P. and Gupta, S., 'Coal ash fusion temperatures—new characterisation techniques and associations with phase equilibria,' American Chemical Society, Division of Fuel Chemistry, Preprints of Papers, *211th ACS National Meeting*, New Orleans, pp. 41(2), 647–651 (1996).
93. Wang, S.M., Wall, T.F., Lucas, J.A., Beath, A.C. and Elliott, L., 'Experimental studies and computer simulation of dissolution of lime particles into coal ash slag,' *Australian Symposium on Combustion Proceedings*, Australian and NZ Section of the Combustion Institute (1995).
94. Wilson, K.M., Tate, A.G. and Wall, T.F., 'Characterisation of coal combustion from individual coal particles,' *Australian Symposium on Combustion Proceedings*, Australian and NZ Section of the Combustion Institute (1995).
95. Visona, S.P. and Stanmore, B.R., 'Modelling NO_x release from a single coal particle I. Formation of NO from volatile nitrogen,' *Combust. Flame*, pp. 105, 92–103 (1996).
96. Visona, S.P. and Stanmore, B.R., 'Modelling NO_x release from a single coal particle II. Formation of NO from char nitrogen,' *Combust. Flame*, pp. 106, 208–218 (1996).
97. Visona, S.P., Singh, B., Rowland, W.L. and Stanmore, B.R., 'Modelling NO_x formation in commercial swirl and low NO_x burners,' *1995 American Flame Research Committee International Symposium*, Monterey, CA (October 1995).
98. Visona, S.P. and Stanmore, B.R., 'Three-dimensional modelling of NO_x formation in a 275 MW utility boiler,' *Fourth Australian Flame Days*, Gawler (November 1995).
99. Visona, S.P. and Stanmore, B.R., 'Prediction of nitric oxide formation in a turbulent, premixed, pulverised coal flame,' *2nd International Conference on Combustion and Emissions Control*, London, p. 199 (December 1995).

8. REFERENCES

100. Morrison, J.L., Miller, S.F. and Scaroni, A.W., 'Preparation of coal water slurry fuels from bituminous coal fines,' *21st Internat. Conf. on Coal Utilization and Fuel Systems*, Coal and Slurry Technology Assoc. and ASME-FACT, Washington, D.C., 487–497 (1996).
101. Morrison, J.L., Miller, B.G. and Scaroni, A.W., 'Preparing and handling coal-water slurry fuels: potential problems and solutions,' *18th Internat. Conf. on Coal Utilization and Fuel Systems*, Coal and Slurry Technology Assoc., Washington, D.C., 361–368 (1993).
102. Scaroni, A.W., Tsai, C.Y., McIlvried, T.S. and Jenkins, R.G., 'The combustion of a coal-water fuel with oxygen-enriched air,' *Eighth Internat. Symp. on Coal Slurry Fuels Preparation and Utilization*, U.S. Department of Energy, Pittsburgh Energy Technology Center, Pittsburgh, PA, 409–421 (1986).
103. Hassel, G., Scaroni, A.W., Maloney, D.J. and Tran, P.X., 'The effect of surfactant additives on the evaporative behavior of coal water slurry fuels,' Fossil Fuels Combustion Symp., *12th Annual Energy Sources Technology Conf.*, ASME, United Engineering Center, New York, NY, 49–52 (1989).
104. Yavuzkurt, S., Ha, M.Y., Koopman, G. and Scaroni, A.W., 'A model of the enhancement of coal combustion using high intensity acoustic fields,' *Proc. 26th National Heat Transfer Conference*, R.K. Shah, Ed., ASME, United Engineering Center, New York, HTD-106, 439–446 (1989).
105. Miller, S.F., Schobert, H.H. and Scaroni, A.W., 'The effect of mineral matter and coal particle size distribution on ash particle size distribution during combustion of pulverized coal versus coal water fuel,' *16th Internat. Conf. on Coal and Slurry Technologies*, Coal and Slurry Technology Assoc., Washington, D.C., 697–707 (1991).
106. Xie, J., Walsh, P.M., Miller, B.G. and Scaroni, A.W., 'Evaluation of erosion–oxidation and ash deposition in the convective section of an industrial watertube boiler retrofitted to fire coal water fuel,' *19th Internat. Conf. on Coal Utilization and Fuel Systems*, Coal and Slurry Technology Assoc., Washington, D.C., 721–732 (1994).
107. Miller, S.F., Morrison, J.L. and Scaroni, A.W., 'The effect of cofiring coal water slurry fuel formulated from coal waste fines with pulverized coal on NO_x emissions,' *21st Internat. Conf. on Coal Utilization and Fuel Systems*, Coal and Slurry Technology Assoc. and ASME-FACT, Washington, D.C., 499–510 (1996).
108. Jennings, P.L., Borio, R.W., Miller, B.G., Scaroni, A.W. and McGowan, J.G., 'Installation and initial testing of micronized coal in a gas/oil-designed package boiler,' *Tenth Annual Coal Preparation, Utilization, and Environmental Control Contractors Review Meeting*, U.S. Department of Energy, 467–474 (1994).
109. Miller, B.G., Bartley, D.A., Poe, R.L. and Scaroni, A.W., 'A comparison between firing coal water slurry fuel and dry, micronized coal in an oil-designed industrial watertube boiler,' *20th Internat. Conf. on Coal Utilization and Fuel Systems*, Coal and Slurry Technology Assoc., Washington, D.C., 267–278 (1995).
110. Patel, R., Thornock, D.E., Borio, R.W., Miller, B.G. and Scaroni, A.W., 'Demonstration of microfine coal firing with the RSFC burner in a gas/oil designed industrial boiler,' *21st Internat. Conf. on Coal Utilization and Fuel*

