Performance prediction in advanced pulverised coal fired utility boilers

Executive Summary

Prepared by

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JOULE III

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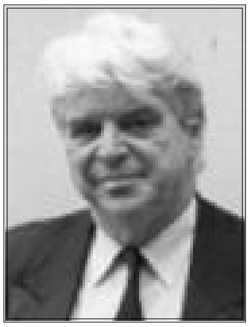
Background - Summary of Objectives



A primary motivation to undertake the research programme described in this document, is the need to address the problems believed to be due to Global Warming, or more evidently Climate Change. In recent years the effects of large-scale combustion on the emissions of green house gases – primarily carbon dioxide – have been widely addressed, leading to what, these days, is typically expressed as **"The Challenge of Kyoto"**. Although the present work was conceived before Kyoto, it relates very clearly to the problems defined, and the agreed international measures to be taken. It concerns the efficient firing of fossil fuels, in particular the firing of pulverised coal in so-called "conventional" utility boilers.

A high proportion of the electricity produced in Europe is based on pulverised coal fired utility boilers. For the reduction of pollutant emissions from coal-fired power plants, numerous techniques, e.g. air staging, reburning etc. have been successfully applied in pilot scale facilities and are already standard or are being demonstrated in practice. The application of these techniques to industrial scale furnaces necessitates an optimisation of the combustion parameters, so that a maximum reduction of pollutant formation can be achieved together with a minimisation of the technical and economical expenditure. The realisation of this optimisation experiment is extremely time-consuming and gives rise to high financial costs.

In contrast, numerical methods allow the testing of many techniques with varying combustion parameters in a much shorter time period and at lower costs. A prerequisite is that computer codes incorporating these numerical methods reach the level of industrial applicability. From an industrial point of view such codes should provide solutions of acceptable accuracy, within an as short as possible period of time and at low financial costs. Furthermore a maximum of flexibility in discretising the physical space is required in order to reproduce properly, the conditions at the computational boundaries.

Thus as the name of the project suggests, the project was primarily concerned with the development of acceptable prediction procedures for the performance of coal fired utility boilers. These procedures were to be applicable to **existing boilers**, to examine the implications of changes to operating procedures, or of retrofitted modifications. As the firing of **coal blends**, where the coals are sourced internationally, is the norm in many locations in Europe, it would be necessary to be able to predict the effects of modifications to the coal mix. Particularly the effect of a more extensive use of lower grade and/or cheaper coals would become more and more important. Finally the retrofit application of environmental protection technologies such as **coal over coal reburn** is foreseen. Thus the modelling should be able to take account of this technology.

Finally the prediction procedures were also to be of use in the optimisation of design concepts for the boilers of the new millennium, with the aim to produce viable, flexible designs, capable of accepting multiple fuels sources, including biomass and waste fuels in an environmentally friendly manner.

It was clearly recognised that the use of more and more powerful digital computers to run more extensive numerical models, in no way precluded the need for extensive experimental research both to provide a basis for improved phenomenological understanding, and extensive data bases for model validation

Programme Implementation

The programme "Performance Prediction in Advanced Coal Fired Boilers" [1, 2], commenced contractually on 1st January 1996. All research tasks for all participants were completed and reported by 31st December 1997. Since that time, the present authors have been engaged in completing the overall interpretation and reporting to the European Commission and further to bringing the information to the attention of the scientific community and ultimately to the "scene of implementation" - Industry.

The objectives of the project were extensive and ambitious and could only be realised through the co-operation of a large number of laboratories and industrial concerns, spread widely throughout the European Union. The management and execution of the work was organised as described in the following section.

Programme Organisation

- **Project Area 1 - Project Area Co-ordinator - Professor M G Carvalho - IST**

  Subject: Full boiler performance modelling - with the participants:

  - The Portuguese power company, EdP – Project 101 - working in co-operation with researchers of the Lisbon based institute, IST – Project 102;
  - The Greek power company, PPC – Project 103 - working in co-operation with researchers from the National Technical University of Athens – Project 104;
  - The German power company, RWE – Project 105 - working together with researchers of the Stuttgart based institute, IVD – Project 106;
  - The Spanish power company, ENDESA – Project 107 - working together with researchers of the Zaragoza based institute, CIRCE – Project 108;
  - The former IC-RR, a UK boiler manufacturer, (now known as ABB Combustion Services) – Project 109 - working in co-operation with a research team from the London based, Imperial College of Science, Technology and Medicine – Project 110;
  - The Scottish boiler manufacturer Mitsui Babcock Energy Limited – MBEL – Project 111;
  - The Pisa Research Laboratories of the Italian power company ENEL – Project 112.

- **Project Area 2 – Project Area Co-ordinator – W L van de Kamp – IFRF**

  Subject: Coal blends combustion – with the participants:

  - The Dutch Power Research Institute KEMA working in co-operation with a number of Dutch utilities and researchers from the TU Delft – Project 201;
  - The IJmuiden Research Station of the IFRF – Project 202;
  - Researchers from the University of Salerno, Italy – Project 203;
  - Researchers from the TU Denmark – Project 204;

- The Swedish based research institute, TPS – Project 205
- Researchers from the University of Ulster - 206.

