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JIEA Low NO_x combustion project STAGE III
Low NO_x combustion and sorbent injection demonstration projects

Final report, volume II
Technical summary

Roy Payne

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IEA LOW NO_X COMBUSTION PROJECT
STAGE III
LOW NO_X COMBUSTION AND SORBENT INJECTION DEMONSTRATION PROJECTS

FINAL REPORT
VOLUME II
TECHNICAL SUMMARY

Prepared for:
The Executive Committee of
the Contracting Parties
for
Canada, Denmark and Sweden

Operating Agent:
Elkraft Power Company Ltd.

Prepared by:

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Förord

Föreliggande rapport benämnd: "IEA Low NO_x Combustion Project Stage III, Low NO_x Combustion And Sorbent Injection Demonstration Projects" med underrubrik "Final Report, Volume II, Technical Summary" utgör slutrapport på ett projekt som startade 1979.

1982 rapporterades steg 1 i projektet under titeln: "NO_x Formation from Different Coal types in a Bench Scale Reactor under Excess Air and Staged Combustion Conditions" och med SVF-nummer 129.

1985 rapporterades steg 2 i två rapporter med SVF-nummer 206 respektive 207 under titeln: Evaluation of Non-US Coals Emission Performance with the Distributed Mixing Burner".

Resultaten från steg 1 och 2 bedömdes vara så intressanta att beslut fattades om att genomföra fullskaleförsök, steg 3, i Canada, Danmark och Sverige. U.S.A., som deltagit i steg 1 och 2 som "Operating Agent" d.v.s projektledare, önskade endast deltaga i steg 3 som observatör. Som bidrag ställde U.S.A. därvid resultaten av fullskaleprov inom LIMB-(Lime Stone Injection Multiple Burner) projektet till förfogande.

Elkraft Power Company Ltd., Danmark, accepterade uppdraget som "Operating Agent" och "Energy and Environmental Research Corporation" (EERC) U.S.A. anlitades som "Contracting Agent" dvs provningsansvarig i likhet med steg 1 och 2.

Steg 3 kunde för Sverige genomföras tack vare ett mycket kraftfullt ekonomiskt stöd från Statens energiverk och Stockholm Energi AB. Administrativt har projektet letts av Värmeforsk med hjälp av en styrgrupp bestående av:
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Till styrgruppsammanträdena har dessutom på önskemål från fall till fall adjungerats medlemmar ur Värmeforsk Bränsleteknikgrupp.

Internationellt har projektet lettas av en "Executive Committee" bestående av:

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Projektets totala genomloppstid för stegen 1-3, 11 år, är ett mått på den tid det kan ta att utveckla nya metoder till full skala. Genomförandet hade inte varit möjligt utan det intresse och helhjärtade stöd som visats projektet av de ansvariga i de deltagande nationerna. På "Executive Committee" vägnar tackar jag alla som bidragit till projektets genomförande.

Roy Carlson

This report, produced by the Contracting Parties to the Low NOx Coal Combustion Agreement, has been reviewed in draft form by nominated experts in the participating countries and their comments have been taken into consideration. It has been approved by the Executive Committee of the IEA Low NOx Coal Combustion Agreement.

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SAMMANFATTNING

Denna rapport sammanfattar de viktigaste resultaten av ett IEA-projekt vars avsikt var att demonstrera hur låg-NO_x-förbränning och inblåsning av absorberande medel kan användas för att kontrollera NO_x- och SO_x-emissionerna från kommersiella pannor som eldas med kolpulver. Projektet har utgått från den information som samlats in under två tidigare steg, där kontrollprocesser för NO_x och SO_x utvärderades i form av såväl grund- som pilotförsök. Utgångspunkt för det aktuella projektsteget (steg III) utgjorde ett unikt samarbete, inom vilket de deltagande länderna (Canada, Danmark, Sverige och USA) slagit samman information från fullskaliga panndemonstrationer med låg-NO_x-brännare och inblåsning av absorberande medel, och tillsammans bidragit till att upprätta en gemensam bas för datautvärdering.

Demonstrationsprov genomfördes framgångsrikt med fem kommersiella pannsystem, alltifrån en värmepanna på 20 MW, som användes för fjärrvärme, till en kommersiell kraftverkspanna på 300 MW el. Samtliga enheter eldades med högflyktigt bituminöst kol med svavelhalter på 0,6-3,2 procent. Vid varje anläggning antingen ändrades eller utbyttes brännarna, för att passa för låg-NO_x-förbränning, och anordningar applicerades för inblåsning av kalciumbaserade absorberande material i eldstaden, för kontroll av SO_2-emissionerna. Detaljerade förberedande utvärderingar genomfördes för de olika pannorna. Dessa omfattade en analys av värmeöverföringsprestanda, utarbetandet av en isotermisk modell av de fysiska flödesförhållandena, en utvärdering av brännarkonstruktionen samt en experimentell reaktivitetsprovning av absorberande material. Dessa analyser användes för att få fram information som underlag för processuppläggningen och tjänade också som utgångspunkt för utvärdering av provningsdata i ett gemensamt format.

Resultaten visade att de sänkningar av NO_x-emissionerna som åstadkoms, relativt de ursprungliga nivåerna, varierade mellan 20 och 40 procent. De största sänkningarna erhölls där man hade genomfört kompletta brännarutbyten, varigenom man fick en större flexibilitet

vid inställning av brännarparametrarna. Absolutvärdena för NO_x-emissionerna visade sig också bero på såväl pannparametrarna som på brännarkonstruktionen. Den viktigaste observationen vid låg-NO_x-drift utgjordes av en tendens mot en ökad kolhalt i askan, medan man iakttog relativt små effekter med avseende på andra pannprestanda under provningstiden.

Resultaten av proven med inblåsning av absorberande medel visade måttliga sänkningar av SO_2-halterna, inom omfånget från omkring 15 procent till 55 procent, vid en molviktsproportion mellan inblåst kalcium och svavel på 2,0, och med pannan vid nominell full effekt. Sänkningen av svavelhalten visade sig bero av flera parametrar i kombination, som t ex det absorberade medlets typ och reaktivitet, kolets svavelhalt samt pannans termiska karakteristika. Mätdata från de olika pannorna visade sig överensstämma relativt väl med de i färväg beräknade sänkningarna av SO_2-halterna, vilket visade att de ovanstående parametrarnas relativa inverkan kunde beräknas nöjaktigt. En viktig följd av inblåsningen av absorberande medel visade sig generellt utgöras av en ökad av askavsättning på värmeöverförings-ytorna, även om detta kunde åtgärdas genom att man ändrade sotningscyklerna och -frekvenserna. Mer omfattande inverkan på elfiltren kunde dessutom observeras vid två av de fyra enheter där denna faktor utvärderades, vilket huvudsakligen berodde på den ökade askmängden och på en större resistivitet hos askan. Dessa svårigheter löstes framgångsrikt med hjälp av rökgaskonditionering.

Även om dessa tekniker för låg-NO_x-förbränning och inblåsning av absorberande medel endast kan betraktas som partiella kontrolltekniker, så kan det föreligga en potential för en omfattande spridning av dem vad avser nyinstallationer och utbyten inom såväl industriländerna som utvecklingsländerna. Inom de senare kan de låga kapitalkostnader som de bägge teknologierna medför vara attraktiva. Allt eftersom energibehovet och användningen av inhemskt kol ökar inom dessa

områden skulle tillämpningen av billig NO_x/SO_x-kontroll väsentligt kunna justera ner prognoserna avseende framtida surt nedfall. I industriländerna kan låg-NO_x/SO_x-förbränningssystem integreras med sekundära reningsprocesser, för att därigenom uppfylla ännu striktare emissionsgränser. Ett antal efterbehandlingsprocesser, såsom befuktning för ökad SO_2-avskiljning och inblåsning av reagensmedel för att selektivt förstöra NO_x, finns nu tillgängliga kommersiellt.

ABSTRACT

This report summarizes the main results from an IEA project concerning the demonstration of low-NO_x combustion and sorbent injection as techniques for the control of NO_x and SO_x emissions from pulverized coal fired utility boilers. The project has built upon information generated in two previous stages of activity, where NO_x and SO_x control processes were evaluated at both fundamental and pilot-scales. The concept for this stage of the project (Stage III) was for a unique collaboration, where the participating countries (Canada, Denmark and Sweden, together with the United States) have pooled information from full scale boiler demonstrations of low-NO_x burner and sorbent injection technologies, and have jointly contributed to establishing a common basis for data evaluation.

Demonstration testing was successfully carried out on five wall-fired commercial boiler systems which ranged in size from a 20 MW thermal input boiler used for district heating, up to a 300 MW electric utility boiler. All of these units were fired on high-volatile bituminous coals with sulfur contents ranging from 0.6-3.2 percent. At each site the existing burners were either modified or replaced to provide for low-NO_x combustion, and provisions were made to inject calcium based sorbent materials into the furnace space for SO_2 emission control. Detailed pre-test evaluations were carried out for each boiler and included: detailed heat transfer performance analysis; isothermal physical flow modeling; burner design evaluation; and experimental reactivity testing of sorbent materials. These analyses were used to generate process design information, and served as a basis for the evaluation of test data according to a common format.

Results from the boiler demonstration programs indicated that the NO_x emission reductions achieved, relative to initial baseline levels, ranged from approximately 20 percent to greater than 40 percent. The greatest reductions were achieved in situations where full burner retrofits had been carried out, reflecting a greater flexibility in setting burner parameters. Absolute values of NO_x emission were also found to depend upon boiler parameters as well as burner design. The major impact of low-NO_x operation

was in a tendency towards increased carbon in ash, with relatively little effect on other aspects of boiler performance over the time period of the tests.

The results of sorbent injection testing showed moderate levels of SO_2 removal which ranged from approximately 15 percent to 55 percent at an injected calcium to sulfur molar ratio to 2.0 and with boiler operation at nominal full load. Sulfur capture was found to depend upon the combined effects of parameters such as: sorbent type and reactivity; peak sorbent temperature; coal sulfur content; and the thermal characteristics of the boiler. The measurement data from each of the boilers was found to be in generally good agreement with a-priori predictions of SO_2 removal, indicating that the relative impacts of the above parameters could be adequately accounted for. A major impact of sorbent injection into the furnace space was generally found to be an increase in ash deposition on heat transfer surfaces, although this could be handled by modifications to the sootblowing cycles and frequency. Major impacts on electrostatic precipitator performance were also observed at two of the four units where this was evaluated, due mainly to the increased ash loading, and increased ash resistivity. These difficulties were successfully overcome by the use of flue gas conditioning.

While these low NO_x combustion and sorbent injection technologies may be considered to be only partial control techniques, there may be considerable potential for their deployment in new and retrofit installations in both developing and industrialized countries. In developing regions, the low capital costs associated with both technologies could be an attractive feature. As energy demand and the utilization of indigenous coals increases in these regions, the application of low cost NO_x/SO_x control could significantly reduce the global forecast for acid rain fall-out. In industrialized countries, low NO_x/SO_x combustion systems may be integrated with secondary control processes to achieve more stringent emission limits. A number of post-furnace processes, such as humidification for enhanced SO_2 capture by unreacted sorbent, and reagent injection to selectively destroy NO_x, are now commercially available.

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1.0 INTRODUCTION

1.1 Background

The potential role of nitrogen oxides (NO_x) and sulphur oxides (SO_x) emissions from combustion sources as a contributory factor in "acid rain" impacts has received considerable attention over the past several years. Since it is clear that such emissions do not follow political boundaries, and are therefore a global issue, there has been a growing international dialogue concerning emissions control for both new and existing combustion sources. Moreover, since it is estimated that coal fired utility boilers contribute significantly to total emissions from man made sources, the development of low-cost and retrofittable control strategies appropriate to this sector of industry has been a subject of particular interest.

In March of 1980 the countries of Canada, Denmark, Sweden and the United States signed an International Energy Agency (IEA) Implementing Agreement, "For the Establishment of a Project on Control of Nitrogen Oxides Emissions during Coal Combustion." This project was designed to build upon a program initiated in 1971 by the United States Environmental Protection Agency (U.S. EPA) as a comprehensive integrated study of pulverized coal combustion, with a special emphasis on the mechanisms of NO_x formation and control. A major development from the U.S. EPA program had been the concept of staged combustion, in which the delayed mixing of coal and air is used to produce locally fuel rich zones which promote the preferential conversion of fuel nitrogen to molecular nitrogen. Since this work had been based solely on U.S. coals, a primary objective of Stage I of the IEA Project was to extend the study to coals of non U.S. origin.

In Stage I of the project twenty different coals from around the world were subjected to bench scale testing under both normal and staged combustion conditions, according to protocols developed under the EPA program. A major objective of the study was to further elucidate the mechanisms of NO_x formation, and the amenability to NO_x emission reduction, as a function of basic coal properties. A major finding of this study [1][2] was that, for

well defined combustion conditions in the bench scale furnace, it was possible to develop empirical correlations relating NO_x emissions to fuel properties such as nitrogen, volatile and fixed carbon content. Such correlations were developed for well mixed (high NO_x) conditions, and for minimum NO_x (optimally staged) conditions.

Following the successful completion of Stage I of the project all countries agreed to proceed with larger scale testing in practical burners under Stage II. At about this time there was considerable interest in the injection of calcium based sorbents directly into the combustion zone of low-NO_x burners as a means of simultaneously controlling emissions of sulfur oxides (SO_x). It was therefore decided to extend the IEA Agreement to include a preliminary evaluation of sorbent injection technology. In Stage II, limited testing was conducted in bench-and small pilot-scale test facilities, in addition to the EPA Large Watertube Simulator (LWS) furnace using a full-scale version of the low-NO_x Distributed Mixing Burner (DMB). Test results generated in this study [3], indicated NO_x emissions reductions of up to 70 percent, and SO_2 emission reduction of 50 percent using limestone sorbents, under conditions believed to be representative of boiler operation.

The successful completion of Stages I and II of the IEA project led to substantial interest in the potential for application of low NO_x combustion and sorbent injection technologies at full scale.

1.2 IEA Agreement - Stage III Project Scope

In 1985 an Executive Committee decision was made to extend the project activities into a third stage. The concept was for a unique collaboration where the participating countries would pool information from full scale boiler demonstration of low NO_x combustion and sorbent injection technologies, and jointly contribute to establishing a common basis for data evaluation. In Stage III of the project full scale field demonstrations of low NO_x coal combustion, combined with sorbent injection for SO_2 control, have been carried out on five wall fired boilers. These were:

- GAGETOWN, in Canada, which is a small boiler with a nominal rated capacity of 20 MW_{th}, used for district heating.

- HASSELBY, in Sweden, with a nominal capacity of 100 MW_{th}, producing approximately 22 MWe of electricity plus hot water for district heating.

- STIGSNAES, in Denmark, a 150 MWe utility boiler.

- LAKEVIEW, also in Canada, a 300 MWe utility boiler.

- EDGEWATER, in the USA, a 105 MWe utility boiler, and the site of EPA's LIMB demonstration project.

All units were fired on high volatile bituminous coals with sulfur contents ranging from 0.6-3.2 percent, fuel nitrogen from 1.2-1.4 percent, and ash contents in the range of 2-15 percent. At each of these boiler sites the existing burners were either modified or replaced to provide for low NO_x combustion, and sorbent injection systems were installed (with the exception of Gagetown) in the upper furnace for SO_2 emission control. Here it should be noted that low NO_x modifications were not implemented on the Lakeview boiler, but rather results from an earlier burner retrofit on a boiler at the Nanticoke Station have been incorporated into this study.

The demonstration projects on each of these boilers were conducted independently, with individual project teams providing their own funding, and taking responsibility for system design, construction and test execution. However, under the IEA Task-Sharing project, each of the boilers in Canada, Denmark, and Sweden was subjected to a common independent analysis, in order to ensure a common approach to performance testing and to facilitate comparison of the different data sets on an equal basis. In order to achieve this the Executive Committee requested the Energy and Environmental Research Corporation to provide technical support to the program by conducting design studies for each boiler and by providing for independent data review and evaluation. Elkraft Power Company Ltd., of Denmark was requested to act as

Operating Agent for Stage III in an overall organization as shown in Figure 1-1.

A detailed organization and breakdown of activities during the process design, and subsequent test planning and test execution phases of the project, is presented in Figure 1-2 and 1-3. These figures show the general structure and phasing adopted for the overall project, and the interrelationship between process design and evaluation activities, and plant modification, testing and data acquisition.

A key element in the execution of the overall project was the performance of detailed pre-test evaluations on each boiler to generate process design information for the application of low NO_x combustion and SO_2 control technologies. These studies also ultimately serve as a common basis for test data evaluation. Detailed studies were conducted for the Gagetown, Stigsnaes, Hasselby and Lakeview boilers. The Edgewater boiler demonstration project was conducted independently, but was incorporated into the study through information supplied by the U.S. EPA.

Detailed pre-test evaluations were based upon boiler design and operational data provided by the individual utility project teams and included: 3-dimensional heat transfer modeling to provide details of the temperature fields and temperature history as a function of major operating variables; isothermal physical flow modeling, in a reduced scale plastic model of each boiler, to define the boiler flow field and to evaluate dispersion patterns produced by candidate sorbent injection schemes; review of boiler and burner designs and performance data for NO_x control evaluation; and experimental testing of sorbent materials to establish their reactivity. The approach to burner modification and to sorbent injection was slightly different for each of the test boilers, depending upon boiler specific considerations and upon the degree of flexibility afforded in each retrofit situation.