Systems, Coal and Slurry Technology Assoc., Washington, D.C. (1996).
111. Pisupati, S.V. and Scaroni, A.W., 'The influence of weathering on the combustion behavior of bituminous coals,' Fossil Fuel Combustion Symposium, *13th Annual Energy Sources Technology Conf.*, PD-Vol. 30, S. H. Singh (Ed), ASME, 87–97 (1990).
112. Pisupati, S.V. and Scaroni, A.W., 'Effects of inorganic changes caused by natural weathering on the combustion behavior of bituminous coals,' *Preprints, Amer. Chem. Soc., Div. Fuel Chem.* **35**(3), 680–688 (1990).
113. Pisupati, S.V., Scaroni, A.W. and Stoessner, R.D., 'Combustion characteristics of naturally weathered (in situ) bituminous coals,' *Fuel Processing Techn.* **28**, 49–66 (1991).
114. Pisupati, S.V., Miller, B.G. and Scaroni, A.W., 'Effect of blending low grade anthracite products with bituminous coals on combustion characteristics in a bench scale stoker simulator,' *Fuel Processing Tech* 32, 159–179 (1993).
115. Artos, V. and Scaroni, A.W., 'TGA and drop tube reactor studies of the combustion of coal blends,' *Fuel* **72**, 927–933 (1993).
116. Rozelle, P.L. and Scaroni, A.W., 'The influence of mining and preparation on the fluidized bed combustion of coal products,' *Joint Power Generation Conf.*, ASME, in Fuel and Sorbent Preparation for Fluidized Bed Boilers, United Engineering Center, New York, NY, FACT-Vol. 3, 35–41 (1988).
117. Morrison, J.L., Miller, B.G., Romans, D.E., Pisupati, S.V., Miller, S.F. and Scaroni, A.W., 'Fluidized bed boilers—SO_2 capture aspects,' *Proc. SO_2 Capture Seminar, Sorbent Options and Considerations*, National Stone Assoc., Washington, D.C., 3.1–3.15 (1993).
118. Pisupati, S.V., Morrison, J.L., Romans, D.E., Miller, B.G. and Scaroni, A.W., 'Importance of calcium carbonate content on the sulfur capture performance of naturally-occurring sorbents in a 30 MW(e) circulating fluidized-bed plant,' *Twelfth Internat. Conf. on Fluidized Bed Combustion*, ASME, San Diego, CA, 1069–1078 (1993).
119. Haji-Sulaiman, M.Z. and Scaroni, A.W., 'The rate limiting step in the sulfation of natural limestones during fluidized bed coal combustion,' *Fuel Processing Tech.* 31, 193–208, (1992).
120. Pisupati, S.V., Wasco, R.S., Morrison, J.L. and Scaroni, A.W., 'Sorbent behavior in circulating fluidized bed combustors: The relevance of thermally induced fractures to particle size dependency,' *Fuel* 75(6), 759–768 (1996).
121. Romans, D.E., Aragon, E.D. and Scaroni, A.W., 'The application of statistical analysis of bench scale data for the prediction of sorbent performance in full-scale CFBC systems,' *Tenth Annual Internat. Pittsburgh Coal Conf.*, University of Pittsburgh, Pittsburgh, PA, 583–588 (1993).
122. Romans, D.E., Liu, Y., Pisupati, S.V. and Scaroni, A.W., 'The effect of experimental technique in determining sorbent performance for FBC applications,' *Proceedings of the 7th International Conference on Coal Science*, Vol II, International Energy Agency, Banff, Alberta, Canada (Sept. 12–17, 1993).