- **Project Area 3 - Project Area Co-ordinator - J Macphail - MBEL**

  Subject: Advanced coal reburning - with the participants:

  - The Scottish boiler manufacturer Mitsui Babcock Energy Limited – MBEL – Project 301;
  - The Pisa Research Laboratories of the Italian power company ENEL – Project 302;
  - Researchers from the University of Pisa, Italy – Project 303;
  - The IJmuiden Research Station of the IFRF – Project 304;
  - Researchers from the TU Denmark – Project 305;
  - Researchers of the Stuttgart based institute, IVD – Project 306.

The overall Project Co-ordination was undertaken by P A Roberts of the IFRF.

Each participant has produced an individual Final Project Report, which are included within the final report book, with which this Executive Summary is associated [3].

In the final report book, each project may be identified through its project number specified in the previous paragraphs.

Full names of the participants with addresses and their individual telecommunications data are presented on the World Wide Web, as described in the section on "The Way Forward" at the end of this document. Their names and email addresses are also presented at the end of the present document.

As indicated above, the work was undertaken in three Project Areas incorporating 19 participants from 9 European Union nations, undertaking 24 tasks to meet the above mentioned objectives within two years. This in itself was aimed to produce a further important deliverable, namely a high degree of European co-operation.

Industry	9 Partners	7 Countries
Research	4 Partners	2 Countries
University	11 Partners	7 Countries

The work reported here, is in many respects a continuation of the work undertaken in the Joule II, 2nd Phase project: "Atmospheric Pressure Combustion of Pulverised Coal and Coal Based Blends for Power Generation" [4-6].

Structural Change of Plan – Extension of the project

Towards the end of 1996, it became clear that it would be necessary to change the overall time scale of the work to allow full possibilities for publication of the work.

Therefore it was agreed with the Commission that the project would be extended for six months to allow this completion.

In fact there was no change in the technical planning and execution. All participants completed their reports substantially on time, according to the original time planning.

Funding Summary

Item	Amount
Total Project Costs:	ε 5,050,372
Total Participant Funding	ε 1,829,848
Total EC Co-funding	ε 3,220,524

The value "Total participant funding" should be interpreted with care for the following reasons:

- At first sight it is not clear that there are a significant number of universities involved who are mostly co-funded on a 100% differential cost basis. Of course the initial infrastructural cost is still borne by the University and cannot be seen within this costing basis.
- Secondly, the industrial participants are co-funded to a maximum of 50% of agreed project costs. Where they exceed their costs for whatever reason, this is not visible in these figures, which are those used in the original agreement.
- Thirdly, there are a number of full-scale trials, which were undertaken during this project. The costs of these trials can only be assessed on a differential basis, which is in itself exceedingly difficult to estimate, or to account. In principle, the execution of research programmes on production equipment gives rise to conflicting goals, namely the research goals and the production goals. In almost all situations the latter takes priority over the former. The quality of the information generated in this project in connection with full scale production plant research, is such that the real costs must be very much greater than that estimated.

Consequently the contribution to the overall project by the participants, particularly those from industry, may well exceed the co-funding from the European Commission.

Summary - Project Area 1 -Full boiler performance modelling

In the table shown below, the list of activities planned at the beginning of the project is listed.

Partner and Task	1st year				2nd year			
	1	2	3	4	1	2	3	4
IST								
1) Characterize heat transfer degradation								
2) Couple CFD with engineering models								
3) Development of domain decomposition techniques								
4) Asses models for NOx emissions (WF)								
EDP								
1) Measurements of NOx emissions and burnout (WF)								
2) Determination of heat transfer degradation								
3) Correlation of data with operating conditions								
PPC								
1) Characterization of brown coal blends								
2) Measurements of ash deposition growth in power plants.								
3) Evaluation of the applicability of the proposed modifications								
NTUA								
1) Computational predictions for 300 MW T fired boiler.								
2) Study of influence of oper. conditions on NOx formation.								
3) Comparison between model predictions and measurements								
4) Investig. of heat transfer modification due to wall deposit.								
RWE								
1) Survey of information on low-NOx combustion systems.								
2) Investigation of the performance of a pilot burner model								
3) Verification of the up-scaled burner in a 150 MWe boiler								
IVD								
1) Development of domain decomposition techniques								
2) Assessment of NOx emissions and model validity								
ENDESA								
1) Installation and commissioning of new instrumental systems								
2) Development of plant test guidelines								
3) Plant tests								
CIRCE								
1) Evaluation of plant measurements reliability and accuracy								
2) Study of new measurements for conventional calculations.								
3) Evaluation of ENDESA test results and models validation.								