Prior to the initiation of any actual demonstration testing, detailed test plans were prepared for each of the boiler projects. Although

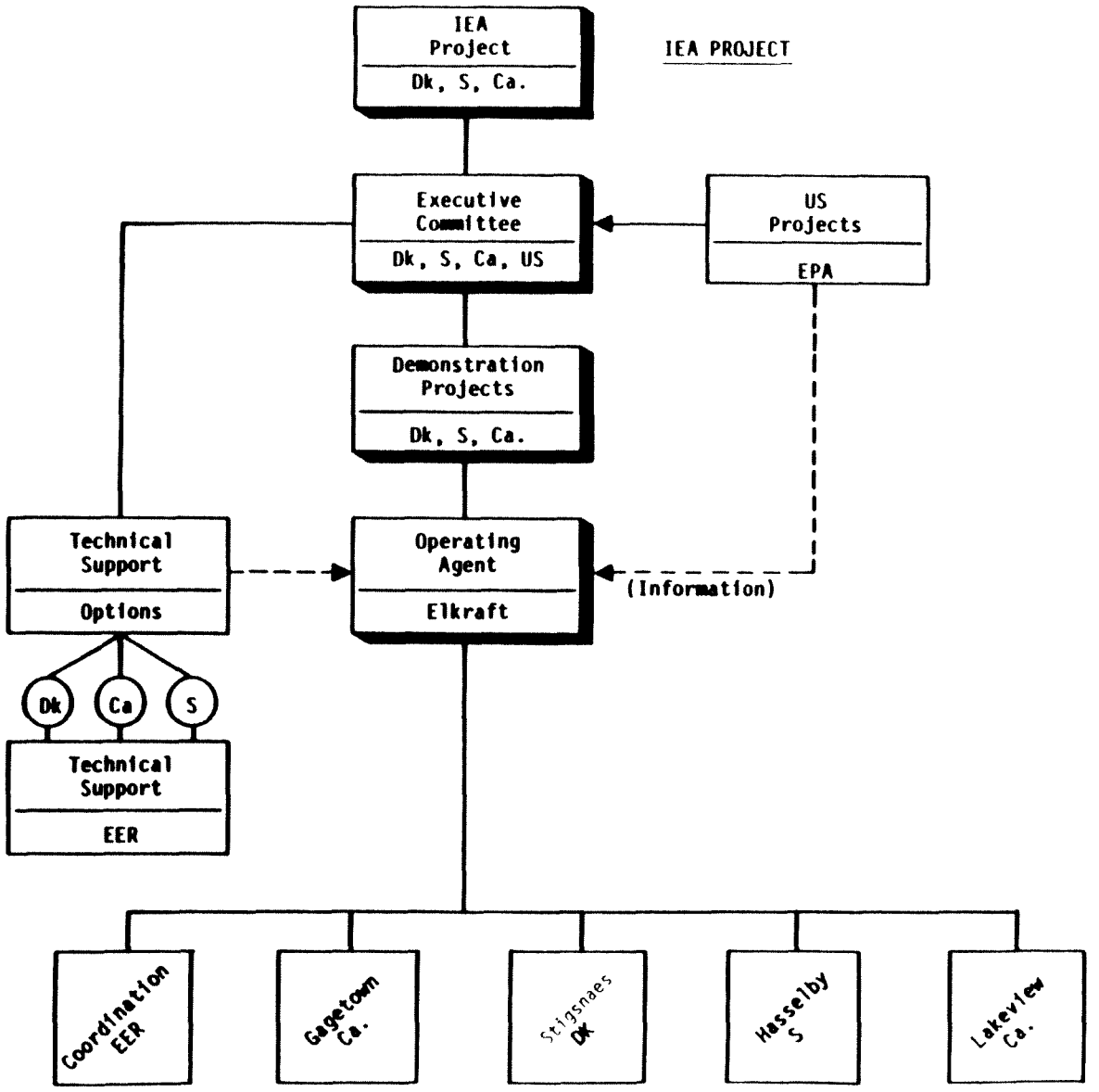


Figure 1-1. IEA Project Stage III - overall organization.

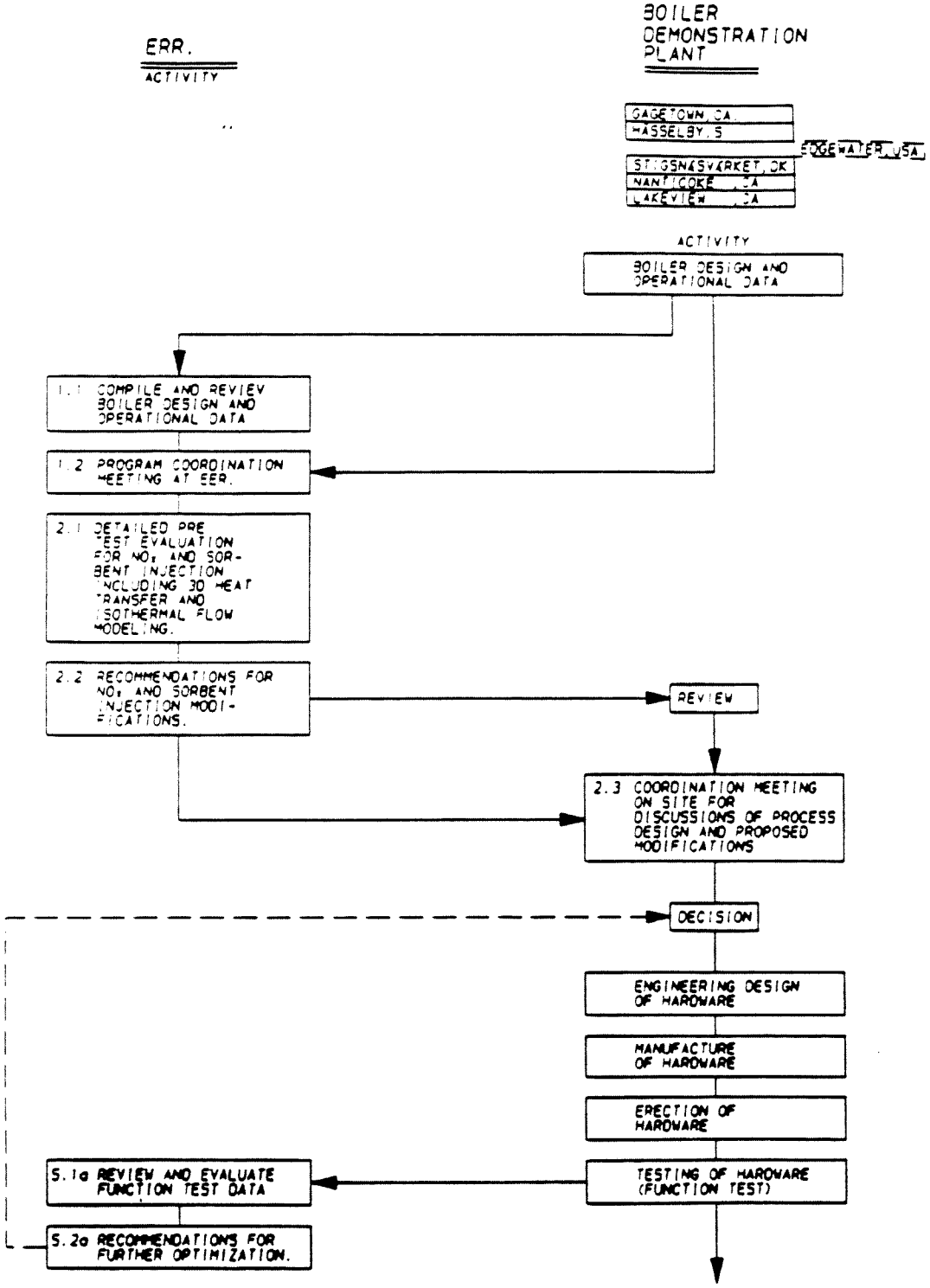


Figure 1-2. **IEA Project Stage III -** Process Design.

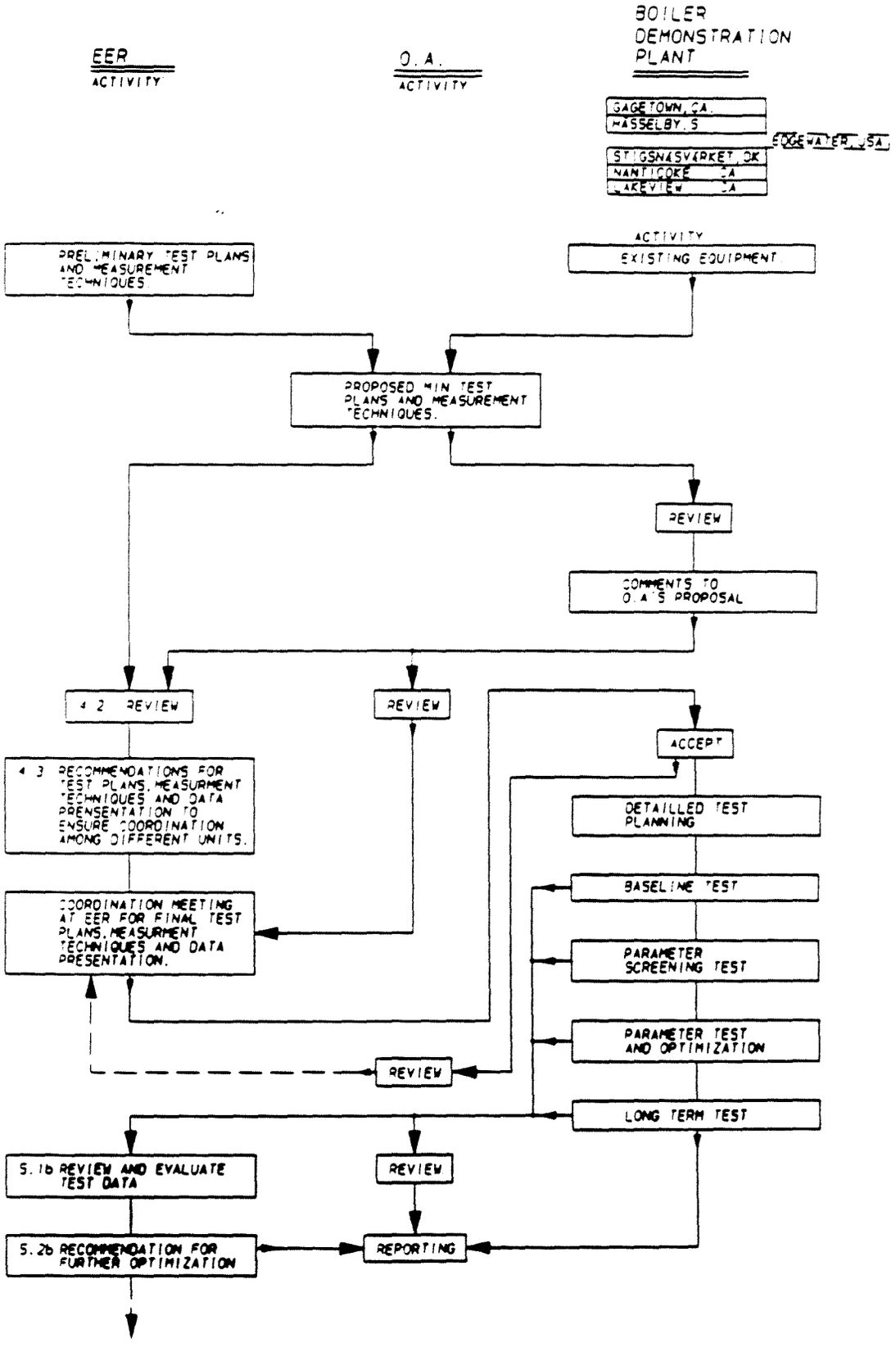


Figure 1-3. **IEA Project Stage III - Organization of Test Planning and Execution.**

individual plans were designed to accommodate the test variable parameters, major goals, and operational constraints unique to each boiler site, there was considerable coordination in plan development. Here, a major consideration was to ensure that a certain minimum test plan and measurements program was conducted in order to permit comparison of test results on an equivalent basis, and that there was some commonality in data presentation format. Additionally, measurement techniques were reviewed, with a particular emphasis on the measurement of SO_2 in the presence of reactive particulate, to ensure that previously documented difficulties were not repeated and that normal data quality assurance procedures were followed. The test plans were established to generate not only emissions data but also to address issues related to system operability, thermal performance, and impacts on ancillary equipment such as the electrostatic precipitator. The structured format for testing included:

- Baseline testing, to establish pre-modification emission levels and boiler performance.

- Parameter screening and optimization tests for low-NO_x burners and sorbent injection, to determine NO_x and SO_2 emissions reduction as a function of major operating and test variable parameters.

- Longer term testing under optimum conditions to provide data on boiler and overall system performance.

The demonstration projects were each conducted on separate schedules and were mostly completed by the Spring of 1988.

1.3 Report Organization

Separate, detailed test reports have been prepared for each of the individual boiler demonstration projects. These reports contain comprehensive information on plant characteristics, equipment design and modifications, and all parametric and long duration test data. The primary objective of this present report is to present a concise summary of the total

project. Consequently, only limited data has been extracted from the main test reports, sufficient only to illustrate trends and to show major conclusions. A major emphasis is however placed on the comparison and generalization of the results from the individual projects, as a means of identifying controlling parameters, and ultimately for extrapolation to other units of a different design.

The report has been divided into five major sections. Section 2 presents a general discussion of boiler characteristics and the approach adopted to burner modification and sorbent injection. This information is supplemented by results from heat transfer and flow modeling studies, with the objective of identifying specific boiler characteristics which are important both for NO_x and SO_2 emission control.

Section 3.0 presents results of the NO_x control portion of the project. As an introduction to this area there is a general discussion of parameters related to both burner and boiler design which previous experience has shown to be important for NO_x emission control. Individual test results are presented and compared in a subsequent subsection, followed by a discussion of the general implications of the results. A similar approach has been adopted in the treatment of SO_2 control data in Section 4.0. A preliminary subsection discusses key parameters affecting SO_2 emission control by sorbent injection, followed by presentation, comparison and discussion of implications of the results.

A final section (Section 5.0) presents summary conclusions from the total project, with a special emphasis on implications for the more general application of low NO_x burner and sorbent injection as low cost retrofit technologies. Areas where further work may be beneficial to enhance reliability and operational performance are also presented and discussed.

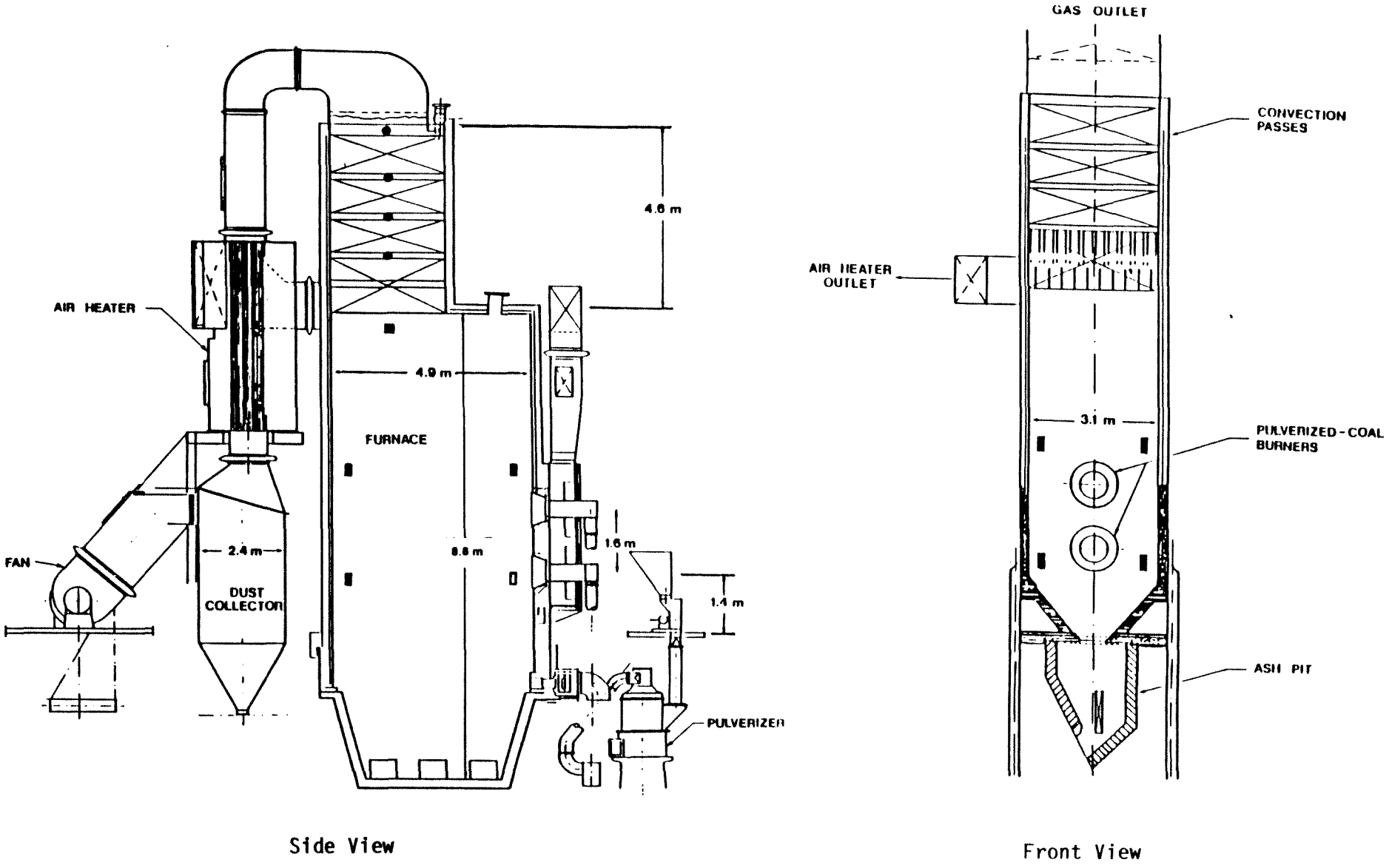
2.0 BOILER CHARACTERISTICS

The purpose of this section is to present brief descriptions of each of the boilers for which data is presented, together with background information appropriate to the demonstration project.

2.1 Gagetown

This boiler was the smallest of the units tested in the IEA project, and was Generator No. 2, located at the Central Heating Plant at Canadian Forces Base Gagetown, in New Brunswick. This boiler is rated at 20 MW thermal input and supplies hot water at 1090 kPa. The unit is fired by two burners, each supplied by a dedicated pulverizer, as shown in Figure 2-1. Normally only the lower burner is in service at generator loads below 60 percent. Although capable of operating without oil support, the burners are co-fired continuously with 2-3 percent oil to prevent ignition failure caused by sudden interruptions in pulverizer output when the incoming coal is excessively wet or frozen. Flue gases leave the furnace at about 250°C and pass through an air heater, a cyclone and an internal setting chamber before entering a tall stack at 200°C.