123. Hu, N. and Scaroni, A.W., 'The fragmentation of calcium-based sorbents under high heating rate, short residence time conditions,' *Fuel* **74**, 374–383 (1995).
124. Hu, N. and Scaroni, A.W., 'Calcination of pulverized limestone particles under furnace injection conditions,' *Fuel* **75**(2), 177–186 (1996).
125. Sharifi, R., 'A numerical and experimental investigation of a retrofitted industrial boiler firing dry micoronized coal,' Ph.D. Thesis, The Pennsylvania State University (1996).
126. Simons, G.A., Oehr, K.H., Zhou, J., Pisupati, S.V., Wójtowicz, M.A. and Bassilakis, R., 'Simultaneous SO_x/NO_x control using BioLime in PCC and CFBC,' *Proceedings of the Thirteenth Annual Pittsburgh Coal Conference*, University of Pittsburgh, School of Engineering, Pittsburgh, PA, pp. 1400–1405 (September 3–6, 1996).
127. Pisupati, S.V., Simons, G.A., Oehr, K.H. and Zhou, J., 'Effect of BioLime atomization characteristics on simultaneous NO_x and SO_x capture in coal combustion systems,' to be published in the *Proceedings of the Fourteenth Annual Pittsburgh Coal Conference*, University of Pittsburgh, School of Engineering, Pittsburgh, PA (Sept. 22–26, 1997).
128. Ramachandran, P., Scaroni, A.W. and Jenkins, R.G., 'Commercial CWSF burners in the United States,' in 'Coal Liquid Mixtures,' *I Chem E Symp. Series* **107**, 219–128 (1987).
129. Kinneman, W., Scaroni, A.W., Miller, B.G., Wincek, R.T. and Jenkins, R.G., 'Conversion of a 1,000 lb/h water tube boiler to fire CWSF,' *13th Internat. Conf. on Coal and Slurry Technology*, Slurry Technology Assoc., Washington, D.C., 725–736 (1988).
130. Miller, B.G. and Scaroni, A.W., 'Superclean coal-water slurry combustion testing in an oil-fired boiler,' *Eighth Annual Coal Preparation, Utilization and Environmental Control Contractors Conference*, U.S. Department of Energy, Pittsburgh Energy Technology Center, Pittsburgh, PA, 27–34 (1992).
131. Miller, B.G., Scaroni, A.W., Kinneman, W.P., Wincek, R.T. and Jenkins, R.G., 'Combustion of CWSF in a 1,000 lb/h water tube boiler,' *13th Internat. Conf. on Coal and Slurry Technology*, Coal and Slurry Technology Assoc., Washington, DC, 119–129 (1988).
132. Wincek, R., Kinneman, W., Miller, B.G., Scaroni, A.W., Kal, F. and Shefet, D., 'Development of an automatic control system for a coal-water slurry fuel fired boiler,' *American Institute of Chemical Engineers AIChE Spring National Meeting*, Houston, TX (April 2–6, 1989).
133. Miller, B.G. and Scaroni, A.W., 'An update of Penn State's superclean coal water slurry demonstration program,' *16th Internat. Conf. on Coal and Slurry Technologies*, Coal and Slurry Technology Assoc., Washington, D.C., 587–598 (1991).
134. Morrison, D.K., Frato, R.L., Melick, T.A., Sommer, T.M., Miller, B.G. and Scaroni, A.W., 'Engineering design considerations of industrial boiler retrofits,' *Tenth Annual Coal Preparation, Utilization, and Environmental Control Contractors Review Meeting*, U.S. Department of Energy, Pittsburgh Energy Technology Center, Pittsburgh, PA, 499–506 (1994).