IC-RR		
1) Selection model parameters construction and commissioning		
2) Detailed flow tests		
3) Analysis of results with ICSTM		
ICSTM		
1) Code extension for burner-burner interaction		
2) Code validation against isothermal data		
MBEL		
1) Set up CFD models		
2) Set up engineering models		
3) Integrate both methodologies		
4) Performance predictions (WF, OF)		
ENEL		
1) Survey information in operation Low-NOx boiler furnaces.		
2) Development of on-line boiler simulators		
3) Full scale boiler data acquisition (TF)		

Table 1: Task description per partner according to the initial planning.

Although no formal links were established there was a strong co-operation between the universities or research centres with the utilities within each country according to Figure 1. Obviously other interactions occurred between the partners according to the topics investigated that defined four main areas as presented in the following section.

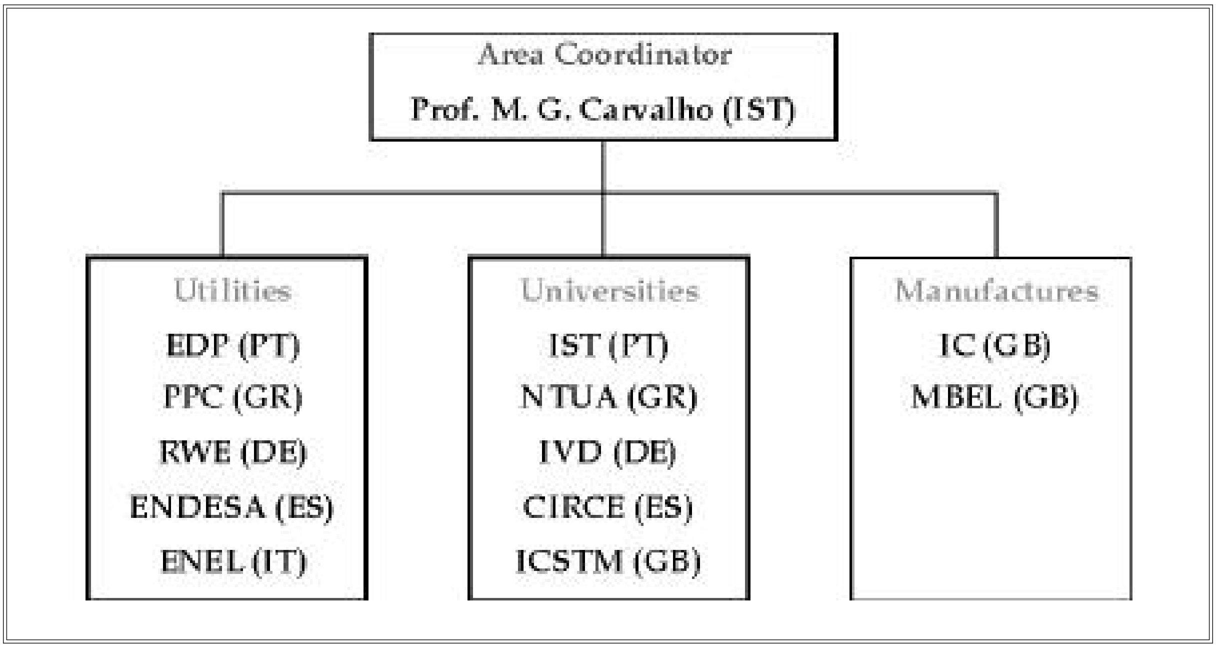


Figure 1: Project partners according to main activity.

Execution

In general the work went according to plan with no major excursion from the original project design. Where there were significant differences in time planning, these were mainly associated with the execution of full-scale boiler trials. However all planned work was completed.

Project Area 1 Conclusions:

The activity carried out accomplished most of the objectives initially established. The project activity was presented in four main topics where considerable progress was made. The main topic of the project was the development and validation of numerical models to predict boiler furnace performance with particular emphasis for scale-up criteria, analysis of burner-burner interaction and on the influence of deposits at boiler walls. The numerical model developments had the objective of enhancing their use by engineering and power plant operator companies.

Data collection from boilers, CFD numerical model development and validation

- The acceptance of numerical models requires a clear assessment of their prediction capabilities and limitations. The performance of comprehensive CFD numerical models was extensively tested based on detailed in furnace measurements performed in four boiler furnaces. Three numerical models from universities were tested with these data sets and in general allowed a good agreement between the predicted and observed data.

- Based on the data from ENEL, the predictions of IVD and NTUA show that the CFD models represent the modifications in NOx emissions and UBC due to the operating conditions for a tangentially fired boiler. The use of the NTUA model is considered by PPC in the design of newer boiler furnaces and in the optimisation of existing units. A CFD based model was also developed by ENEL to use a relatively coarse grid allowing predictions to be obtained in short time periods to assist boiler operation.