As a part of the demonstration program, the existing circular coal burners and their associated burner management system were replaced with commercial low-NO_x coal burners. These burners were of the distributed mixing burner (DMB) type, having an annular coal nozzle, a single secondary air register with variable swirl, and four outboard tertiary air ports to deliver staged mixing air. Several modifications were made to these burners during the test program to optimize NO_x emission control and to reduce carbon carry over. Burners of this type lend themselves readily to the injection of sorbent through the outboard air ports, which was the main configuration employed during testing. This configuration also represents the original "limestone injection multistaged burner" (LIMB) concept proposed by the U.S. EPA.



Side View

Front View

Figure 2-1. Section views of generator No. 2 - Gagetown CHP.

The sorbent feeding system installed at Gagetown was a commercial system, employing a single 100 m^3 storage bunker with a conical, fluidized bottom. Limestone feeding from the bunker was via a rotary valve through an impact plate weighing device, and into an ejector system for pneumatic transport to the furnace. A distributor was used to divide the main sorbent/transport air stream into eight separate streams, where final injection was through nominal 32 mm diameter pipes located centrally within the tertiary air ports of each of the burners.

Testing was conducted using two high-volatile bituminous coals having 3.5 percent and 1.5 percent sulfur respectively. Both coals, which had about 10 percent moisture and a calorific value of 28.8 MJ/kg, were pulverized to 75 percent less than 74 microns.

During the pre test evaluations, boiler characteristics were evaluated using a combination of heat transfer modeling and isothermal flow modeling. Selected results from the heat transfer study are presented in Figure 2-2 for a boiler heat input of 21.8 MW., 20.4 percent excess air and burner operation under nominal staged conditions. Temperature levels in this unit are expected to be moderate compared to larger utility boilers, but generally conductive to sorbent injection as will be discussed in subsequent sections. However, because of the temperature levels, carbon carry over is expected to be high, even with high reactivity coals. Flow modeling studies showed the most significant feature of the boiler flow field to be a large slow moving recirculation zone positioned in the furnace above the burners. Tracer studies showed this zone to entrain a significant amount of injected sorbent materials.

2.2 Hasselby

Located north of Stockholm in Sweden, the Hasselby power plant comprises a pulverized coal/oil fired heat-electric station with a capacity of 192 MW heat for district heating and 66 MW electricity, and also an oil fired condensing unit with a capacity of 160 MWe. The demonstration project was carried out on boiler No. 2, one of three coal fired units, with a thermal

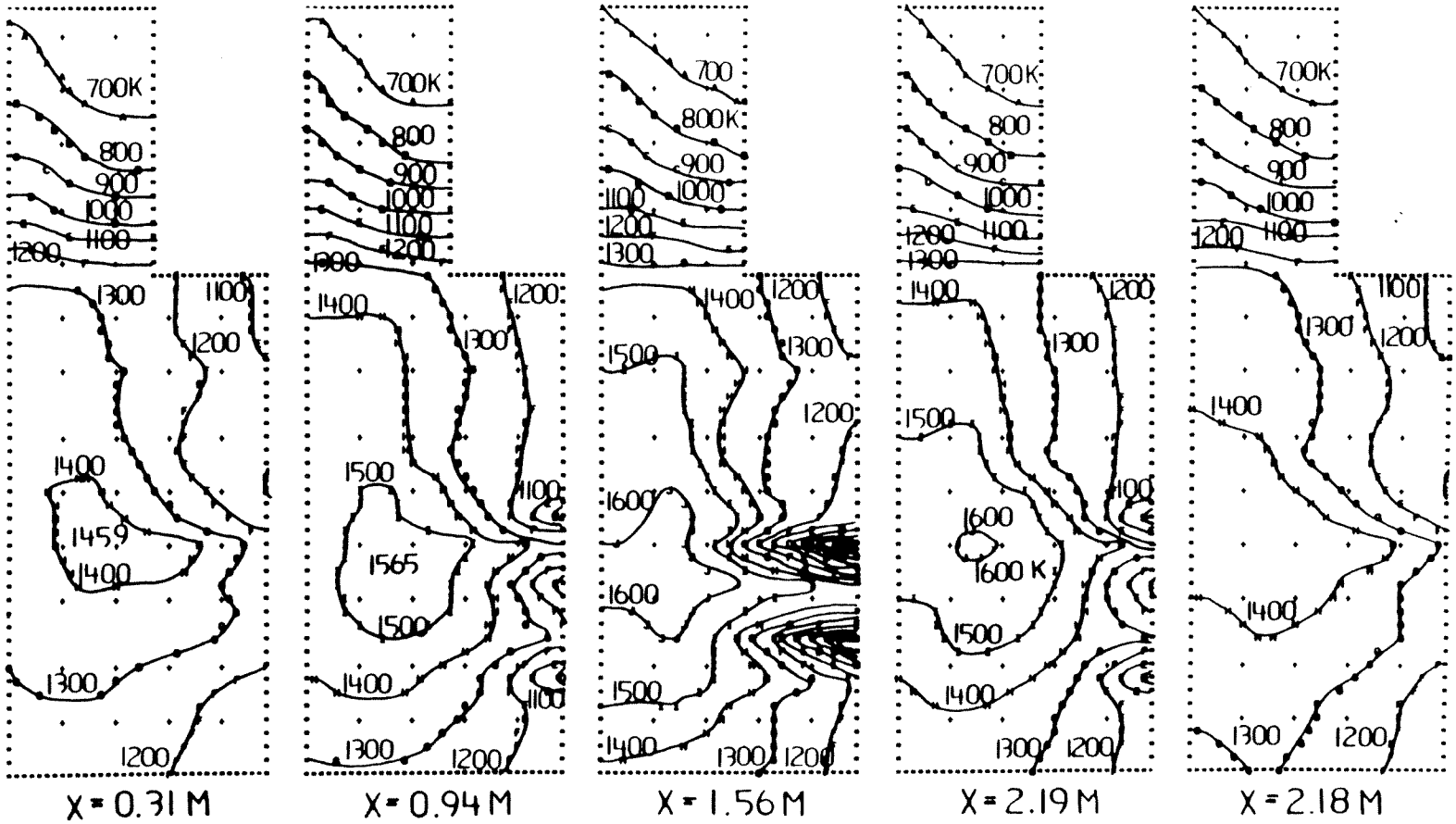


Figure 2-2. Predicted temperature profiles - Gagetown full load.

capacity of 100 MW_t producing 64 MW heat and 22 MW electricity. The steam boilers are designed for 84 bar and 520°C steam temperature, with two stages of superheat. The boiler is of the pure radiant type, built for natural circulation, and is front fired with four pulverized coal/oil burners. The boiler is equipped with a Ljungstrom type air heater and an electrostatic precipitator with a specific collection area of 87 m^2/S. An overview of the unit is presented in Figure 2-3.

In 1982 the boiler underwent a major retrofit in which the existing burners were replaced by low-NO_x burners of the dual-register type, and the old impact crushers were replaced by ball mills. As a part of this test program several additional modifications were made to the burners to improve flame stability, reduce NO_x emissions, and to minimize carbon carry over. Polish coal is the normal fuel supply for this plant, and was used throughout the demonstration test program. This coal is a high volatile bituminous coal, with a volatile content of approximately 31 percent, 8 percent moisture, and less than 10 percent ash. The mean sulfur content throughout the test was 0.61 percent, nitrogen 1.24 percent and the gross calorific value 30.9 MJ/kg.

As part of the pre evaluation studies conducted for this boiler extensive heat transfer modeling and isothermal flow modeling was carried out. The main objectives of the heat transfer studies were to evaluate temperature fields for the location of sorbent injectors, and to study the potential impact of coal particle size on carbon burn out. Selected results of the heat transfer analysis are presented in Figure 2-4 for full load operation (101 MW_t), 23 percent excess air, and a coal grid of 88 percent minus 74 microns. This figure shows predicted temperature profiles at different planes throughout the boiler, and is based on the assumption that furnace walls are relatively free from ash deposits. This latter assumption was necessary in order to bring predicted temperatures into close agreement with earlier measurements. Based upon the heat transfer analysis, a boiler elevation of 19.3 m, where the mean temperature is approximately 1500 K, was selected as the most appropriate for sorbent injection. The rationale for this will be discussed in a later section.

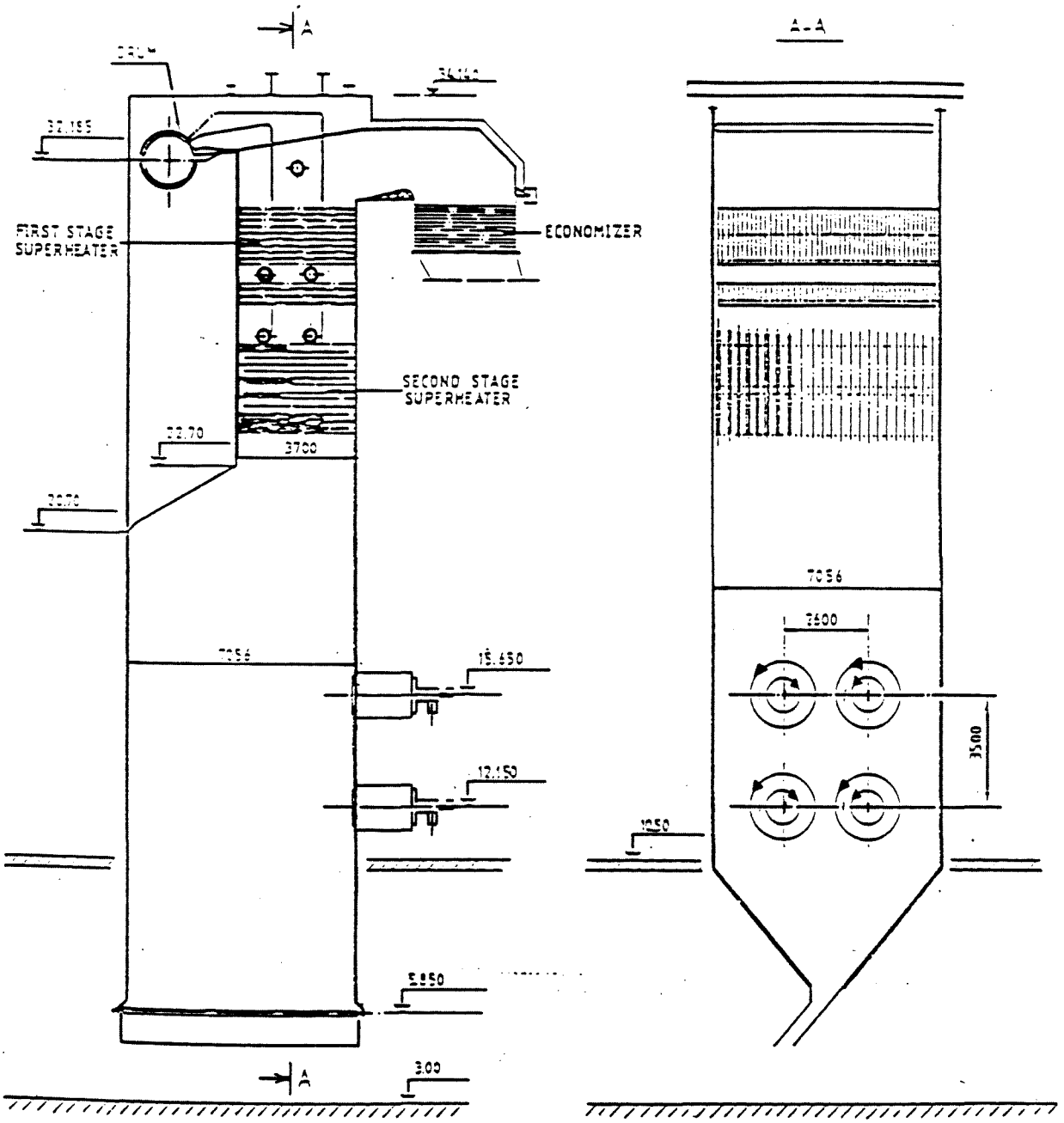


Figure 2-3. General arrangement - Hasselby boiler.

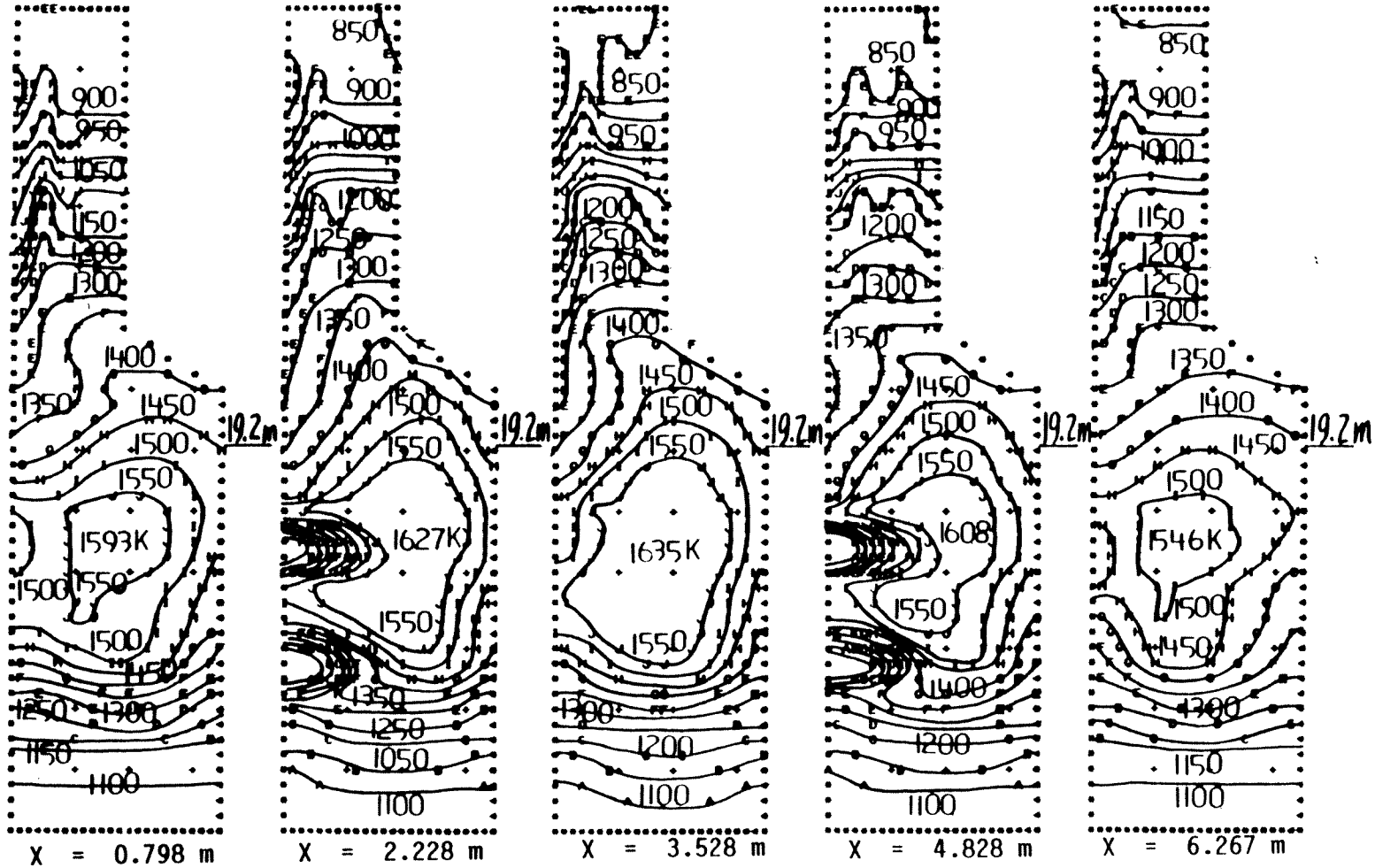


Figure 2-4. Predicted temperature profiles (°K) - Hasselby, full load.

Isothermal flow modeling was also carried out as a means of evaluating the boiler flow field, and of selecting sorbent injection parameters which would yield the best dispersion of the sorbent materials through the flue gases. These studies yielded a recommendation to place four injectors on the furnace rear wall, and two additional injectors on the side wall to cover an observed asymmetry in the flow field which was believed to be caused by the particular configuration of burner swirl directions. This general arrangement of sorbent injectors is shown schematically in Figure 2-5. Two sets of injectors were provided, having diameters of 62 mm and 76 mm and yielding velocities of 54 and 36 m/s respectively, based on 4 percent of the secondary air flow as transport air. Individual nozzles could be tilted $\pm 15^{o}$ in the vertical direction.

The sorbent feeding system employed at Hasselby was designed specially by Stockholm Energi and made use of an existing 200 m^3 concrete bunker with internal fluidization as the main storage silo. A pneumatic sorbent sender located under the main storage silo was used to transfer material to a 4 m^3 feed silo. From the feed silo, six double screws, driven in pairs by three motors, were used to discharge the sorbent into six pneumatic transport lines for delivery to the furnace injectors. The transport air was provided by a 4000 Nm^3/h high pressure fan with independent flow metering on each of the six lines. Sorbent feed rate was determined from a computer based system coupled to three load cells supporting the feed silo.

2.3 Stigsnaes

The Stigsnaes Power Station, located in the southwestern part of Sjaelland, Denmark, is owned and operated by the power company SEAS which, in the Elkraft Group, cooperates with the other power stations in the eastern part of Denmark.