11. REFERENCES

135. Thring, M.W., 'Proposal for the establishment of an international research project on luminous adiation,' The British Iron and Steel Research Association, Physics Note No. 40 (November 22, 1948).
136. Flame Radiation Research Joint Committee, List of Reports of 1949 Trials at IJmuiden, with Journal References, *Supplement to the Journal of the Institute of Fuel* (January 1952).
137. Hubbard, E.H., 'The effect on flame emissivity and radiation of the addition of carbon black to liquid fuels,' *J. Inst. Fuel* (July 1959).
138. Mayorcas, R. and Rivière, M., 'Description of trials and results,' *J. Inst. Fuel* (October 1953).
139. Rivière, M., 'The influence of mixing conditions on flame characteristics: Performance trials No. VI, carried out on original furnace,' *J. Inst. Fuel* (January 1956).
140. Thring, W.M. and Newby, M.P., *The Fourth International Symposium on Combustion*, Baltimore, The Williams &Wilkins Company, Cambridge, MA, 789 (1953).
141. Chigier, N.A. and Beér, J.M., 'Velocity fields in double concentric jets,' IFRF Doc. No. G 02/a/1 (1962).

142. Beér, J.M., 'Some results of the first trials on pressure jet oil flames in the IJmuiden furnace,' *J. Inst. Fuel* (January 1962).
143. Michelfelder, S. and Jacobs, J., '20 Jahre Kohlenstaubfeurungs-Forschung der IFRF/DVV und aktuelle Versuchsergebinsse von Kohlenstaubflammen,' *VGB Kraftwerkstechnik* 58, Heft 12, 904–915 (December 1978).
144. Craya, A. and Curtet, R., 'Sur l'evolution d'um jet en espace confiné,' *Compt. Rend.*, 241, 1, pp. 621–2 (1955).
145. Hubbard, E.H., 'Recirculation in cold models of furnaces: A review of work carried out at SOGREH,' *J. Inst. Fuel* (April 1962).
146. Chedaille, J., Leuckel, W. and Chesters, A.K., 'Aerodynamic studies carried out on turbulent jets by the International Flame Research Foundation,' *J. Inst. Fuel*, **39**, 506–521 (1966).
147. Chigier, N.A. and Beér, J.M., 'Velocity and static-pressure distributions in swirling air jets issuing from annular and divergent nozzles,' *ASME J. Basic Engng*, 86D, 788–796 (1964).
148. Leuckel, W., 'Swirl intensities, swirl types and energy losses of different swirl generating devices,' IFRF Doc. No. G02/a/16 (1967).
149. Fricker, N. and Leuckel, W., 'Flow and mixing patterns in gas flames with swirl in the annular air stream,' IFRF Doc. Nr. G 02/a/182 (June 1969). See also *J. Inst. Fuel*. **49**, 152–158 (1976).
150. Chedaille, J. and Braud, Y., *Measurements in Flames*, Edward Arnold (Publishers) Ltd., London (1972).
151. Beér, J.M.. and Chigier, N.A., *Combustion Aerodynamics*, Applied Science Publishers Ltd., London (1972).
152. Lowes, T.M., Bartelds, H., Heap, M.P., Michelfelder, S. and Pai, R.B., 'Prediction of radiant heat flux distribution,' IFRF Doc. No. G 02/a/26 (1973).
153. Bartelds, H., Heap, M.P. and Lowes, T.M., 'Radiative heat transfer in enclosures,' Vol. I and II, IFRF Doc. No. G 04/a/6 (1977).
154. Michelfelder, S. and Lowes, T.M., 'Report on M-2 trials,' IFRF Doc. No. F 36/a/04 (1973).
155. Michel, J.B. and Payne, R., 'Detailed measurements of long pulverized coal flames for the characterization of pollutant formation,' IFRF Doc. No. F 09/a, 23 (1980).
156. Heap, M., Lowes, T.M. and Martin, G.B., 'The optimization of aerodynamic design variables to control the formation of nitric oxide in fossil flames,' IFRF Doc. No. K20/Q/70, IJmuiden (1979).
157. Leikert, K. and Michelfelder, S., 'Operating experience and field data of a 700 MW coal- fired utility boiler with retrofit low-NOx staged mixing burners,' *Joint EPA/EPRI Symposium on Stationary Combustion NOx Control*, Vol. 1, Denver/USA (October 1980).
158. Phelan, W.J. and Bortz, S., 'Studies on the influence of burner design parameters on NOx reduction when staging the combustion air for four diverse coals,' IFRF Doc. No. F 137/a/14 (1984).
159. Flament, G., 'Direct sulphur capture in flames through the injection of sorbents,' IFRF Doc. No. G 19/a/9 (November 1980).
160. Thorneycroft, W.S. and Flament, G., 'Direct SO_2 capture by ash or calcium based additives in long pulverized coal flames with flue gas recycling, for unwashed and washed French coals,' IFRF Doc. No. F 038/a/4 (1985).