- For wall fired boilers detailed data was collected in an EDP boiler furnace. This data set acquired by IST was already requested by different groups for model validation and was used by IST within the project. For a top wall fired boiler the data collected by RWE in their scale-up study was compared with predictions made by IVD using a very fine grid. Further swirling burner model validation was performed by IC-RR using commercial codes.

- Based on the large set of validation studies it was clearly demonstrated how current state of the art CFD numerical models predict furnace performance. The main differences observed are partly attributed to lack of grid refinement in certain areas, a problem that is alleviated with the use of domain decomposition or local grid refinement techniques. The combination of these techniques with the use of parallel processing was demonstrated by IVD allowing a full boiler furnace calculation to be performed within 5 minutes, a time that is fast enough for the industry requirements. This performance was based on the use of advanced computer resources that are concentrated only in some research centres but can be assessed at acceptable cost. The use of (ever)-cheaper workstations is also a valid alternative where the cost is reduced but time response is lost. In any case the preparation time of the calculations is still large for the numerical models from the universities and thus the development of user-friendly input interface are still necessary.

Development of scale-up criteria and analysis of burner-burner interaction

- An isothermal test rig was assembled and an extensive set of measurement was performed by IC-RR to characterise the near burner flow field and the entrainment rate of burner arrays with different number and spacing. Results were compared with CFD model predictions for this scale (1/13th) and with results from previous projects at half scale for isothermal flow showing a good agreement. Based on this and on favourable comparisons for combustion conditions, CFD models were used to explore the influence of burner spacing on NOx emissions. Reducing the burner pitch below two burner diameters led to a flame attachment and a sharp increase in NOx with four burners. Further studies were carried out by ICSTM for the burner arrays in a front wall fired boiler showing significant interactions with the ash hopper.

- The optimisation of burner settings performed by RWE at a 1MWt showed that momentum ratio should be higher than 1.4. The same burner settings were confirmed to improve emissions and reduce carbon in ash at a full-scale top wall fired unit. For the industrial unit the measurement of temperature was found to be of primary importance to control combustion performance. An emission spectroscopy was tested at full scale with this purpose. The conclusions derived from the tests were confirmed by the numerical model application showing a further potential to reduce costs in these studies.

Development of engineering boiler performance models for operation and design

- MBEL prepared a suite of computer programs to extract flow and heat release patterns calculated by CFD models and use them in simpler heat transfer calculation models. This procedure was developed and demonstrated in the project using data from EDP furnace and in parallel was used for other boiler retrofitting projects.

- Following similar ideas, IST isolated the heat transfer calculation model from its CFD model and used it retrieving previously calculated CFD results. This approach was shown to give comparable results as the CFD simulations using interpolated CFD results. This model is intended for use during boiler operation or to analyse the influence of modifications in wall boundary conditions within minutes.

Assessment of heat transfer degradation and ash deposition to boiler walls

- A direct measurement of the deposition rate was performed in PPC power plants providing relevant information for operation.

- The numerical simulation of deposition was carried out by NTUA for a selected boiler furnace allowing the identification of a region adjacent to a burner column out of service with larger propensity for ash deposition.

- CIRCE analysed the reliability and precision of on-line plant measurements in an ENDESA power plant boiler. Based on this analysis, new calibrations were performed or new instrumentation was installed allowing a better characterisation of the plant. The plant data was used to validate simple heat balance models.

- These models have the potential to identify heat transfer degradation.

Summary - Project Area 2 - Coal blends combustion

In order to achieve the overall objectives, a two-year programme of experimental studies and mathematical modelling was executed with the following specific objectives:

- To obtain practical data and experience on coal blends combustion in a full scale tangentially fired utility boiler of 600 MWe in The Netherlands (KEMA).
- To perform detailed input/output measurements and in-flame measurements at the scale of 2.5MW for obtaining blends combustion information and to distribute these samples to the other participants for detail analysis (IFRF). In these experiments also the determination of the effect of turbulence on the blends char combustion is determined (TPS).
- To undertake controlled studies in Isothermal Entrained Flow reactors for determination of blends volatile release, high temperature fate of fuel nitrogen, char burnout and slagging characteristics (IFRF, KEMA, University of Salerno). This information will provide valuable basics for the coal blends combustion modelling.
- Slag samples of different blends (IFRF) are analysed for determination of characteristic slagging features when firing a blend (University of Denmark). These observations are compared with full-scale information.
- To make use of the experience gained at all the different levels of analysis and to perform a techno-economic evaluation (University of Ulster) for the full scale Amer Power station which is a relatively modern plant, which frequently uses a wide range of coals.

The programme consisted of the following parts:

- Full scale tests in a 600MWe boiler
- Semi-industrial scale (SIS) tests at 2.5 MW
- Analysis of turbulence spectra derived from the SIS
- Detail analysis of the coals and the char burnout
- Slagging potential analysis
- Techno- economic evaluation based on the total information package obtained

Execution

The major deviation from the original plan concerned the choice of boiler for the full-scale studies. Originally another boiler (Maasvlakte) was envisaged for the studies. But in the event, there would have been difficulties in the integration of the potential studies on that boiler within the overall planning.