The IEA Low-NO_x Combustion project was performed at the Stigsnaes Power Station Unit 1, which has a gross capacity 150 MW_e. This is a once-through Benson-type boiler with a reheat steam cycle. At full load the boiler produces 450 t/h steam with conditions of $540^{o}C$/184 bar and $540^{o}C$/39 bar at

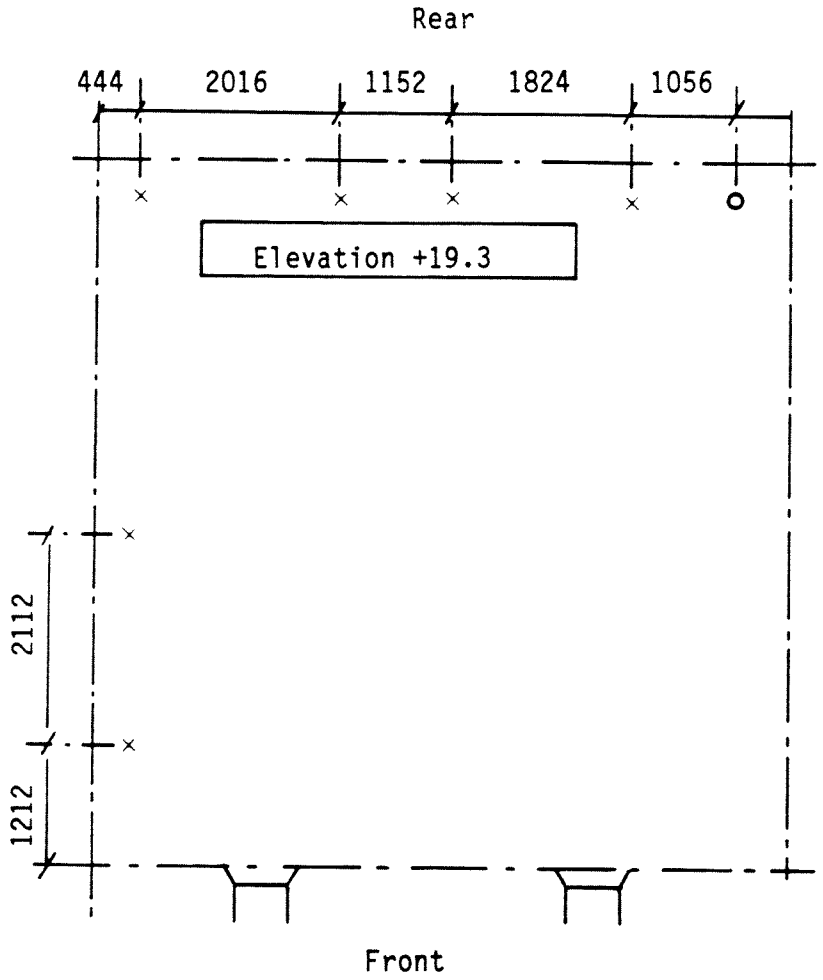


Figure 2-5. Sorbent injection arrangement - Hasselby

superheater and reheater outlets respectively. This unit also has Ljungstrom air preheaters and an electrostatic precipitator with a specific collecting area of 82.7 $m^2/m^3/s$. An overview of the unit is presented in Figure 2-6.

The burner configuration employed is horizontally-opposed-fired with an arrangement of 3 rows of 2 burners on each of the side walls. In 1983 this boiler was converted from heavy fuel oil firing to 100 percent coal firing, at which time twelve low-NO_x burners of the internally staged type (dual air registers) were installed. A number of modifications to these burners were made in 1986 as part of the IEA project, with changes to the coal nozzle, tertiary swirl, and secondary dampers. All modifications had the primary objective of improving low-NO_x emission performance. One further unique feature of this boiler is the possibility to maintain full load operation on any two elevations of the three burner rows, which yielded one additional test parameter in the NO_x and SO_2 emission reduction evaluation.

Stigsnaes Unit 1 was designed to operate on a wide range of coal types imported from around the world. During the test program data was obtained on four different high-volatile bituminous coals. The majority of the test work was conducted using a U.S. coal (volatiles 27 percent, ash 13 percent, S 1.5 percent, N 103 percent, and 25.2 MJ/kg), with additional testing conducted on Columbian coal (0.6 percent S), a blend of Australian and Columbian coals (0.7 percent S) and a Polish coal (0.6 percent S).

As with other boilers studied in the project, extensive heat transfer and flow modeling work was carried out during the pre test evaluation period. Selected heat transfer model predictions are presented in Figure 2-7, and show predicted temperature distributions at various vertical planes in the furnace. The conditions modeled here are for nominal full load operation (150 MW_e) with the lower two elevations of burners in service and operation on U.S. coal. Because of the opposed-fired configuration it will be noted that temperatures in the upper furnace region are expected to peak towards the center of the furnace. Optimum temperature levels (1500°K) for sorbent injection are expected in the vicinity of the boiler nose plane. Isothermal model studies showed the boiler flow field to be typical for this kind of

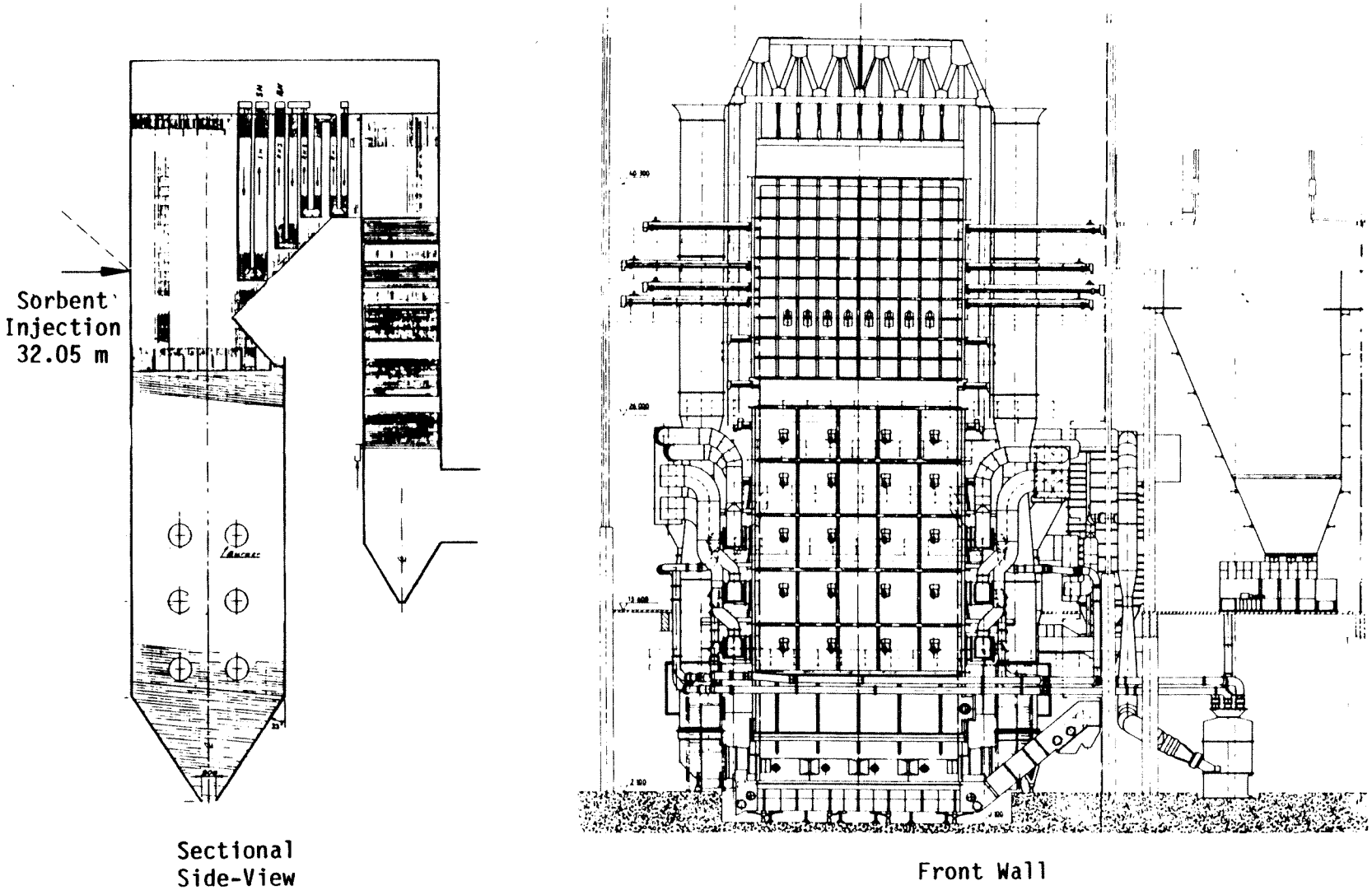


Figure 2-6. General arrangement Stigsnaes Unit 1.

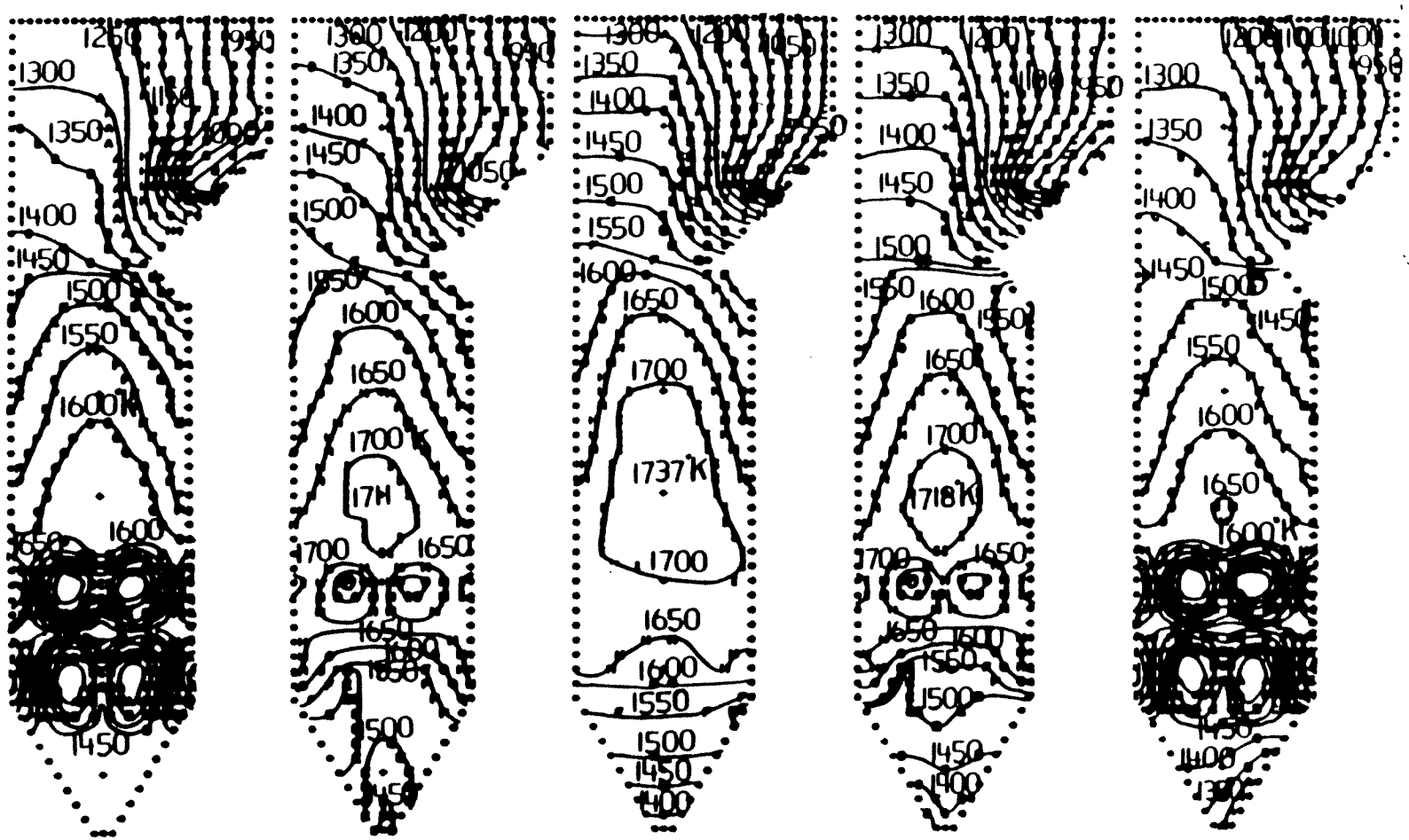


Figure 2-7. Predicted temperature profiles (°K) - Stigsnaes, full load.

general arrangement. In the upper furnace, velocities tended to be higher near to the nose arch and to peak slightly at the center of the furnace. No significant impact on the structure of the flow field was observed with different elevations of burners in service. Several possible sorbent injection configurations were evaluated for this unit, with the final design being a compromise between ideal requirements and practical considerations. This final configuration incorporated 8 equispaced injectors located on the boiler front wall at an elevation of approximately 32 m, just above the nose arch. Individual injectors were 81 mm in diameter, giving 100 m/s injection velocity, and with a downwards tilt capability of 45°.

The sorbent feed system employed at Stigsnaes was an adaptation of a system used in earlier scoping tests, with a series of modifications designed to handle an increased amount of sorbent and to improve control and measurement of sorbent feed rate. The system was based on a 10 m^3 storage silo with two outlets. The silo was equipped with level indicators and a rotating blade to ensure continuous flow to the two outlet openings. Sorbent feed from the silo was controlled by two gravimetric feeders, in which an agitator and single screw prefeeder were used to dose the sorbent material onto a gravimetric belt. Control of the two feeders was independent, with one feeder supplying sorbent to the four central injectors on the boiler wall, and the other feeder supplying the four wing injectors. From the feeders, sorbent was fed into the transport lines through rotary valves and feeding shoes. Sorbent transport, through two distributors to individual injectors, was by means of a fixed air supply (960 Nm^3/h). Additional air was provided by a manually controlled booster fan to yield the appropriate injection velocity in a double concentric injector arrangement.

2.4 Lakeview

Unit number 5 at the Lakeview generating station, operated by Ontario Hydro, Canada, was the largest of the boilers evaluated in the IEA project. The unit is a 300 MW_e front fired boiler where the furnace is divided into three sections by partial division walls which extend approximately one third of the furnace depth from the front and rear walls. It is a radiant type,

pulverized fuel-fired boiler with a design operating pressure of 169 bar, and maximum continuous rating is 2,000,000 lb/h of steam at 540°C superheat and 540°C reheat temperatures respectively. The unit has 18 burners arranged in three rows of six, dual Ljungstrom air heaters, and is equipped with flue gas recirculation. A recent pressure restriction had been imposed the boiler which limited MCR during the tests to 235 MW_e. A schematic side elevation and cross section of the boiler is presented in Figure 2-8.

The normal fuel burned at Lakeview is a U.S. bituminous coal from West Virginia and Pennsylvania with an average sulfur content of 1.7 percent, and a calorific value of 32 MJ/kg. Part of the program also included burning a blended coal mixture. This was a 50/50 blend of 2.2 percent sulfur U.S. coal and a 0.2 percent sulfur Western Canadian Coal. The blended coal had a lower sulfur content (1.2%) requiring less sorbent to be injected for SO_2 removal. Unit 5 has a 3 field, electrostatic precipitator with a design effective specific collecting area (SCA) of 47.7 $m^2/m^3/s$.

Heat transfer modeling studies carried out for the Lakeview boiler yielded predicted temperature profiles as shown on Figure 2-9 for operation at 78 percent MCR (235 MW_e). At this operating condition the selected location for sorbent injection was at boiler elevation 358 feet, where the mean temperature level is expected to be approximately 1500K. Isothermal flow modeling work had however shown that mass flows in the upper furnace zone were strongly biased towards the boiler rear wall, due to the single wall firing configuration and the aspect ratio of the boiler. Because of the particular boiler configuration, access to the furnace rear wall in the upper furnace was not possible, and the isothermal flow modeling studies showed that front wall sorbent injectors would require relatively high velocities (130 m/s) to achieve adequate penetration and mixing with the flue gases. The injection scheme developed by Ontario Hydro is shown in the sectional plan and side view in Figure 2-8, and comprised four front wall injectors and two side wall injectors to provide coverage of the flow in the rear of the furnace.

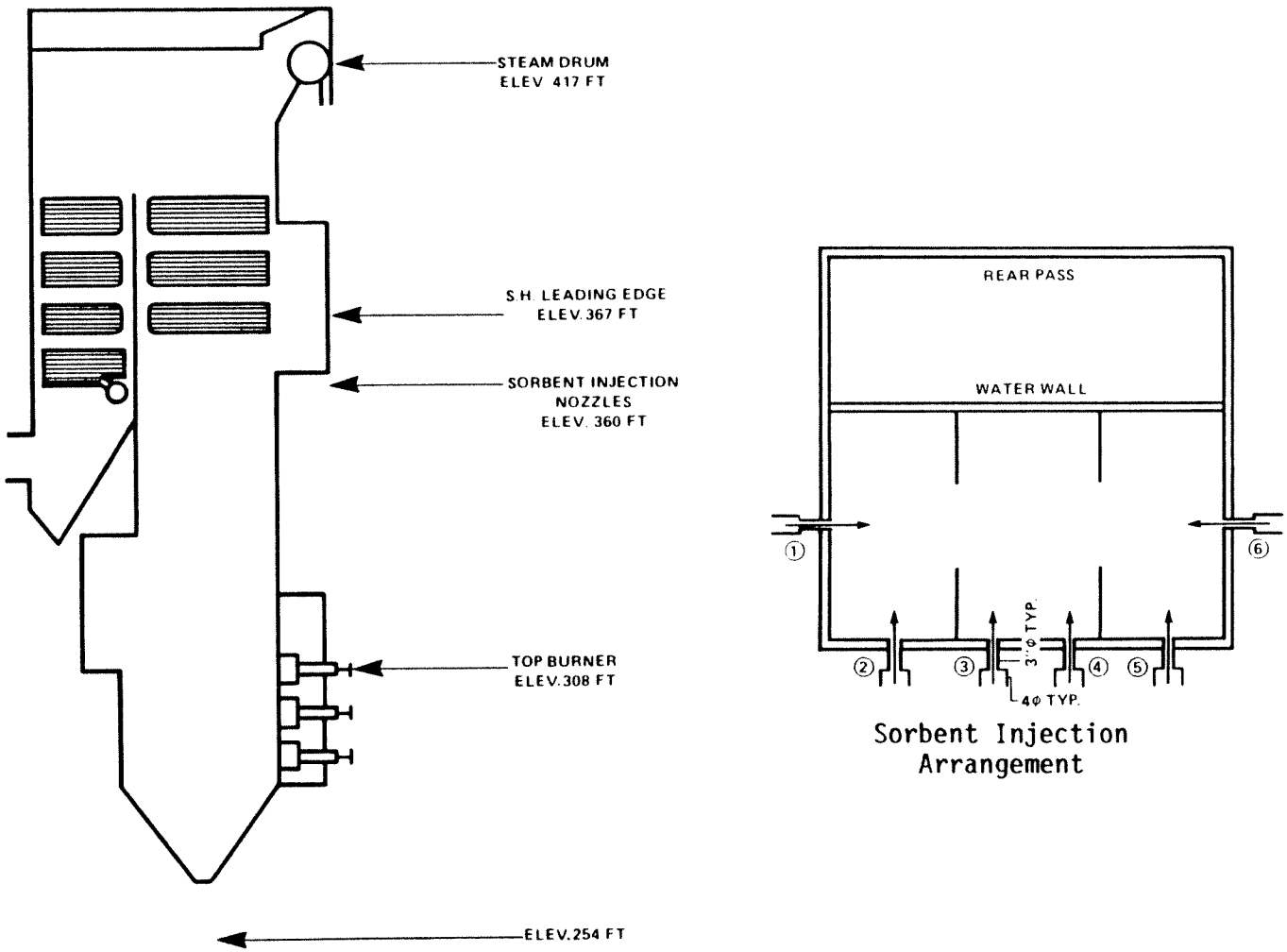


Figure 2-8. Schematic arrangement - Lakeview Unit 5.