161. Brice, H., *et al.*, 'Reduction of sulphur dioxide emissions from a coal fired power station by direct injection of calcium sorbents in furnace,' *The First EPRI/EPA Joint Symposium on Dry SO2 and Simultaneous SO_2/NO_X Control Technologies*, San Diego, California (November 1984).
162. Flament, P., Weber, R. and Bortz, S., 'Calcination and sulphation of calcium based sorbents under controlled condition,' IFRF Doc. No. F 138/a/7 (1986).
163. Weber, R., Smart, J.P. and Phelan, W.J., 'NO_X reduction with coal firing by application of both internal air staging and fuel rich precombustors,' IFRF Doc. No. 037/a/16 (1987).
164. Smart, J.P. and Weber, R., 'NO_X reduction and burnout optimization using aerodynamic air staging and air staged precombustors,' IFRF Doc. No. 037/a/18 (1987).
165. Smart, J.P. and Weber, R., 'Reduction of NO_x and optimization of burnout with an Aerodynamically Air-Staged Burner and an Air-Staged Precombustor Burner,' *J. Inst. Energy*, Vol. LXII, No. 453 (1989).
166. Smart, J.P., Knill, K.J., Visser, B.M. and Weber, R., *The 22nd International Symposium on Combustion*, The Combustion Institute, pp. 1117–1125 (1988).
167. Knill, K.J., Kimura, N. and Smart, J.P., 'Effect of coal particle size and gun design on NO_X reduction using an aerodynamically air staged burner,' IFRF Doc. No. F 88/a/6 (1987).
168. Knill, K.J., Dekker, J.S. and Morgan, M.E., 'Evaluation of the effect of process variables on NO_X and nitrogen species reduction in coal fuel staging,' IFRF Doc. No. F 37/a20 (1988).
169. Knill, K.J., Nakamura, T. and Morgan, M.E., 'The effect of mixing on coal fuel staging,' IFRF Doc. No. F 37/y/21 (1989).
170. Knill, K.J. and Morgan, M.E., 'The influence of mixing on NO_X reduction by coal fuel staging,' IFRF Doc. No. K 70/y/27 (1990).
171. Knill, K.J., Maalman, T.F.J. and Morgan, M.E., 'Development of a combustion characterization technique for high volatile bituminous coals,' IFRF Doc. No. F 88/a/10 (1989).
172. Smart, J.P. and Maalman, T., 'An analytical procedure for the quantitative determination of NH_3 and HCN in combustion systems,' IFRF Doc. No. F 72/1/16 (1987).
173. Beér, J.M. and Claus, J., 'The traversing method for radiation measurements in luminous flames,' IFRF Doc No. C 72/a/6 (1967).
174. Sayre, A., Lallemant, N., Dugué, J. and Weber, R., *The 25th International Symposium on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 235–242 (1994).
175. Dugué, J., Horsman, H., Mbiock, A. and Weber, R., 'Flow visualization and mixing characterization in industrial natural gas flames,' *International Gas Research Conference*, Cannes, France (November 6–9, 1995).
176. Sayre, A.N., Dugué, J., Weber, R., Domnick, J. and Lindenthal, A., 'Characterization of semi-industrial-scale fuel-oil sprays issued from a Y-jet atomizer,' *J. Inst. Energy* **67**, pp. 70–77 (June 1994).
177. Breussin, F.N. and Peters, A.A.F., 'IFRF user defined subroutines to fluent, pulverized coal combustion software package, Part 1: User manual to main subroutines,' IFRF Doc. No. L19/y/01 (1995), 'Part 2: User manual to NO_X post-processor,' IFRF Doc. No. L19/y/02 (1995).
178. Peters, A.A.F. and Weber, R., 'Mathematical modeling of a 2.4 MW_t swirling pulverized coal flame,' *Combust. Sci. and Tech*, in press.
179. Peters, A.A.F. and Weber, R., 'Mathematical modeling of a 2.25 MW_t swirling natural gas flame. Part 1: Eddy break-up concept for turbulent combustion; Probability density function approach for nitric oxide formation,' *Combust. Sci. and Tech.* Vols. 110–111, pp. 67–101 (1995).
180. Rhine, J.M., Shepherd, K., Sherwood, G., Hargrave, G. and Graham, D., 'Report on British Gas/GRI collaboration on turbulent combustion,' British Gas, Loughborough, UK, October (1995).
181. Weber, R., Driscoll, J.F., Dahm, W.J.A. and Waibel, R.T., 'Scaling characteristics of the aerodynamics and low NO_x properties of industrial natural gas burners,' The Scaling 400 Study, Part I: Test Plan, GRI-93/0227, Gas Research Institute, Chicago, IL (1993).
182. Weber, R., Scaling Characteristics of Aerodynamics, 'Heat transfer and pollutant emissions in industrial flames,' *The 26th International Symposium on*