At the end of year planning meeting in November 1996 at Heathrow airport, an alternative plan was adopted, whereby a special trial at the AMER9 boiler, would be adopted within the programme. This allowed the detailed measurement of very specific blends of two well-characterised coals. As a result these coal were used in the semi-industrial scale trials, the large laboratory scale trials and the laboratory experiments, giving a consistent set of results, which is virtually unique. Within this restructuring, it was agreed that KEMA would delete a semi-industrial scale trial, which became superfluous and sub-contract N analysis work.

To conclude, the revised objectives were met and the work of the Project Area 2 was completed.

Project Area 2 Conclusions:

The overall objectives of the project were achieved with the addition of an extensive programme change, which allowed an unforeseen chance to compare the firing of variable ratio blends of two different coals on a full-scale boiler, a semi-industrial scale test rig and in two laboratories. This unusual event provided valuable data for model verification. Further, experimental testing at laboratory and pilot scale provided the necessary data to assist in the development and validation of mathematical models, and to provide process information for a plant feasibility study.

It was shown that the optimisation of coal blends of variable quality is a possibility to reduce the electricity production price, with all other aspects maintained. However, based on the investigations the blends require a certain selection process based on ash composition and the combination in which they are fired. Further, the aerodynamics and burner operation can be critical in determining which part of the blend is burned out sufficiently well and which part is not. The following specific conclusions arose from the work undertaken:

Coal Characterisation

- High temperature volatile yields were measured in a number of test facilities at a range of heating rates and final temperatures. A greater proportion of the fuel nitrogen is released with the volatile matter as temperature is increased. This is of importance when firing blends of different rank coals with low NOx burners.
- The different characteristics of each single coal could be determined under laboratory conditions. However, in practice this is less obvious due to the higher temperatures and the different thermal-chemical environment in the flame. A low volatile, low reactivity coal will burn at a different location when compared to a high volatile, high reactive coal, which dilutes the distinction between the two coals in the blend.
- Coal combustion characterisation is an essential tool to predict the performance trends when using a coal blend instead of a "single" coal.

Experimental Work

- Full-scale tests were performed on the Amer Power Station (630 MWe) in The Netherlands. In total 13 different coal blends were evaluated. In particular blends of a North American sub-bituminous coal and a "standard" blend were fired. The same blends were also tested in detail at the scale of 2.5 MW and subsequently samples of the coals, the blends, char and slag were analysed and evaluated in detail by the University of Salerno and University Denmark.
- The slagging characteristics were observed to have similar trends in both the full-scale facility and the semi-industrial scale furnace. Different regions of slagging potential were determined for the different blends, i.e. in the burner belt or further downstream on the superheaters. These phenomena could be explained by the calcium content in the coal ashes and the combination of the different ash constituents in the blend.
- Coal blends combustion was clearly identified as a possibility but careful selection is required. The price for the lower quality coals in the blend should be lower compared to the higher quality coal and all aspects of operation cost should be taken into account.
- Good quality data was obtained and is available for the validation of mathematical models on blends combustion, burnout predictions, NOx formation potential and slagging predictions.

Mathematical Modelling

- Improved sub-models to describe the NOx formation potential, char combustion and slagging were developed. These models have a semi-empirical –fundamental character and will provide a useful tool for evaluating in advance a tendency when using a coal blend. However, it should be realised that a large number of the cheaper import coals are unknown to the user and therefore reliable operation of the power station can result in trial and error optimisation. The outcomes of this project part are a systematic approach towards this optimisation process.

Techno-Economic Feasibility Study (University of Ulster)

- The technical and economic feasibility of using a coal blend to a large tangentially fired utility boiler was demonstrated at full scale.

- Based on detailed information of the power station boiler operation, in combination with the analysis of the other participants it was possible to determine the breakeven points when using different coal blends.

Summary - Project Area 3 - Advanced coal reburning

The original task allocations were as shown in Table 2.

Table 2 presents a summary of the main tasks originally proposed to meet the objectives of the Project Area 3 participants.

Activity Description	Planned																							
	Year 1												Year 2											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
MBEL																								
Pilot Scale Tests - Design & Modifications																								
Pilot Scale Tests - Testing and Analysis																								
Feasability Study - Set Up Models																								
Feasability Study - Performance																								
Feasability Study - Sizing and Layout																								
Final Report																								
ENEL																								
5 MW Tests																								
80 MW Tests - Santa Gilla																								
Furnace Model Development																								
Feasability Study																								
Final Report																								
UNIVERSITY OF PISA																								
Devolitisation Experiments																								
Validation of Submodels																								
Char Combustion Experiments																								
Char Reactivity vs. Conversion																								
Oxidation Model																								
Final Report																								
IFRF																								
NOx / UBL Model																								
Flow Modelling																								
Slag/Fouling Model																								
IPFR Tests																								
2.5 MW Tests																								
Final Report																								
TUD																								
Literature Study																								
Preliminary Model																								
Parametric Tests																								
Laboratory Experiments																								
Model Refinement																								
Final Report																								
IVD																								
Pyrolysis Model																								
EFR Tests																								
Final Report																								

Table 2: *Original Work Plan For Project Area 3*

Figure 2 illustrates the task interactions between the individual participants.