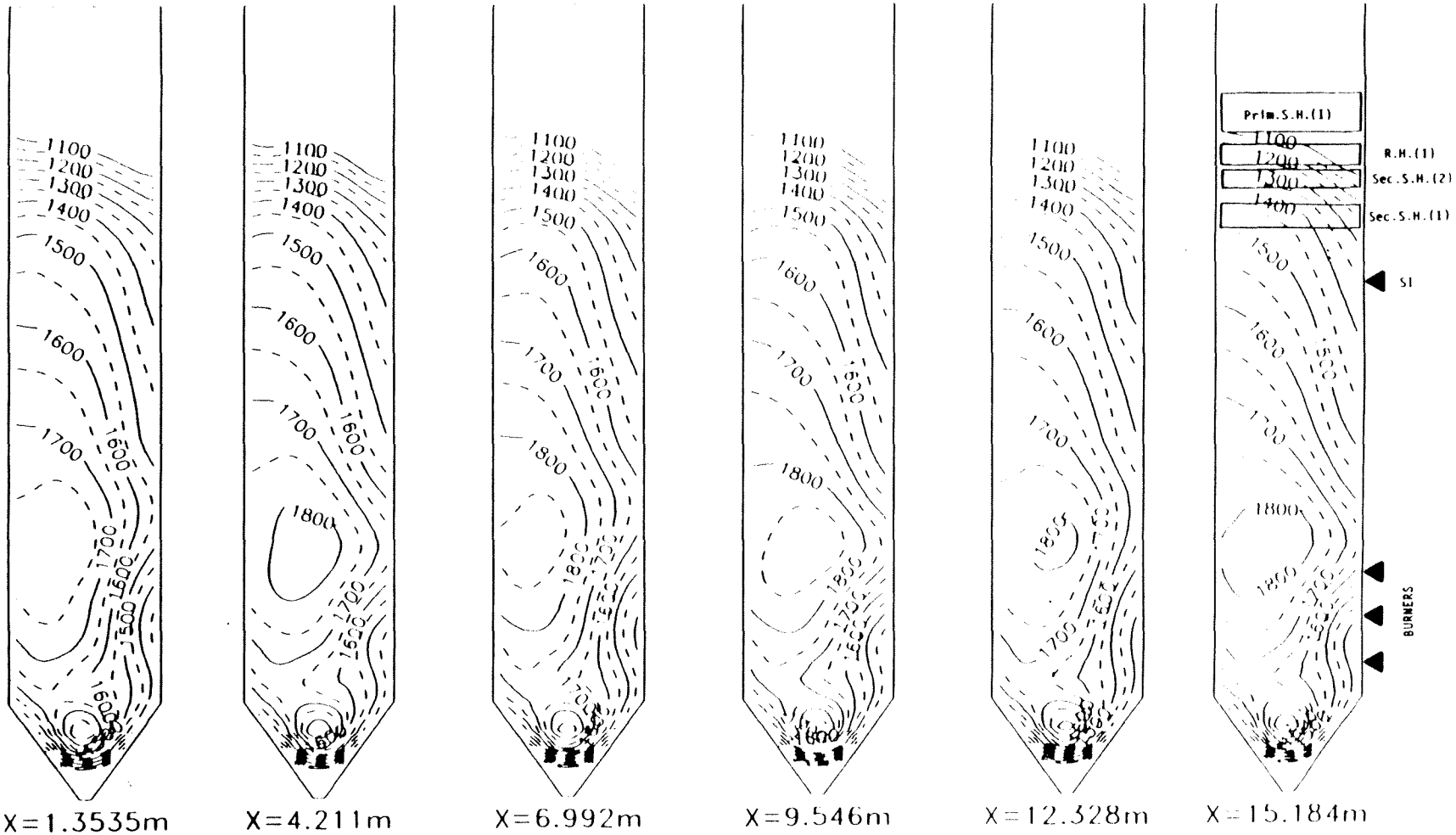


Figure 2-9. Predicted temperature profiles (^{O}K) - Lakeview, 235 MW.

At Lakeview, sorbent was delivered by tanker truck to a storage silo with a capacity of 45 tons of limestone. Discharge from the silo was assisted by aeration stones, with feed rate being controlled by a rotary feeder driven by a variable speed motor. Feed rate was monitored by means of load cells on each of the silo supporting legs. From the rotary feeder, the sorbent discharged into a surge silo feeding a Fuller-Kinyon pump, and then into a pneumatic conveying line for transport to the injection elevation. At the injection elevation a flow splitter was used to divide the sorbent into six streams to individual injectors, each line having a ball valve to permit balancing of individual flows.

Burner modifications for low-NO_x operation were not carried out at the Lakeview unit. However, Ontario Hydro had carried out a comprehensive low NO_x burner development and retrofit program[4], in the time period of 1982-1984, on a series of 500 MW_e coal fired boilers at the Nanticoke station. In this project conventional circular burners with coal impellers, similar to those employed at the Lakeview Station, were replaced with burners of the dual register type which were subsequently modified to optimize NO_x and unburned carbon emissions. In view of the synergism with the IEA program it was requested to incorporate the main results of the Nanticoke retrofit into the overall NO_x evaluation study. A schematic of the Nanticoke boilers is included as Figure 2-10 for reference.

2.5 Edgewater

The U.S. EPA sponsored demonstration of sorbent injection combined with low NO_x burners was carried out on boiler number 4 at Ohio Edison's Edgewater station in Lorain, Ohio. This demonstration project was conducted independently of the IEA project, but has been incorporated into the study through published information[5][6] supplied by the U.S. EPA. The Edgewater boiler has a nominal MCR of 105 MW_e, and is rated at 87 kg/s main steam flow at 102 bar/538°C. The unit is fired on a high sulfur (2.5 to 3.0 percent) bituminous coal through four elevations of three burners. As part of the demonstration program the existing high intensity circular burners were replaced with commercial low-NO_x burners which are a second generation of the

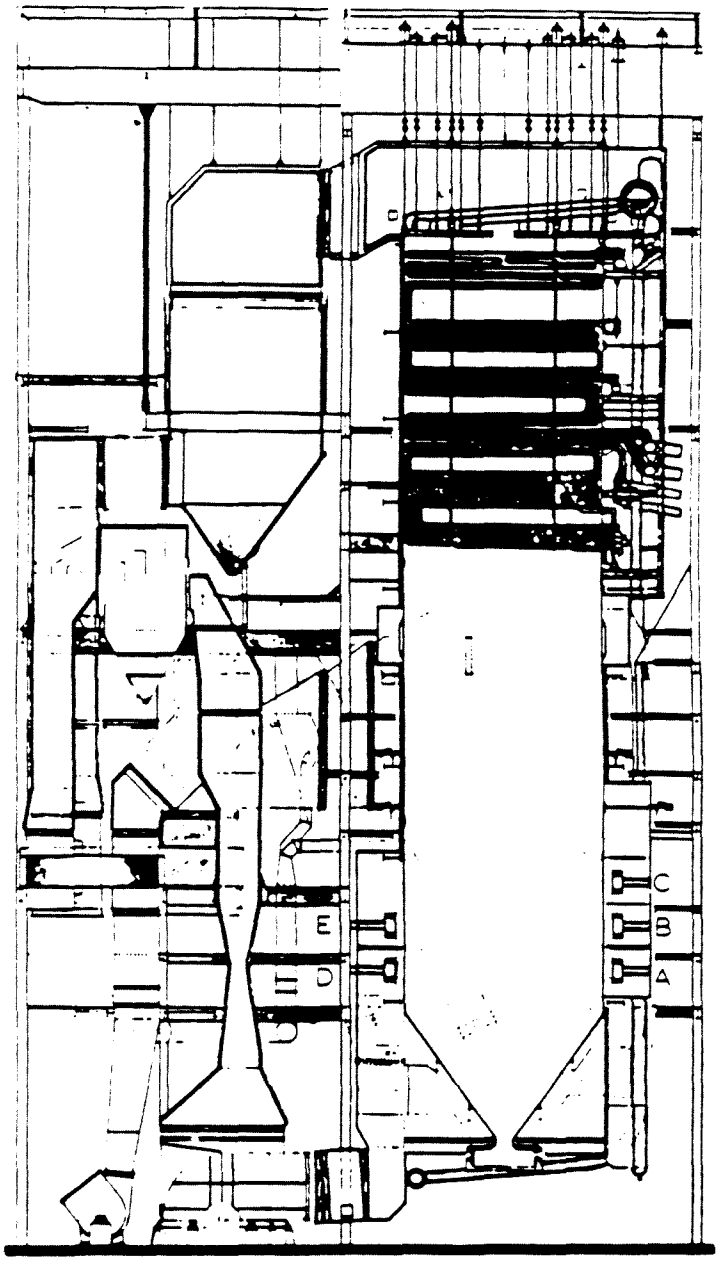


Figure 2-10. General arrangement - Nanticoke boiler.

dual-register design. In 1982 the Edgewater boiler was also retrofitted with a substantially oversized electrostatic precipitator with an SCA of 118 $m^2/m^3/s$. A schematic showing the overall arrangement of the Edgewater boiler is presented in Figure 2-11.

Temperature profiles predicted for the Edgewater boiler are presented in Figure 2-12 for several vertical planes through the unit. Based upon the predicted and measured temperature levels, and upon parallel isothermal flow modeling work, a flexible sorbent injection scheme was installed on the front wall of the unit comprising three rows of tilting nozzles at boiler elevations 181, 187 and 191 feet (55, 57, 58 m).

At Edgewater the hydrated lime/limestone was shipped to the site by truck and transferred pneumatically to a large storage silo. From the storage silo the sorbent was transferred to a smaller feed silo equipped with a dual feeding system. The feeding system provided a controlled feed rate of sorbent to each of the injection elevations and used rotary valves to supply sorbent to the feed pump inlet hoppers. The distribution system was capable of providing sorbent to two injection elevations through separate distributer bottles. At the 181 ft. (55 m) elevation, eight nozzles were located on the boiler front wall, while at the 187 ft. (57 m) elevation there were eight nozzles on the front wall and two on each of the boiler side walls. Sorbent transport to the injection location was in relatively dense-phase, with a double concentric nozzle arrangement being used to introduce auxiliary air to provide appropriate injection velocities (up to 300 ft/s, 91 m/s) and adequate sorbent penetration.

2.6 Boiler Comparison

From the above presentation of general boiler characteristics it can be seen that the demonstration boilers which have been incorporated into this study represent a wide range of unit size, configuration and duty. This large difference in boiler characteristics leads to some difficulty in making direct comparisons between test data generated on the different units. Of particular interest to this study are reductions in NO_x emission through

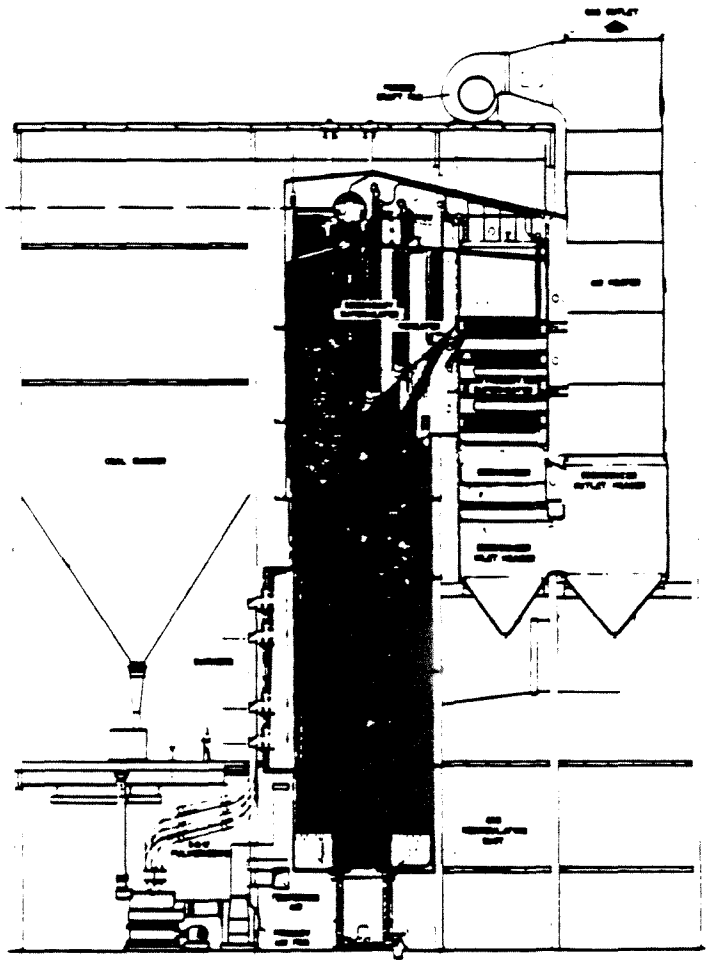


Figure 2-11. General arrangement - Edgewater boiler.

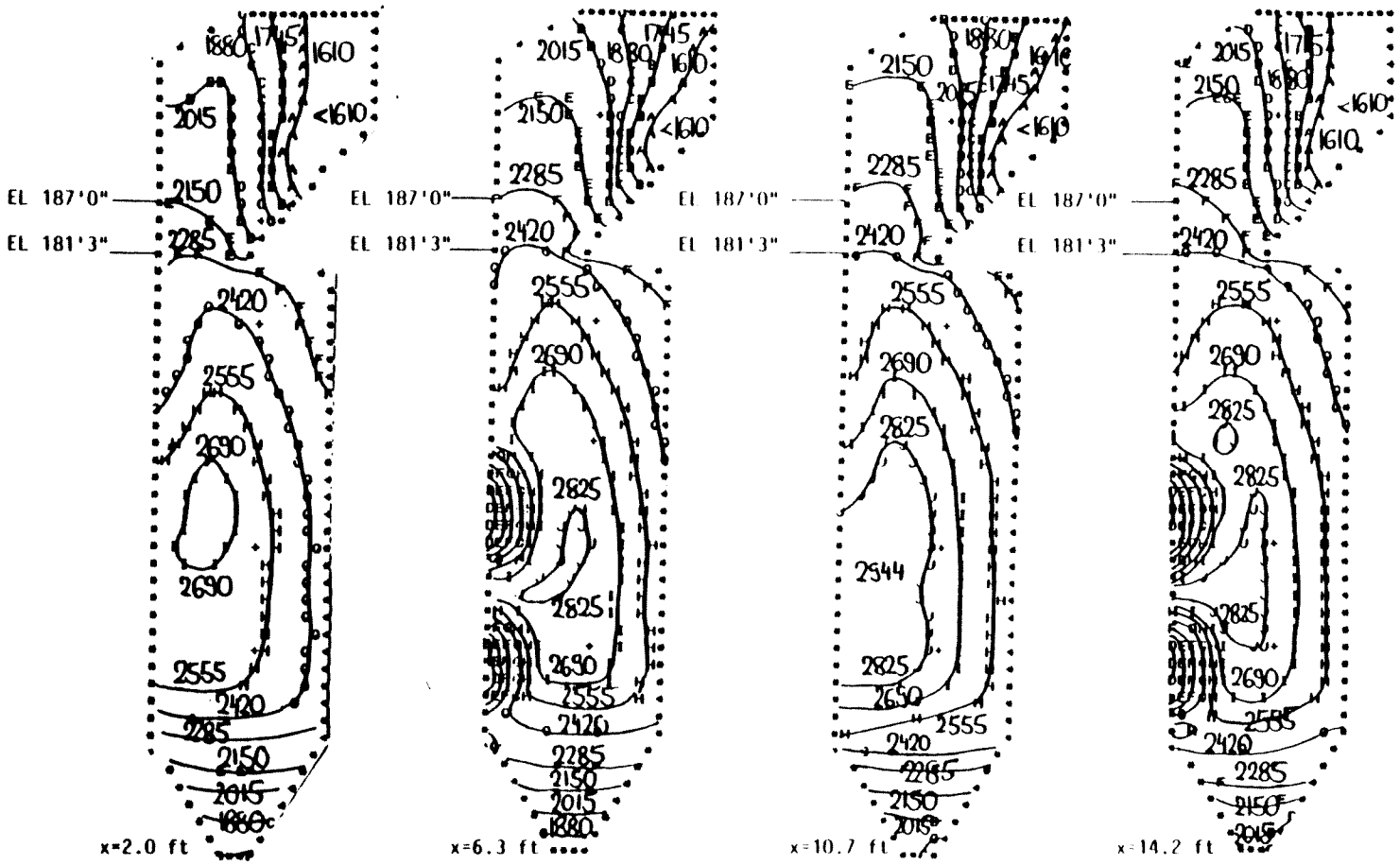


Figure 2-12. Predicted temperature profiles (^{O}F) - Edgewater, full load.

combustion modification, and SO_2 control through injection of calcium based sorbent materials directly into the furnace cavity. Both processes are impacted by thermal conditions and by geometrical considerations, as will be discussed in subsequent sections of this report. In view of this, it is possible to derive certain parameters from boiler design and operational data which will be useful as a basis for data comparison in subsequent discussions.