Combustion, The Combustion Institute, Pittsburgh, PA, pp. 3343–3359 (1996).
183. Smart, J.P., Morgan, D.J. and Roberts, P.A., *The Twenty-Fourth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 1365–1372 (1992).
184. Haas, J.H.P., Maalmann, T. and Gallagher, G., 'Pulverized fuel combustion characterization of coal blends,' F 37/y/38 (1997).
185. Hass, J.H.P., Lockemann, S.A. and Van de Kamp, W.L., 'Combustion characterization for a suite of differenet coals,' IFRF Doc. No. F 37/y/35 (1995).
186. Knill, K.J., 'Fuel staging and its implementation in a novel internally staged burner,' Ph. D. Thesis, TU Delft, The Netherlands (1990).
187. Smart, J.P. and Morgan, D.J., 'The effectiveness of multi-fuel reburning in an Internally Fuel-Staged Burner for NO_x reduction,' *Fuel* **73**, 1437–1442 (1994).
188. Nakamura, T., Smart, J.P., van de Kamp, W.L. and Morgan, M.E., 'Evaluation of the behavior of blends in an aerodynamically air staged burner,' IFRF Doc. No. F 37/y/22 (1990).
189. Morgan, D.J. and van de Kamp, W.L., 'The co-firing of pulverized bituminous coals with biomass and municipal sewage sludge for application to the power generation industry,' IFRF Doc. No. F 100/y/3 (1995).
190. Van de Kamp, W.L. and Daimon, J., 'Further studies on the effect of burner design variables and fuel properties on the characteristics of cement kiln flames,' IFRF Doc. No. F 97/y/3 (1996).
191. Bortz, S., 'Measurements of pulverised coal combustion under conditions simulating a blast furnace environment,' IFRF Doc. No. F 09/a/30 (1982).
192. Morgan, D.J., Sayre, A.N. and Holthuysen, A.M., Meijer, H.K., Teerhuis, C.P. and Bernard, J.G., 'Experimental research upon the reduction of iron ore using a prototype experimental cyclone,' IFRF Doc. No. C 35/y/4, Hoogoven Arch. Lab.: 78111, IJmuiden (1994) (Confidential).
193. Breithaupt, P.P. and Roberts, P.A., 'Improvement of burners for reheating furnaces with respect to heat transfer and emissions,' *European Steelmaking Developments and Perspectives in Rolling and Heating*, R. Tomellini (Ed), European Commission, Luxembourg (1995).
194. Visser, B.M. and Weber, R., 'Modeling of full industrial-scale combustion equipment,' IFRF Doc. No. F36/y/ (1992).