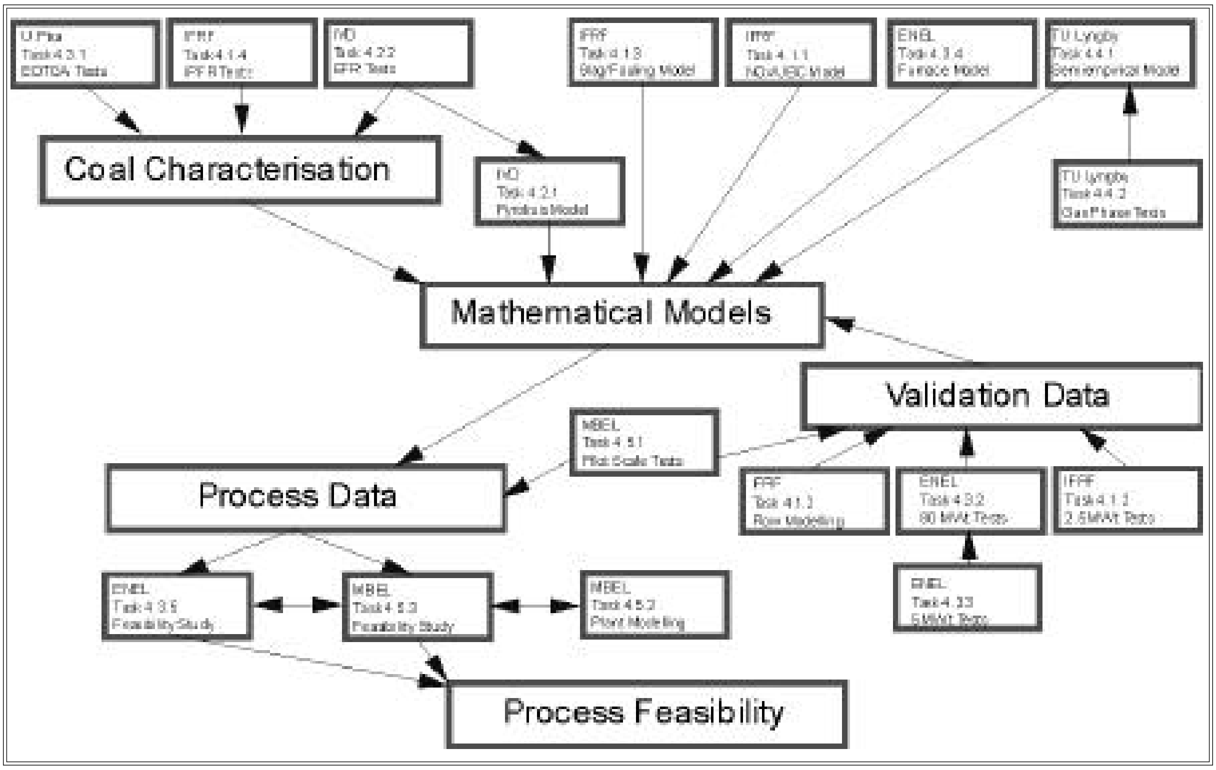


Figure 2: ***Task Interactions For Project Area 3***

Execution

In general, the project proceeded to the plan outlined in Table 2, but there were some departures from this and these are discussed below.

At the time the project was proposed there was no certainty that the THERMIE Vado Ligure coal over coal reburn demonstration project would proceed, and so it was structured in such a way that it would be self-sufficient. In fact the Vado Ligure project was approved and the programme for this project was amended to take this into account. The most significant impact was upon the selection of the coals to be considered for the JOULE project, these were chosen to complement the Vado Ligure design coal (Ashland) for which experimental data and coal samples were made available. This proved to be extremely beneficial when delays in the supply of the Polish and Illawara coals would have severely compromised the attainment of the technical programme. Work was able to proceed using the Ashland coal and the overall impact of the problems in supplying the coal were minimised.

ENEL had proposed to conduct pilot scale combustion testing of the coal over coal reburn process on a 5 MWth facility which they intended to build at Santa Gilla. However, owing to difficulties in obtaining the necessary planning consents from the local authorities, the construction of the test facility was significantly delayed, and it was not available for testing to be undertaken within the project timescale.

In recognition of this, ENEL proposed an alternative programme of work. This was established in consultation with the other project participants. The activities undertaken provided detailed coal characterisation information on the Ashland, Polish and Illawara coals, and were used to support the model development activities.