Presented in Table 2-1 is a comparison of boiler characteristics based upon parameters derived from design and operational data and pretest evaluation studies. For the most part the parameters are self explanatory, and serve to describe the boilers in terms of size, firing configuration and geometry. Individual burner capacity and available firing depth have important implications for NO_x formation and control, since these parameters relate to the size of individual flames and the space available to accommodate them. The parameters heat release per plan area, and burner zone heat liberation are also of importance to NO_x control. (Here the burner zone heat liberation is defined as the ratio of total thermal input to cooled burner zone surface, which is considered to be represented by the four sides and bottom of a cuboid box with the same width and depth as the furnace and extending one half burner spacing above and below the upper and lower burner rows). Both of the above parameters have a relationship to the intensity of heat release in the combustion zone. High values imply high combustion intensity, high temperatures and short residence, times which are expected to less favorable for NO_x control. Low values on the other hand, imply low combustion intensity, but may also lead to low temperatures and problems in achieving good carbon conversion with difficult coals. The importance of these parameters will be considered in more detail in Section 3.0.

The remaining parameters in Table 2-1 refer to thermal conditions in the upper furnace and initial convective passes, and are of particular interest to SO_2 removal by injected sorbents. The most favorable temperature range for the reaction of CaO with SO_2 is between approximately 1225 and 870°C, and the rate of temperature decay (quench rate) through this zone is of particular interest. High values imply short available residence times for

TABLE 2-1. COMPARISON OF BOILER CHARACTERISTICS

	Gagetown	Hasselby	Stigsnaes	Lakeview	Nanticoke	Edgewater
Nominal Capacity Electric (MW)	--	22	143	235	500	104
Thermal (MW)	21	100	355	636	1350	274
Firing Configuration	Single Wall	Single Wall	Opposed Wall	Single Wall	Opposed Wall	Single Wall
Number of Burners	2	4	8/12	18	40	12
Burner Capacity (MW)	10.5	25	44/30	35	34	22.8
Firing Depth (m)	4.9	7.06	(12.7)/2	7.9	(10.4)/2	6.7
Heat Release per Plan Area (MW/m^2)	1.4	2.0	3.5	4.9	6.1	4.4
Burner Zone Heat Liberation (MW/m^2)	0.29	0.41	0.91/0.66	1.14	1.48	0.78
Mean Furnace Exit Temperature (^oC)	1060	1100	1260	1225	ND	1280
Mean Quench Rate ($^oC/s$) (1225-870^oC)	250	240	243	390	ND	390

reaction, while low values imply longer times and are expected to be more favorable for high SO_2 removal efficiency. Mean temperature profiles derived from heat transfer modeling studies for each of the five boilers of interest are presented in Figure 2-13, while mean quench rates are compared in Table 2-1. Again, the relative importance of these parameters will be discussed more fully in subsequent sections.

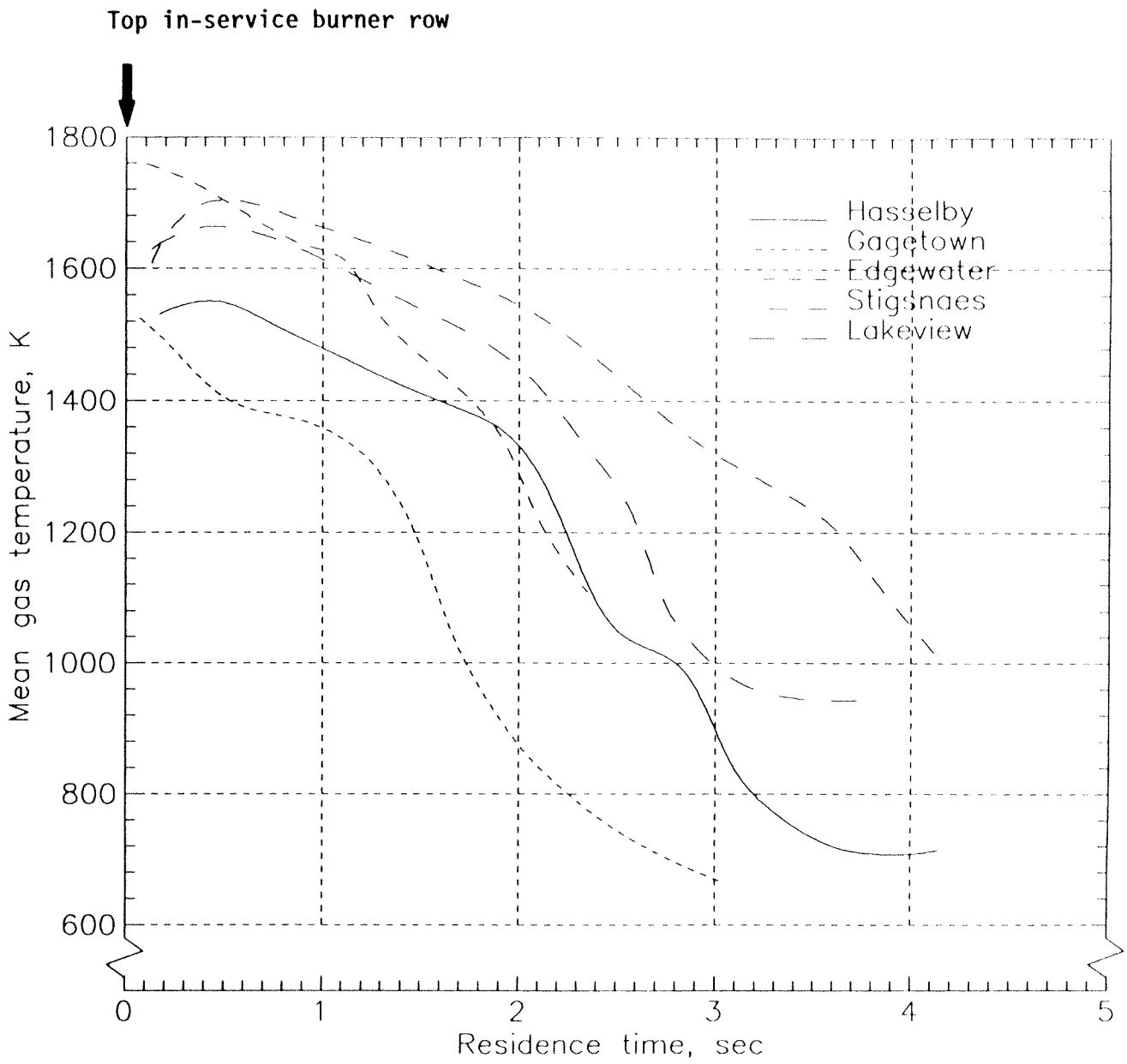


Figure 2-13. Comparison of mean temperature profiles.

3.0 NO_X EMISSION CONTROL

The purpose of this section is to summarize the main results from the different burner modification tests implemented to reduce NO_X emissions in each of the demonstration projects, and to compare the results in such a way that the conclusions may be generalized. As an introduction to this section background material is presented concerning NO_X control in pulverized coal combustion, and burner and boiler design parameters which are known to impact NO_X emissions.

3.1 Parameters Affecting NO_X Emissions

3.1.1 NO_X Formation and Control in Pulverized Coal Combustion

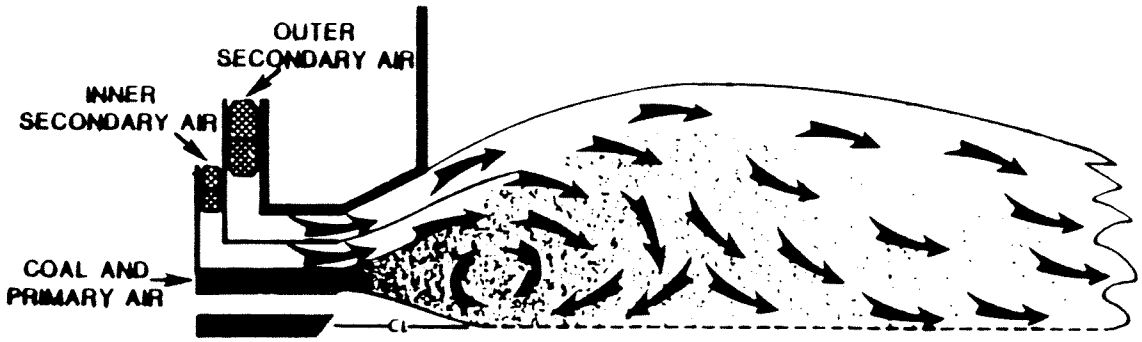
In recent years a great deal of information has become available concerning both the formation and reduction of NO_X emissions in coal fired combustion systems. This information ranges from the very fundamental, obtained on bench scale laboratory equipment, to the very practical and applied resulting from full scale burner development programs. It is not the intention here to review the available literature in detail, but rather to identify those process requirements which are believed to be critical for the reduction of NO_X, particularly insofar as these relate to burner and boiler design.

It is well established that, during the combustion of coal, nitrogen oxides can be formed by at least two fundamentally different chemical mechanisms: high temperature fixation of atmospheric nitrogen (leading to thermal NO_X), and the oxidation of nitrogen chemically bound in the fuel (leading to fuel NO_X). In coal combustion under normal burner conditions, at least 70 percent of the NO_X formed is due to the oxidation of coal bound nitrogen, and efforts directed towards the reduction of NO_X have concentrated on understanding the phenomena which control the fate of this fuel nitrogen. In Stage I of the IEA project[1] it was shown that a key parameter controlling fuel NO_X formation from a given coal is the gas phase reactant stoichiometry. This depends both upon the evolution of nitrogen and fuel

volatile species from the coal, and upon the local availability of oxygen. The most effective means of reducing the conversion rate of fuel bound nitrogen to NO_x have been shown to be those involving the principles of delayed mixing and staged combustion. These processes have formed the basis of many of the low NO_x systems developed to date, and typically involve the production of initial fuel rich combustion zones in which the reduced availability of oxygen favors those gaseous phase reactions which promote the reduction of nitrogen species to N_2. The most successful combustion modification techniques applied to date have employed some form of staged combustion, either through external staging (Biased firing, over-fire air ports, off-stoichiometric combustion), burner modifications (staging via delayed mixing), or compartmentalization (primary combustion furnace). In all of these concepts a portion of the combustion air is diverted from the normal burner air and added some distance downstream.

Combustion modification techniques which involve major changes to the distribution of fuel and air throughout the boiler, such as low excess air, overfire air, and biased firing, have proven capable of yielding moderate reductions in NO_x emissions (typically 20-30%). Usually the level of NO_x control achievable is limited by the onset of operational problems such as slagging, corrosion and increase carbon carryover. A more favored approach is therefore the use of low NO_x burners, or burner modification to produce low-NO_x staged combustion, where conditions can be controlled within the flame envelope. Two of the most typical approaches to low NO_x burner design are presented in Figure 3-1, and are referred to as externally staged and internally staged concepts. The externally staged approach is that initially developed by the U.S. EPA as the Distributed Mixing Burner (DMB), and provides a portion of the combustion air (Tertiary air) through discrete ports in the boiler wall away from the main burner zone. This concept reduces combustion intensity through delayed fuel/air mixing, and creates an initial fuel rich zone in which fuel nitrogen species are converted to N_2, while the balance of the combustion air mixes downstream to complete combustion. Optimum low-NO_x conditions are usually found when the combustion air (secondary plus primary) to fuel ratio is in the range of 0.6-0.8 of stoichiometric . In the internally staged approach the same overall effect

a) Internally Staged



b) Externally Staged

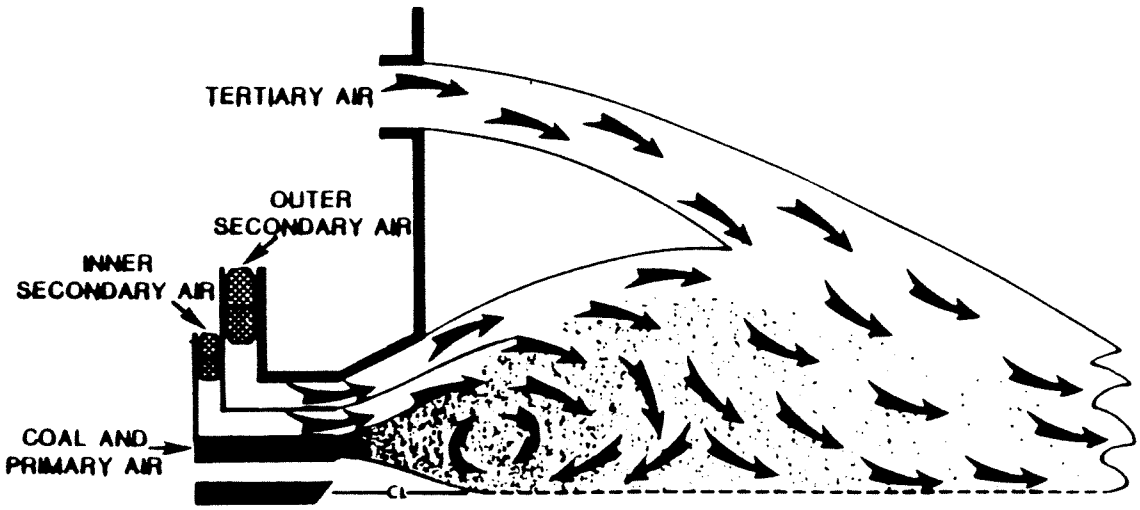


Figure 3-1. Low NO_x burner concepts.

is achieved through aerodynamic control of the air distribution at the burner throat. This latter approach has been the one most generally favored by commercial manufacturers, mainly because of the practical difficulties and costs associated with multiple waterwall penetrations to accommodate discrete tertiary ports in most retrofit situations. Both burner types are however manufactured commercially, with many variations to individual components reflecting different proprietary positions.

As indicated above, fuel nitrogen is the major source of NO_x emissions in coal combustion, and fuel composition can have a significant impact on emission levels, even under staged combustion conditions. As a result of some of the more fundamental studies on NO_x formation, empirical correlations have been developed[2] which relate fuel properties to NO_x emission under a series of well defined mixing conditions. These are:

d) premixed combustion

$$NO_x = 385 + 1280 \frac{N_o}{1.5} + 180 \frac{VM}{40} \frac{NO_{eq}}{3200} - 840 \frac{FC}{60} \frac{NO_{eq}}{3200}$$

b) diffusion flame

$$NO_x = 340 + 835 \frac{N_o}{1.5} + 20 \frac{VM}{40} \frac{NO_{eq}}{3200} - 395 \frac{FC}{60} \frac{NO_{eq}}{3200}$$

c) Optimum staged combustion

$$NO_x = 150 + 80 \frac{N_o}{1.5} - 30 \frac{VM}{40} \frac{NO_{eq}}{3200} + 100 \frac{FC}{60} \frac{NO_{eq}}{3200}$$

where N_O = wt% fuel nitrogen (daf)

VM = wt% volatile matter (daf)

FC = wt% fixed carbon (daf)

NO_{eq} = ppm NO equivalent for complete conversion of fuel nitrogen.

It will be noted from the above correlations that, in addition to a direct impact of fuel nitrogen content on NO_x emission, there is a significant effect of coal volatility. This is because the volatile content of the coal is assumed to influence the fate of the nitrogen species. Under normal excess air conditions, high volatile coals will release a large fraction of the fuel nitrogen early in the combustion process, under high O_2 conditions, and high NO_x emissions would be expected to result. Conversely, under staged combustion conditions an early release of nitrogen under fuel rich conditions is most favorable, and high volatile coals are expected to be most amenable to NO_x emission reduction by such combustion modifications.

It should be noted that the above correlations may not be used directly to make quantitative estimates of NO_x emissions from practical combustion equipment, since they relate only to the specific thermal and mixing conditions of the experimental furnace in which they were derived. The correlations are however believed to be useful in estimating trends in NO_x emission as these are influenced by coal quality parameters in a given system. The application of the above correlations to the coals used in the different demonstration projects is shown in Figure 3-2. Based solely on fuel composition, the figure suggests that the different coals should behave similarly, and be equally amenable to NO_x control by staged combustion.