13. REFERENCES

195. Zhang, M.Y., Li, D.J., Cai, N.S. and Xu, Y.Q., 'A development suggestion for power generation technology in China,' *Power Engineering* (China) **14**(2), 1 (1994).
196. Sun, X.X., Zeng, H.C., Fan, K.S. and Tang, B.G., 'The cold aerodynamic flow characteristic of bluff-body flame stabilizer,' *Journal of Huazhong Institute of Technology* **9**(6), 77 (1981).
197. Chen, D.X., Han, C.Y., Zheng, C.G. and Lin, K.Y., An investigation on the bluff-body flame stabilizer for inferior coal in the thermal state,' *Journal of Huazhong Institute of Technology* **9**(6), 87 (1981).
198. Sun, X.X., Chen, D.X., Han, C.Y. and Zheng, C.G., 'Adaptability of bluff-body burner to power plant boilers,' *Journal of Huazhong Institute of Technology* **11**(3), 71 (1983).
199. Zheng, C.G. and Ma, Y.Y., 'Numerical model of the separated turbulent flow field created by a bluff-body burner,' *J. of Huazhong Inst. of Technology* **14**(1), 115 (1986).
200. Zheng, C.G. and Ma, Y.Y., 'Numerical model of the bluff-body burner for pulverized coal and its mechanism of flame stabilization,' *J. of Huazhong Inst. of Technology* **15**(3), 83 (1987).
201. Zhou, X.Q., 'On development of electrical power industry in China,' *6th National Congress of Chinese Society for Electrical Engineering*, pp.70–80, Beijing, China (1994).
202. Yuan, J.W., Xiao, L. and Han, C.Y., 'The aerodynamic structure and combustion characteristics of cavity-bluff-body PC stabilizer,' *Thermal Power Equipments* (4), 142 (1990).
203. Xu, M.H., Yuan, J.W., Han, C.Y. and Zheng, C.G., 'Investigation of particle dynamic and pulverized coal combustion in a cavity bluff-body burner', *Fuel* **74**, 1913 (1995).
204. Chen, J.Y. and Sun, X.X., 'Kinetic studies of coal particles pyrolysis,' *Journal of Engineering Thermalphysics* **11**, 335 (1990).
205. Chen, C.X., Sun, X.X. and Ma, Y.Y., 'Volatile composition evolution model of pulverized coal pyrolysis,' *Progress in Natural Science* **5**, 83 (1995).
206. Chen, J.Y. and Sun, X.X., 'Effects of devolatilization and volatile composition on the ignition behavior of coal,' *Power Engineering* (China) **7**(5), 17 (1987).
207. Chen, H., Zhang, X.K. and Sun, X.X., 'The effect of residual volatile on reactivity of chars', *Journal of Engineering Thermalphysics* **15**, 368 (1995).
208. Chen, H. and Sun, X.X., 'Devolatilization of pulverized coal during combustion and reactivity of the residual char,' *Journal of Huazhong University of Science and Technology* **22**(3), 47 (1994).
209. Simons, G.A., 'The role of pore structure in coal pyrolysis and gasification,' *Prog. Energy Combust. Sci.* **9**, 269–290 (1983).
210. Smith, I.W., 'The combustion rates of coal chars: A review,' *Nineteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 5, pp. 1045- 1065 (1982).
211. Chen, H., Sun, X.X. and Han, C.Y., 'Effects of porous structure on coal particle reactivity of combustion,' *Journal of Chemical Industry and Engineering* (China) **45**, 327 (1994).
212. Qiu, J.R., *et al.*, 'Research on combustion characteristics of blended coal,' *The 5th International Energy Conference*, pp. 1018–22, Seoul, Korea (1993).
213. Qiu, J.R., Ma, Y.Y., *et al.*, 'Emission of nitrogen computers and NO_x formation during blended coal combustion,' *Journal of Engineering Thermophysics* **16**, 115 (1995).
214. Qiu, J.R., Ma, Y.Y., *et al.*, 'Slagging characteristics of blended coals and comprehensive evaluation of slagging degree,' *Journal of Engineering for Thermal Energy and Power* (Chinese) **9**(1), 3 (1994).
215. Li, F. and Qiu, J.R., 'Research on the fusibility of blend coals and mineral characteristics,' *National Conference on Combustion*, pp. I.37-I.41, Wuhan, China (1996).
216. Qiu, J.R. 'Comprehensive research on characteristics of blended coal,' Ph.D. Thesis, HUST, China (1993).
217. Zhou, H.C. and Han, C.Y., 'Simulation study on dynamic analysis of tangential combustion process Part II. Results and analysis,' *Proceedings of Chinese Society for Electrical Engineering* **14**(2), 25 (1994).
218. Zhou, H.C., Lou, X.S. and Ying, H.L., *et al.*, 'Experimental study on combustion stability assessment of pulverized-coal combustion in a single-burner pilot-scale furnace,' *National Conference on Combustion*, pp. II.46-II.51, Yichang, China (1995).
219. Zhou, H.C. and Han, C.Y., 'Method of quantitative flame color characterization for pulverized coal combustion diagnosis,' *Spectroscopy and Spectrial Analysis* (China) **14**(2), 32 (1994).
220. Ouyang, Z.H., Zeng, H.C. and Lu, X.H., 'The investigation of the enrichment of heavy metals in fire particles in coal combustion,' *Journal of Combustion Science and Technology* (China) **2**(2) (1996).
221. Zhou, J.P., Yao, H., *et al.*, 'Effect of SO_2 and NO_x