During the first year of the project the activities of IVD and TUD gave an indication as to the importance of understanding the processes, which occur when coal particles are rapidly heated to high temperature. To provide further information on this ENEL conducted pyroprobe tests, accompanied by a major laboratory scale analysis exercise. Data was obtained on the devolatilisation of coals, high temperature volatile yields, nitrogen partitioning between char and volatiles, char structural changes, and gaseous species evolved (both major species such as H2, CO, CH4, and minor species - the volatiles were broken down into a total of 44 separately identifiable species using a gas chromatograph equipped with a flame ionisation detector and thermo conductivity detector). In addition detailed investigations into the mineral matter were undertaken, data was obtained on the ash fusion behaviour (i.e. parameters such as initial deformation temperature which are often used to characterise a coal's slagging propensity) and chemical composition (using a Computer Controlled Scanning Electron Microscope - CCSEM). The data obtained would be necessary input for any ash deposition model.

Project Area 3 Conclusions:

The overall objectives of the project were achieved. Experimental testing at laboratory and pilot scale provided the necessary data to assist in the development and validation of mathematical models, and to provide process information for a plant feasibility study. It was shown that the coal over coal reburn process is both technically and economically viable on modern utility plant. The following specific conclusions arose from the work undertaken:

Coal Characterisation

- High temperature volatile yields were measured in a number of test facilities at a range of heating rates and final temperatures. All facilities gave the same general trends, but entrained flow reactors give higher yields than captive sample tests at a given temperature. Given the variability in this parameter, and its importance with respect to coal combustion and reburning, it is evident that some standardisation of the test is required.
- A greater proportion of the fuel nitrogen is released with the volatile matter as temperature is increased. Measurements of the major volatile species showed considerable variability between the various laboratories. In general, however, the methane content was higher at low devolatilisation temperatures. As temperatures were increased there was greater production of hydrogen, possibly indicating that the methane was being decomposed.
- Kinetic rate constants were determined from the measured data. Significantly it was observed that chars produced under flame conditions were considerably less reactive than those produced in the laboratory. It was also observed that as the combustion proceeds, the reactivity of the laboratory chars reduces with burnout, the effect was less apparent in chars produced under flame conditions.

Experimental Testing

- Gas phase reaction kinetics were determined for the NO-HNO reaction. However it was not possible to determine the rate constants for the NO-HCCO reaction owing to the presence of decomposition products of C2O3 and the difficulties in achieving a constant inlet concentration of this reagent.

- Process design data was obtained by testing at the 160 kWt scale. Tests conducted at other scales supported the findings of this facility.
- Coal over coal reburning can achieve NOx reductions of up to 60% (compared to low NOx burners alone) even for the relatively low volatile Illawara and Polish coals. All facilities indicated that the optimum reburn zone stoichiometry is between 0.8 and 0.9. Residence time in the primary zone must be sufficient for the main coal combustion to be complete, in the reburn zone the residence time must be sufficient for the coal to devolatilise and the gas phase NOx reduction reactions to take place.
- The use of coal as the reburn fuel was found to be as effective as using natural gas. It was the main coal quality, which had the greatest impact on overall NOx emission.
- For fixed reburn zone stoichiometry it was found that the NOx emissions were insensitive to reburn coal heat input. This finding was obtained on both MBEL's NRT furnace and the IFRF semi-industrial scale furnace, but initial inspection of the results could have led to contradictory conclusions being drawn - the interpretation of results from different test facilities needs to take careful consideration of the operating regime etc..
- Particle size did not have a significant effect on NOx or burnout for the finenesses tested. However these were all better than 70% passing 75µm and a coarser size distribution would be expected to have a detrimental impact on carbon in ash.
- Good quality in-flame data was obtained and is available for the validation of mathematical models.

Mathematical Modelling

- Improved sub-models to describe the devolatilisation, char combustion and gas phase reactions have been developed and implemented in various mathematical models. Each of the sub-models has been tested against experimental data obtained from within the project at various scales/degrees of complexity, and also against suitable published data.

- Validation of CFD codes (ENEL in-house, IFRF FLUENT) was undertaken making use of the experimental data acquired during the project with varying degrees of success. The implementation of the University of Pisa's sub-models into ENEL's CFD code was successfully demonstrated. The IFRF NOx and carbon in ash models incorporated into FLUENT were tested under coal reburning conditions, whilst unburned loss was reasonably well predicted there was a discrepancy in the NOx calculation. It is believed that this arises from the level of detail to which the hardware, and in particular the overfire air injector, was modelled.

Feasibility Study

- The technical and economic feasibility of installing coal over coal reburn to a large utility furnace of modern design was demonstrated.
- For a typical bituminous coal anticipated NOx emissions were conservatively estimated at 325 mg/Nm3 % 6% O2, but may be as much as 100 mg/Nm3 lower than this. Higher NOx was anticipated for lower volatile coals.
- Carbon-in-ash levels were predicted to be less than 5% for a wide range of coal properties. Combustion efficiency is better for coal over coal reburning compared to furnace air staging owing to the presence of an oxidising primary zone - this also leads to a less aggressive furnace environment with respect to ash deposition and fireside corrosion.
- Furnace exit gas temperature was only slightly increased, the effect of raising the elevation of the heat input being offset by the use of recycled flue gas to convey the reburn coal to the furnace. Similarly

boiler outlet gas temperature was only marginally increased. Existing control measures are able to maintain final and reheat steam temperature.