In addition to coal composition, test data has also shown that coal grinding can affect NO_x emission performance. Under normal excess air combustion conditions fine grinding generally leads to an increased combustion intensity and correspondingly high NO_x. However, under properly staged combustion conditions fine grinding will enhance ignition stability, and the faster rate of fuel nitrogen release has been shown to contribute to improved NO_x reduction. Moreover, fine grinding of the coal is also expected to improve carbon burnout in the final stages of combustion, a parameter

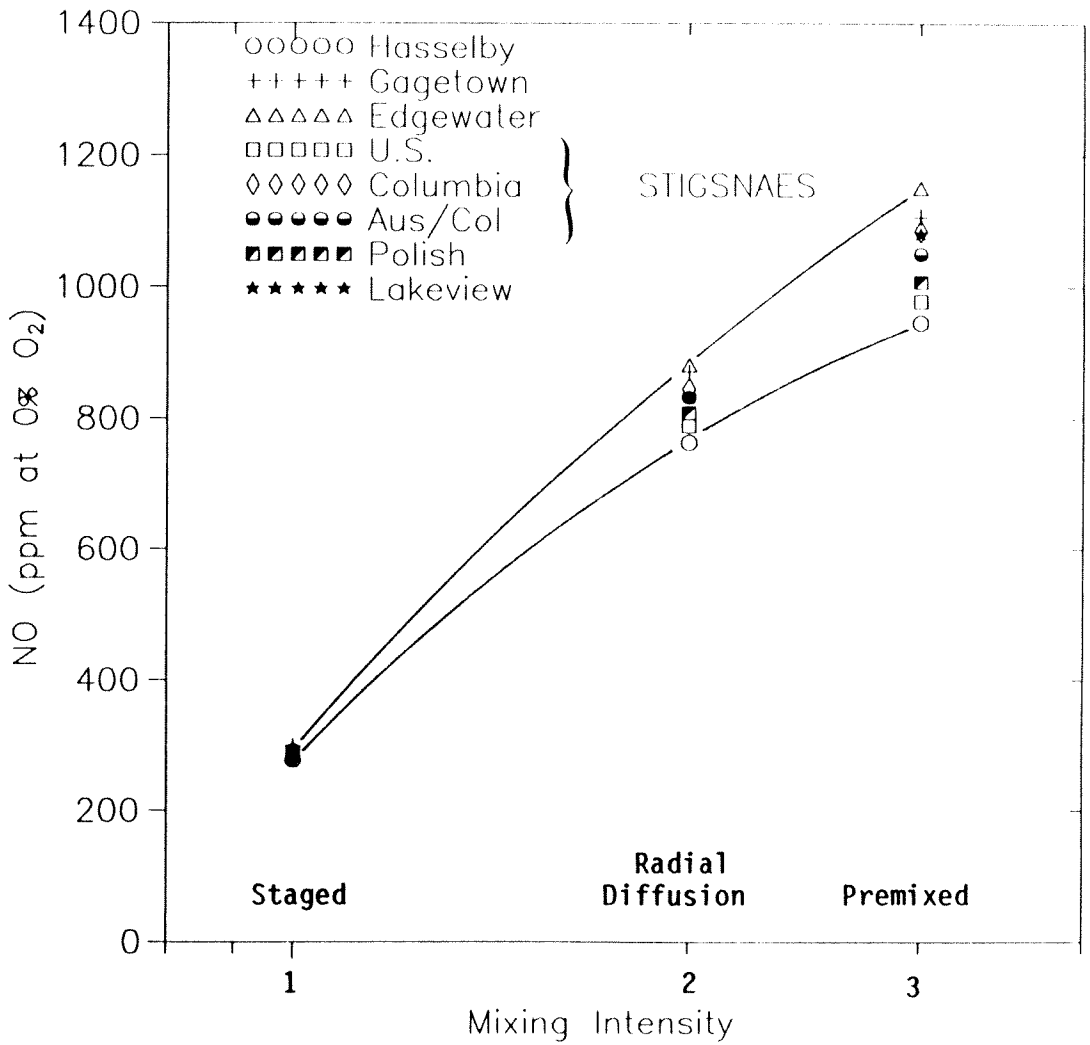


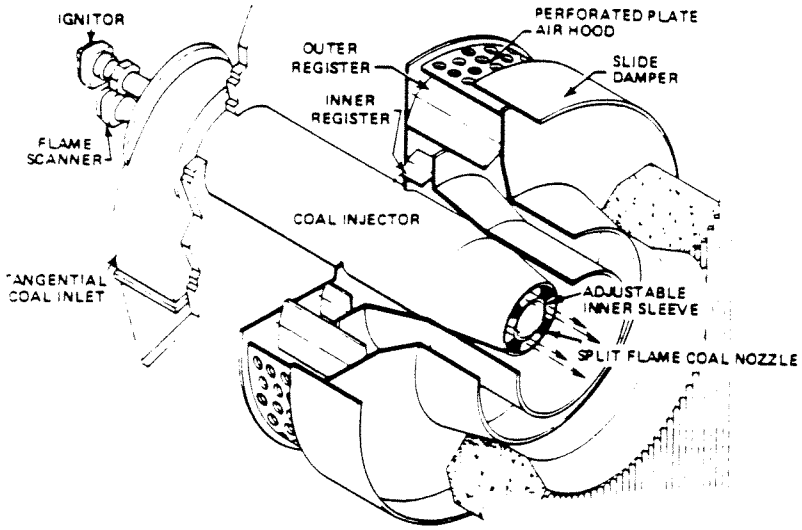
Figure 3-2. NO_x emissions potential of coals.

which is most often compromised when delayed mixing or other combustion modification techniques are applied.

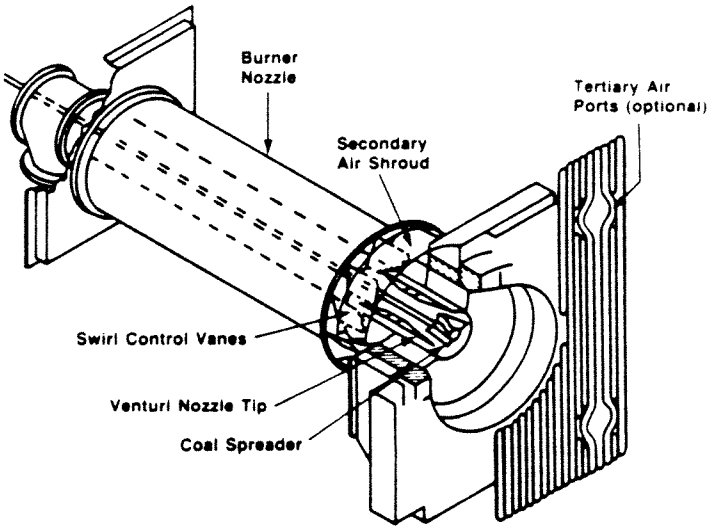
3.1.2 Low NO_x Burners and Burner Modification

Low NO_x burners for coal fired power plant may be considered to be a fully commercial technology. There are many examples of low NO_x burners in both new and retrofit applications; most major manufacturers now offer low-NO_x burner systems, and are usually prepared to offer performance guarantees. Although there are many different designs of burners for wall fired boiler applications, all operate according to the same general principle: staged combustion. As discussed in the preceding section, in staged combustion the coal and air supplies to the burner are arranged in such a manner that mixing is delayed. Ignition and initial combustion take place under fuel-rich conditions, while the balance of the combustion air enters downstream in the flame to complete combustion. The reducing zone in the core of the flame reduces NO formation during devolatilization, and subsequent reaction pathways to molecular nitrogen, through reduced nitrogen and hydrocarbon species, are favored over oxidation to NO.

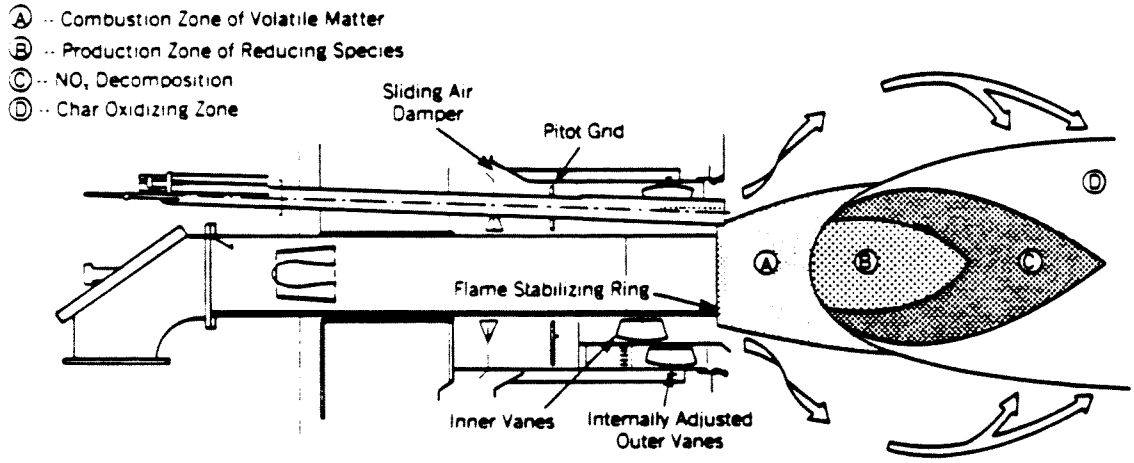
Typical examples of commercial low NO_x burners are shown in Figure 3-3. These are examples from each of the major U.S. manufacturers of wall fired boilers, and are selected not necessarily because they represent better technology, but because they illustrate features common to many low NO_x burner designs. Of the burners shown in Figure 3-3 two (the controlled flow/split flame (CF/SF), and the XCL) employ divided combustion air registers, with the ability to independently control air distribution and swirl level to the secondary and tertiary passages. The remaining burner (the controlled combustion venturi (CCV)) employs a single large air register, but offers optional outboard tertiary ports for improved NO_x reduction performance. It is also of interest to note that in each of the burners shown the coal spreader, which is characteristic of many high intensity/high NO_x burner designs, has been replaced by a variety of devices which serve both to enhance ignition stability and provide for more controlled distribution of the coal stream. Such devices take the form of coal flow splitters (CF/SF),



a) Foster Wheeler Controlled Flow/ Split Flame (CF/SF) Burner



b) Riley Stoker Controlled Combustion Venturi (CCV) Burner



c) Babcock & Wilcox XCL Burner

Figure 3-3. Some commercial low NO_x burners.

a venturi combined with moderate primary stream swirl (CCV), and a bluff body stabilizing ring (XCL). These are considered to be important components of present burner designs, since the achievement of stable ignition immediately at the burner exit, and the subsequent control of coal distribution to prevent excessive flame length or too rapid mixing, are believed to be critical to optimum low NO_x performance. Other burner designs have also used flue gas recirculation, applied selectively at the burner throat (e.g. in an annulus around the primary coal pipe), as an effective supplement to NO_x control.

Burners of the type described above have proven effective in many boiler retrofit applications and have demonstrated the feasibility of reducing uncontrolled NO_x emissions of 600 ppm (at 0% O_2) and higher, down to values in the range of 300-400 ppm (0% O_2). Lower emission levels have also been reported when low NO_x burners are combined with other techniques such as the use of overfire air ports. It is however not possible to identify a minimum NO_x level which is achievable with low NO_x burners under all circumstances, since there are many other factors which combine to impact control potential.

It is however of interest to consider low NO_x burner design parameters, since these can provide guidance for the development of new designs, or the modification of existing burners for low NO_x conditions. In this regard, air and coal velocities at the burner throat are important parameters in combination with the staged air distribution techniques described above. In high intensity coal burners, combustion air velocities are normally high and, when combined with divergent coal injection produced by spreaders, typically results in intense mixing and high NO_x emissions. Reducing combustion air velocities and primary air/coal velocities, is an effective means of reducing mixing intensity and lowering NO_x emissions. This is often evidenced by the reduction in NO_x emissions which accompanies burner turn-down. A further example of the impact of velocity on NO_x is presented in Figure 3-4, where experimental data are presented for burners designed for different capacities but fired at the same rate. Here the larger burner produces the lowest emissions. However, there is of course a limit to which velocities may be

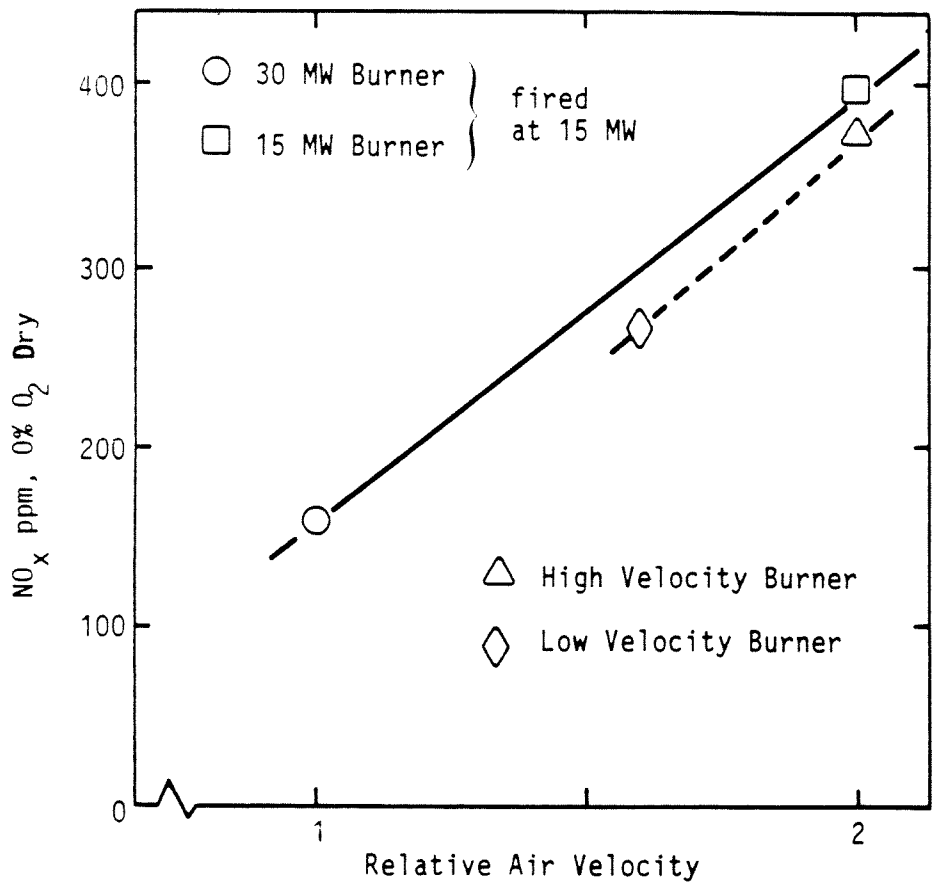


Figure 3-4. Velocity NO_X effects for different burners.

reduced since it is necessary to maintain effective control over mixing and resulting flame shape during turn-down operation.

A comparison of nominal combustion air and primary air/coal velocities employed in typical burner designs is presented in Table 3-1. This table compares velocity data, which has been derived from a review of the available literature and various experimental and developmental studies, for typical high intensity burners and low NO_x burners of the internally staged and externally staged (DMB) types. The significant differences in velocity, swirl level, and distribution of stoichiometry are clearly evident.

It should be noted that the above low NO_x burner data have been developed for new burner designs, without any consideration of constraints which might be applied in a retrofit situation. The use of lower velocities implies a need for larger openings in the boiler water walls to accommodate increased burner diameters, which may not always be possible or desirable under retrofit conditions. The values presented in Table 3-1 may therefore be considered to be targets to be achieved when modifying existing burners. Where these velocity levels and distribution of combustion air cannot be reached, then the lowest possible NO_x emission levels may not be achieved. This is just one example where boiler retrofit constraints can act to limit the extent to which NO_x emission may be reduced when modifying existing burners. Other important parameters include the available pressure drop and space limitations in existing windboxes, both of which may combine to limit the flexibility afforded to the burner designer in modifying burner internal components. The impact of such parameters on the lowest NO_x emission achievable in a given boiler situation cannot readily be generalized and must be judged on a site specific basis.

Two further parameters which are important and are consequences of low NO_x operation are an increase in flame volume, and a tendency towards increased carbon in ash. Changes in flame characteristics are usually manifested as increased flame length, as illustrated in Figure 3-5 by data from a 35 MW experimental DMB. In boiler situations where the available firing depth is limited, or burner-wall spacings are close, such changes in

TABLE 3-1. COMPARISON OF TYPICAL BURNER DESIGN PARAMETERS

Design Parameter	Typical High Intensity Burner	Low NO_x Burners	
		Internally Staged	DMB
Primary Air/Coal Mass Ratio	2.0	1.5	2.0
Coal Injector	Impeller	Various	Various
Velocities (m/s)			
Primary	20-25	18	20
Secondary	60	13-16	18
Tertiary	--	30-40	15
Swirl Levels			
Secondary	Variable	Variable	Variable
Tertiary	--	Variable	0
Stoichiometric Ratio			
Primary & Secondary	1.2	0.35-0.5	0.6-0.7
Total	1.2	1.2	1.2
Exit Length/Throat Dia.	0.1-0.3	0.3	0.5-1.0
Exit Half Angle (Deg)	25	25	25

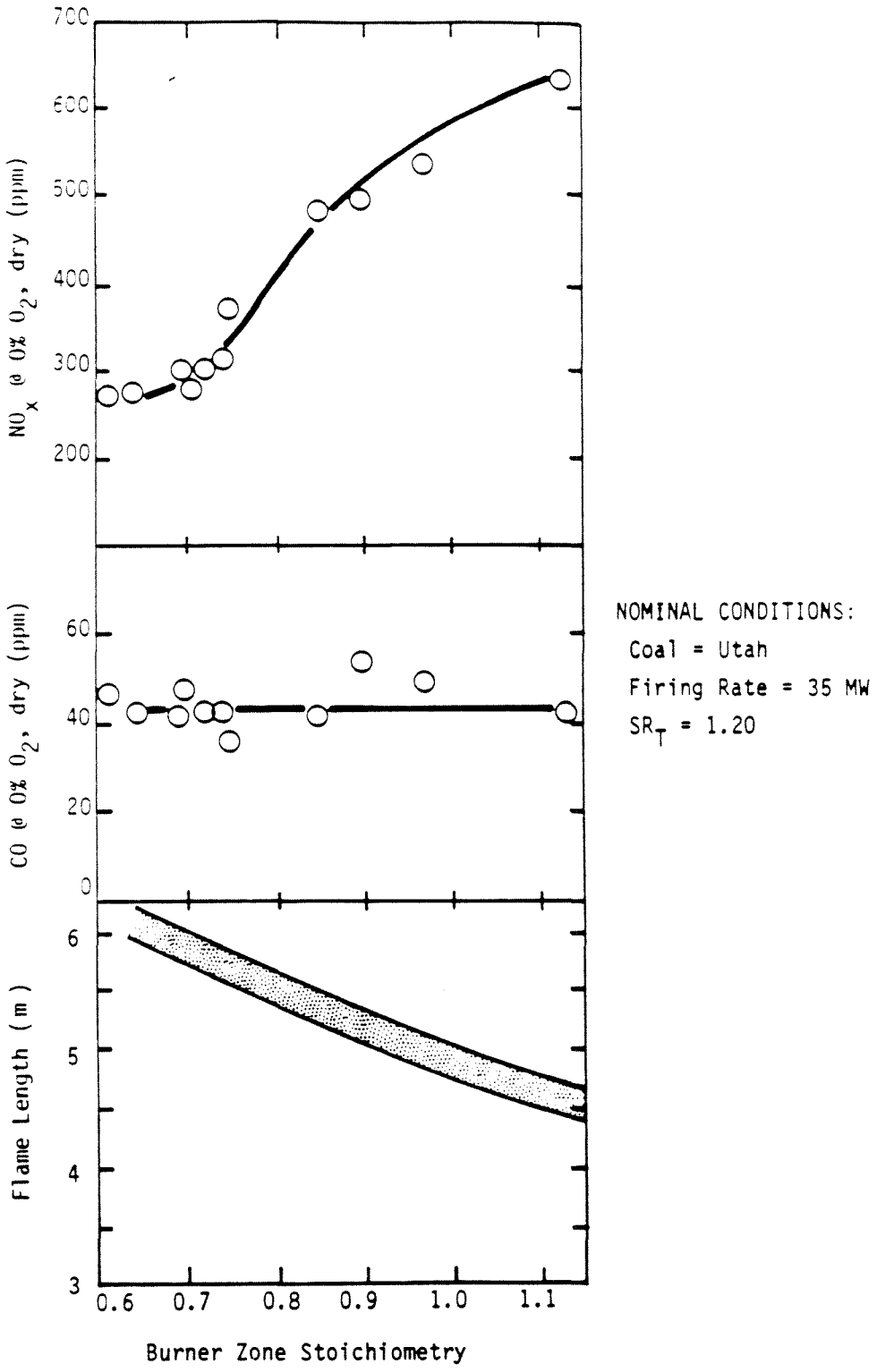


Figure 3-5. Effect of staging for a 35 MW DMB.

flame characteristics may lead to flame impingement directly on boiler waterwalls, with potential consequences for increased slag deposition, corrosion, and carbon carryover due to flame quenching. Increased carbon loss is also a direct consequence of the delayed mixing process used to control NO_x and is often one of the main factors affecting the lowest NO_x levels which are achievable in practice. Flame impingement problems can often be countered by ensuring that the burner has sufficient adjustment (e.g. swirl level, air distribution) such that conditions can be adjusted in-situ to tailor flame shape to the furnace space. Carbon burnout may additionally be improved by mill adjustments to increase fineness, and by careful attention to balancing coal and air flows for greater control over local stoichiometry. Again, if sufficient control is not available and the retrofit conditions are constraining, then the full potential of a given low NO_x burner may not be achieved.