emission under limestone-desulphurization in pulverized-coal-fired boiler,' *National Conference on Combustion*, pp. IV.96-IV.101, Wuhan, China (1996).

222. Feng, B., Yuan, J.W., Lin, Z.J., *et al.*, 'Mechanisms of heterogeneous destruction of N_2O under condition of fluidized bed combustion,' *Journal of Engineering Thermophysics* **16**, 111 (1995).
223. Yuan, J.W., Feng, B., Cai, X.J., *et al.*, 'Study on the mechanism of N_2O formation and decomposition of coal combustion in fluidized bed,' *Proceedings of the Chinese Society for Electrical Engineering* **14**(4), 1 (1994).
224. Zhou, X.Y., Zheng, C.G., Feng, B. and Ma, Y.Y., 'PDF modelling and experiment analysis of NO_x and N_2O formation of NH_3–NO–O_2–N_2 plug-flow,' *J. of Combust. Sci. & Tech.* (China) **2**(1), 65 (1996).
225. Zhou, X.Y., Zheng, C.G. and Ma, Y.Y., 'A general approach to reduce the reaction mechanism in turbulant reaction flow,' *National Conference on Combustion*, pp. II.52-II.56, Yichang, China (1995).
226. Xu, H., Li, S.M. and Zheng, C.G., 'The Lattice Boltzman method of fluid dynamics and its realization,' *J. of Combustion Science & Tech.*, **2**, 406 (1996).
227. Zhou, X.Y. and Zheng, C.G., 'Simulating the pulverised coal air two-phase flow of tangential fired furnace: comparison of several discrete arithmetic schemes,' *The 2nd International Conference on Multiphase Flow*, Kyoto, Japan (1995).
228. Zhou, X.Y., Zheng, C.G. and Ma, Y.Y., 'Comparison of several discrete arithmetic schemes for simulating a constrained jet and a lab-scale tangential fired furnace,' *Comput. Methods Appl. Mech. Engrg.* **130**, 279 (1996).
229. Zheng, C.G., Wang, B.C. and Yan, R., 'The formation and deposit of fume and the analog computation,' *J. Huazhong Univ. of Sci. & Tech.* **21**, 99 (1993).
230. Liu, Z.H., Liu, Y.H., Zhou, Y.B. and Zheng, C.G., 'The correlation of structure and radiative properties of burning char: modeling and analysis,' *J. of Combustion Science & Technology*, **2**, 393 (1996).
231. Zhou, H.C., Lou, X.S., Ying, H.L., *et al.*, 'On a monitoring method of two-dimensional temperature distribution in furnaces for combustion diagnostics,' *Proc. of 3rd Asia-Pacific Intern. Symp. on Combs. & Energy Utilization*, pp.626–630, H. K. (1995).
232. Zhou, H.C., Lou, X.S., *et al.*, 'Study on application of monochromatic flame image processing technique in combustion monitoring and control of boilers,' *Automation of Electrical Power Systems* **20**(10), 18 (1996).
233. Zhou, H.C., Lou, X.S., *et al.*, 'Measurement method of three-dimensional combustion temperature distribution in utility furnaces based on radiation image processing,' *Proceedings of Chinese Society for Electrical Engineering* **16**, 391 (1996).
234. Zhou, H.C., Lou, X.S., *et al.*, 'Model establishment of fuel controlled objective in utility boilers based on signal of radiation energy form furnaces and simulation on its control,' *Proceedings of Chinese Society for Electrical Engineering* **16**, 226 (1996).
235. Lu, J.D., Huang, S.H. and Qian, S.Z., 'An analysis on heat transfer processes in bubbling fluidized beds,' *Journal of Engineering Thermalphysics* **17**, 108 (1996).
236. Lu, J.D. and Flamant, G., 'A quantitative analysis of charactersitic regions of heat transfer in gas–solid fluidized beds,' *Journal of Chemical Industry and Engineering* (China) **46**, 212 (1995).
237. Liu, D.C., Wu, W.H., *et al.*, 'Development and shake-down operating test of a CFB boiler of 10T/h steam capacity,' *Proc. of 13th Intern. Conf. on FBC*, pp. 1091–1094, ASME (1995).
238. Liu, D.C., Chen, H.P., *et al.*, 'Design of PI type CFB boilers,' *Fluidized Bed Combustion*, pp. 585–588, ASME (1991).
239. Wang, T., Liu, D.C., Saxena, S.C., *et al.*, 'Particle movement in a square section circulating fluidized bed,' *Fluidized Bed Combustion- Volume 2*, pp. 1011–1020, ASME (1993).

14. REFERENCES

240. Feng, J.K., Xu, X.C. and Zhou, L.X., 'New achievements of science and technology of coal combustion in China,' *The Proceedings of 1st International Symposium on Coal Combustion*, Beijing, Hemisphere Press, pp. 33 (1987).
241. Zhou, L.X., 'Recent studies on modeling of turbulent gas-particles flows and coal combustion in China,' *Proceedings of 3rd International Symposium on Coal Combustion*, Science Press, pp. 3–12, Beijing (1995).
242. Hong, T. and Zhou, L.X., 'Numerical simulation of three-dimensional turbulent gas-particle flows in a boiler furnace by a continuum model of particle phase,' *Proc. 1st Asian- Pacific Symposium on Comb. and Energy Util.*, Intern. Academic Publisher, pp. 184–189, Beijing (1990).
243. Fu, W.B., Zheng, S.M. and Zhang, B.L., 'A unified approach for determining kinetic parameters of coal char combustion,' *Proceedings of 3rd International Symposium on Coal Combustion*, Science Press, pp. 89–100, Beijing (1995).
244. Fu, W.B. and Zeng, T.F., 'A general method for determining chemical kinetic parameters during ignition of coal char particles,' *Combustion and Flame* **88**, 413–424 (1992).
245. Jin, Y., Zheng, Q.Y. and Liu, X.G., 'Studies and counter-measures of combustion characteristics of char particles in CFBC,' *Proceedings of 3rd International Symposium on Coal Combustion*, Science Press, Beijing (1995).
246. You, C.F., Doerk, Jeans, Yue, G.X. and Ye, D.J., 'Investigation on three-dimensional gas flow in a square-shaped separator,' *Proceedings of 3rd International Symposium on Coal Combustion*, Science Press, pp. 448–456, Beijing (1995).
247. Li, D.K., Shen, Y.T. and Xu, X.Q., 'The technology for tri-cogeneration of gas, heat and power and its market prospects in China,' *Electricity-CSEE* **5**, 4 (1995).

15. REFERENCES

248. EIA, 'Annual Energy Review,' Report No. DOE/EIA 0384 (95), Energy Information Administration, U.S. Department of Energy, Washington D.C., 20585 (1995).