- The volumetric flow rate of the flue gas leaving the air heaters is increased with the introduction of coal over coal reburning, and this may have a negative impact upon the performance of the electrostatic precipitators if it is decided to take the recycle flue gas from downstream of these. Alternatively the flue gas recycle could be taken from the economiser outlet, but additional particulate clean-up equipment would be required.
- CFD techniques were demonstrated for the optimisation of reburn coal and overfire air injection arrangements. Independent analysis by MBEL and ENEL using different codes gave comparable results.

Overall Programme Conclusions

It is concluded that:

- The programme has been completed in terms of research information generation and primary reporting;
- The technical goals have been well met, with results over and above those envisaged, due to programme changes made "on the fly". Such changes include the change in boiler/blends to be studied in Project Area 2 and the advent of the Vado Ligure demonstration project and its resultant effect on the contents of Project Area 3;
- The research information has been well disseminated within the project and to the participants of related Joule 3 projects. A major task for the future is to ensure that the information is well disseminated to industry. Undoubtedly the results generated are of a sufficiently high quality to warrant this remark;
- The possibility to manage such a large cluster project has been demonstrated to be viable within the structure used. This has been significantly due to the positive attitude of the participants.

The Way Forward

- In the first place, it is being more and more regularly demonstrated that "full boiler modelling" is a practical and useful reality, when carried out by combustion engineers/scientists who are well acquainted with the phenomena which within the combustion chamber of the boiler. Therefore continuing research is essential not only to increase the range of validation of models, but also to provide the "hands-on" environment in which the new generations of combustion scientist ands engineers can learn their profession.
- The absolute values predicted should be reviewed with caution, but trends are becoming more and more correct and often are a very useful product in their own right.
- The burner-burner interaction experiments and predictions carried out in Project Area 1 lie in an area of research which so far was largely unexplored, and essential for the detailed prediction of NOx and carbon-in-ash.
- In both Project Areas 2 and 3, the importance of coal characterisation was clearly demonstrated. The need to be able to produce quickly and accurately, "numbers" relating to specific coals and blends which relate the time/temperature history to which the particles will be subjected in a given boiler combustion system, cannot be underestimated. Predictions of combustor performance without the "numbers" for the coal or blends being fired will give results of very limited value.
- The number of combustion related parameters, which can be addressed in this way should be

extended, and the rate at which the data can be produced (at lower cost) should be enhanced. These points form the basis for future R&D in this area, which should be promoted in the EC Framework Programme 5.

- The requirements accepted within the Kyoto agreement will give rise to the modification to the operation of existing boiler equipment, and the need of well designed retrofit equipment for example to facilitate reburn/waste or biomass co-firing. This in turn means that the full boiler modelling tools presently under development will become essential to the industry, if rapid progress is to be made. This finally means that "combustion science and technology" education and training must become more focused and integrated within the European Union.
- The present R&D results are very encouraging and have been well disseminated to the participants of the different project areas, and to the partners of the associate projects within Joule Thermie Programme "Clean Coal Technologies for Solid Fuels" [1, 2]. This took place in the November 1998, Brussels Conference "Coal and Biomass, High-Tech Fuels for the Future".
- However the essential point is to utilise the results for industrial developments. The development of university/research institute-industrial partnerships, demonstrated in this programme, is one clear way of achieving this end. A further method is to integrate the research information into new measurement or modelling procedures, which then may be made commercially available to industry. But in any case, industry must be aware of the existence of the work, for example through presentations at this conference.
- The ad-hoc Steering Committee for co-ordinating the projects within the Joule Thermie Programme "Clean Coal Technologies for Solid Fuels", have set up a web site to advertise the programme and disseminate the R&D information. This site may be found on the web at www.euro-cleancoal.net where full details of all eight projects within the programme may be found. Further it is the intention to publish information of all research reports on this site. As a precursor, the Joule II programme, Clean Coal Technologies R&D, 2nd Phase Executive Summaries [4], have been published as "portable document format (PDF)" files, which may be downloaded from the server, read directly on screen and/or printed at a local printer. For the present programme, all executive summaries and individual project reports will be similarly published.
- In this way the true work of conferences in bringing the research scientists in contact with the engineers who will apply the work in industry, will be augmented by the use of modern communication techniques.

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Further Information

For further information, the reader is referred to:

www.euro-cleancoal.net.

There the reader can gain full information of the EC - Joule-Thermie Programme, Clean Coal Technologies for Solid Fuels R&D (1996-1998), the constituent research projects and the project co-ordinators.

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