From the above discussion it may be concluded that standard parameters and fixed performance expectations for low NO_x burners do not exist. Low NO_x burners have often been referred to as a 50 percent NO_x control technology, implying that a 50 percent reduction in NO_x can be achieved consistently relative to existing baseline emission levels. In practice, however, and especially in retrofit applications or where existing burners are modified, there are many site specific factors which can act to restrict the NO_x performance which can be achieved.

3.1.3 Correlation of NO_x Emissions

Over the years various approaches have been developed to the study of low NO_x burners and to the extrapolation of their performance to different firing situations. Such approaches are typically based on correlations developed from pilot and full scale burner development tests and data from actual boiler applications. The most commonly applied method of projecting burner performance is through correlations of NO_x emissions against a burner zone heat liberation parameter which relates total thermal input to the cooled surface in the burner zone. Several manufacturers have developed such parameters in an attempt to correlate NO_x emissions from full scale boilers,

and in some cases to extrapolate the results of burner tests in small scale furnaces. The correlations are similar but not strictly comparable because of differences in the methods of defining cooled surface areas in the burner region. Burner zone heat liberation rate is to some extent a measure or indicator of temperature levels in the flame region, and is also indirectly related to the volumetric heat release rate in the flame zone. High volumetric heat release rates reflect rapid air/fuel mixing and would be expected to correlate with NO_x emissions.

For the purposes of comparison, NO_x emission data available to EER for boilers and large scale burner tests have been correlated using one definition of the burner zone heat liberation parameter. This considers the burner area cooled surface to be the four sides and bottom of a cuboid box with the same width and depth as the furnace and with a height extending half a burner spacing above and below the upper and lower burner rows, respectively. This type of correlation is believed to be applicable to wall fired boilers with both single-wall and opposed firing configurations, but is generally not suitable for tangentially fired boilers. The use of the parameter defined above is illustrated in Figure 3-6 for NO_x emission data from a wide variety of wall fired boilers. A wide range of boiler and burner designs, unit size and firing patterns are incorporated into the data base. The data are, however restricted to boilers firing high volatile bituminous coals. Although there is considerable scatter in these data points, an upper limit in NO_x emission can be identified, which increases with increasing burner zone heat loading. This upper limit is indicated by a trend line for which the slope is 250 ppm per MW/m^2. Inspection of the data which lie close to the upper limit shows these points to be associated with boilers in which high-turbulence burners are employed. On Figure 3-6, the NO_x emission data which lie below the upper limit line represent boilers with alternate burner designs, or situations where different NO_x control strategies have been applied. At the lower levels of NO_x emission, the boilers have been retrofitted with low NO_x burners and optimized for maximum NO_x control. As might be expected, the burner zone heat liberation parameter does not provide a universal correlation with NO_x emissions, since it fails to take into account the important effects of variables such as burner design and coal

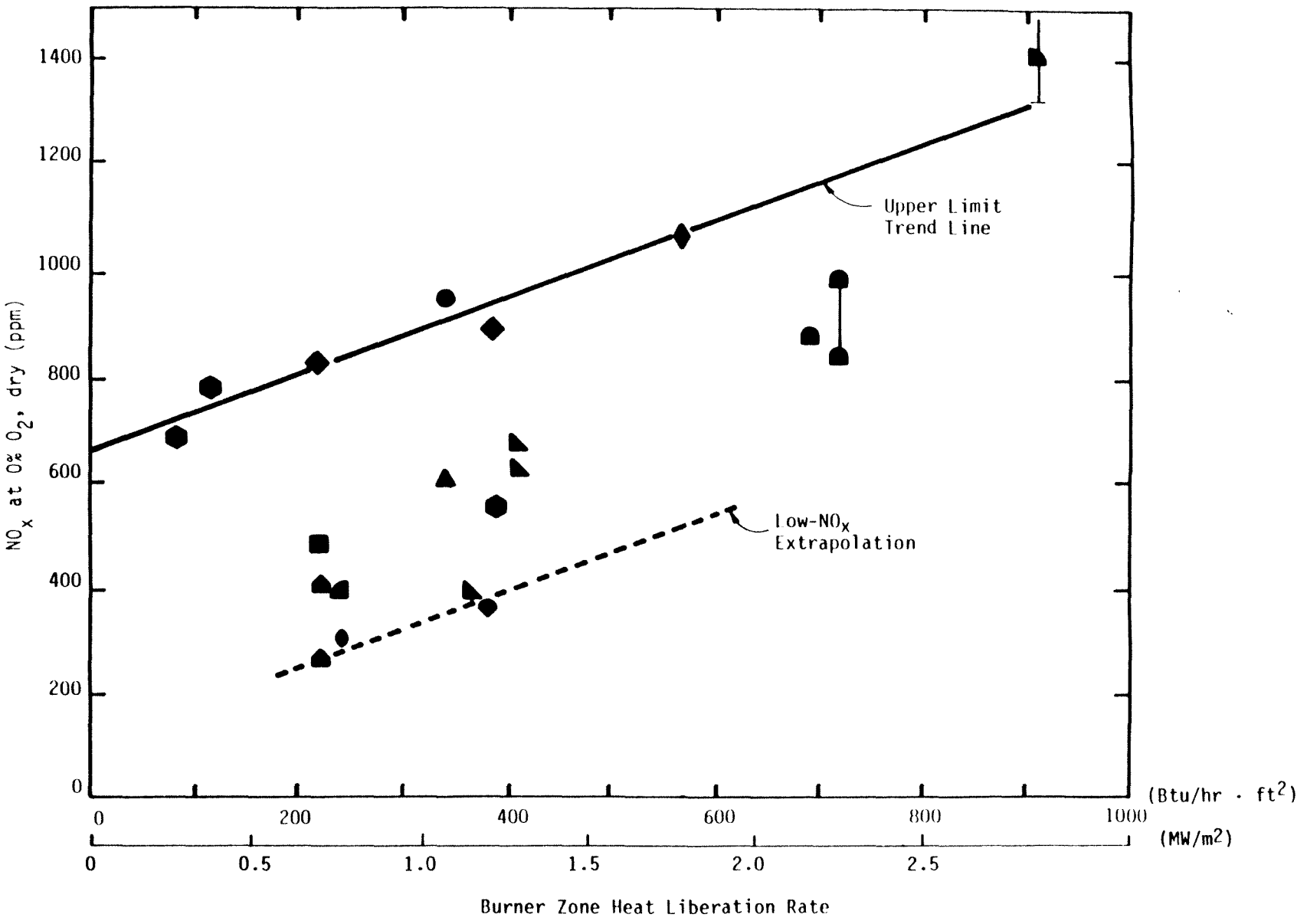


Figure 3-6. Correlation of boiler NO_x emissions.

type. Indeed the parameter was developed strictly to provide a means of extrapolating the performance of a given burner design into an alternate firing situation.

To incorporate experimental data into this kind of analysis, EER has defined an effective burner zone parameter which takes into account the fact that test furnaces normally have a high surface-to-volume ratio (relative to full scale) and consequently employ some degree of refractory insulation to maintain a representative thermal environment. The use of experimental data is extremely attractive in that burner performance data over a wide range of operating conditions are usually available. This provides a means of assessing how burner performance might be affected by specific retrofit constraints (e.g. firing depth limitations, available pressure drop), and then extrapolating this performance to full scale. In Figure 3-7 selected experimental data for a range of wall fired burner designs are presented on the basis of an effective burner zone heat liberation. The experimental data (open symbols) are for selected single full-scale burners where corresponding boiler data (solid symbols) are available. Again, it can be seen that a reasonably consistent correlation exists.

The use of correlations of the type shown in Figures 3-6 and 3-7 is, however, conditional upon a number of factors, namely:

a) The experimental data are derived from full-scale or near full-scale burners.

b) The same burner design and operating conditions are used in all applications.

c) The same coal type is used.

d) All the data are restricted to acceptable firing conditions; i.e., where the flame fits within the confines of the furnace; unburned carbon levels are low; the burner operates satisfactorily over the required turn-down range.

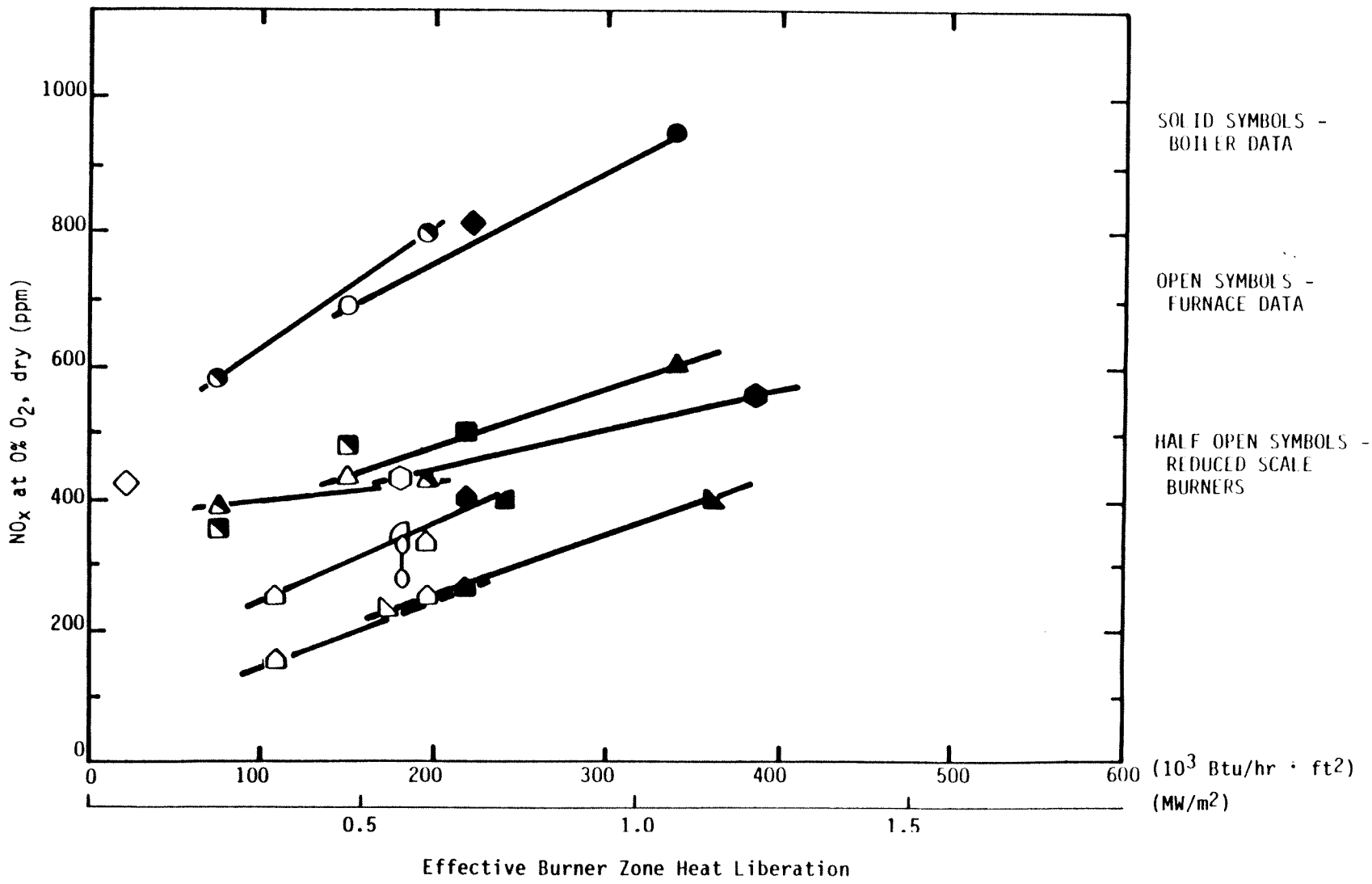


Figure 3-7. Correlation of experimental furnace data.

Condition d) above is an obvious one in that the extrapolation can be based only upon operating conditions which are acceptable. In this regard, flame dimensions are an important consideration for low NO_x burners, since the flame must be constrained within the space available in the boiler. This is related to condition a) which restricts the extrapolation essentially to burners with the same firing capacity. If different scale burners are used, then another variable is introduced: the effect of burner size on NO_x emissions. Indeed, the reduced scale burner data presented in Figure 3-7 do not extrapolate to field conditions with the same trend established for full scale data. It has for example been observed that a 15 MW burner scaled to have the same velocity and geometry as a 30 MW counterpart will tend to show higher NO_x emissions. The exact relationship between burner design, burner size, the burner scaling approach employed, and NO_x emissions, is however not well understood and what little information is available is poorly documented.

Although the burner zone heat liberation parameter does not expressly take into account many of the boiler specific variables which can impact NO_x emission performance, it is considered to be useful tool for assessing relative NO_x performance and potential limits in different boiler furnaces. It will be used in this study as one means of comparing performance achieved in the different demonstration projects.

3.2 Comparison of NO_x Emission Data

Throughout the various demonstration projects a considerable amount of data was generated, relating both to NO_x emissions control and to boiler operation. This section of the report will summarize the main results and data trends from each of the projects to facilitate a comparison of the results.

3.2.1 Summary of NO_x Control Data

Gagetown

On the Gagetown boiler the existing high intensity burners were replaced with commercial low NO_x burners of the distributed mixing type. This design was characterized by an annular coal nozzle, a single swirled secondary air register, and four outboard tertiary air ports. Because of the full burner retrofit, baseline measurements on generator number 2 were not possible within the time frame of the test program, and baseline NO_x emission levels were established on the identical but unmodified Unit 3. With moderate levels of oil support, baseline NO_x emission levels of 690 - 875 ppm* at full load, and 490 ppm at half load were recorded. Initial tests with the new burner system as installed produced NO_x emissions down to approximately 290 ppm, but only with significant operational problems related to unacceptable flame stability and excessive carbon carryover (greater than 50% carbon in ash).

In view of this initial experience a series of burner modifications were implemented to improve performance. Initial modifications included the addition of a swirler to the coal nozzle, moderate reduction in primary velocity, and deflection of the tertiary air towards the center of the flame. While these modifications resulted in a 50 percent increase in NO_x emissions, there was only marginal improvement in ignition stability and carbon in ash, with evidence of significant flame impingement on the boiler rear wall. Subsequent modifications were carried out to substantially reduce the air flow through the pulverizer and to increase the coal pipe diameter, and the coal swirler was replaced by a ring of platelets mounted to the inside edge of the outer coal pipe. These final modifications significantly improved flame length and shape, eliminated the ignition stability problems, and reduced carbon in ash levels to values commensurate with pre modification

*All NO_x ppm values are referenced to 0 percent O_2, dry basis.

experience. Heat transfer and combustion modeling studies were used to determine whether further improvements in carbon burn out could be expected. Results from these studies indicated however that carbon in ash would be limited to about 12-20 percent, depending upon reactivity of the coal char, due to the comparatively low temperature levels experienced in this boiler. These results were substantially validated in the field tests, in that under optimum conditions the unit was operating with carbon in ash values in the range of 10-12 percent.

In a final round of acceptance tests, NO_x emissions of 470 ppm were measured under optimally staged conditions at full load, representing approximately 50 percent reduction relative to pre retrofit levels. Further analyses also showed that boiler efficiencies, based on Higher Heating Value (HHV), were increased from 78 to 81 percent.

Hasselby

As discussed earlier, unit number 2 at the Hasselby power plant was already equipped with burners of the dual register type, which had been installed after conversion work in 1982. These burners have variable tertiary swirl and fixed 45° swirl vanes in the secondary passage, where the distribution of air between secondary and tertiary is controlled by sliding sleeve dampers. In preparation for the demonstration program only relatively small changes were made to the existing burners. The most significant change was the replacement of the existing 90° coal impeller with a 30° impeller of modified design, whose position within the coal pipe was adjustable. A further modification involved reversing the swirl direction on two of the burners to produce a counterrotating pattern, in an attempt to correct an observed tendency for the flames to migrate to the right hand side wall of the boiler. Major burner variables available during the test program therefore included, air distribution, swirl level, and coal impeller position.

The main results from the Hasselby test program are presented in Figure 3-8, and show the impact of air staging and excess O_2 on NO_x emissions and

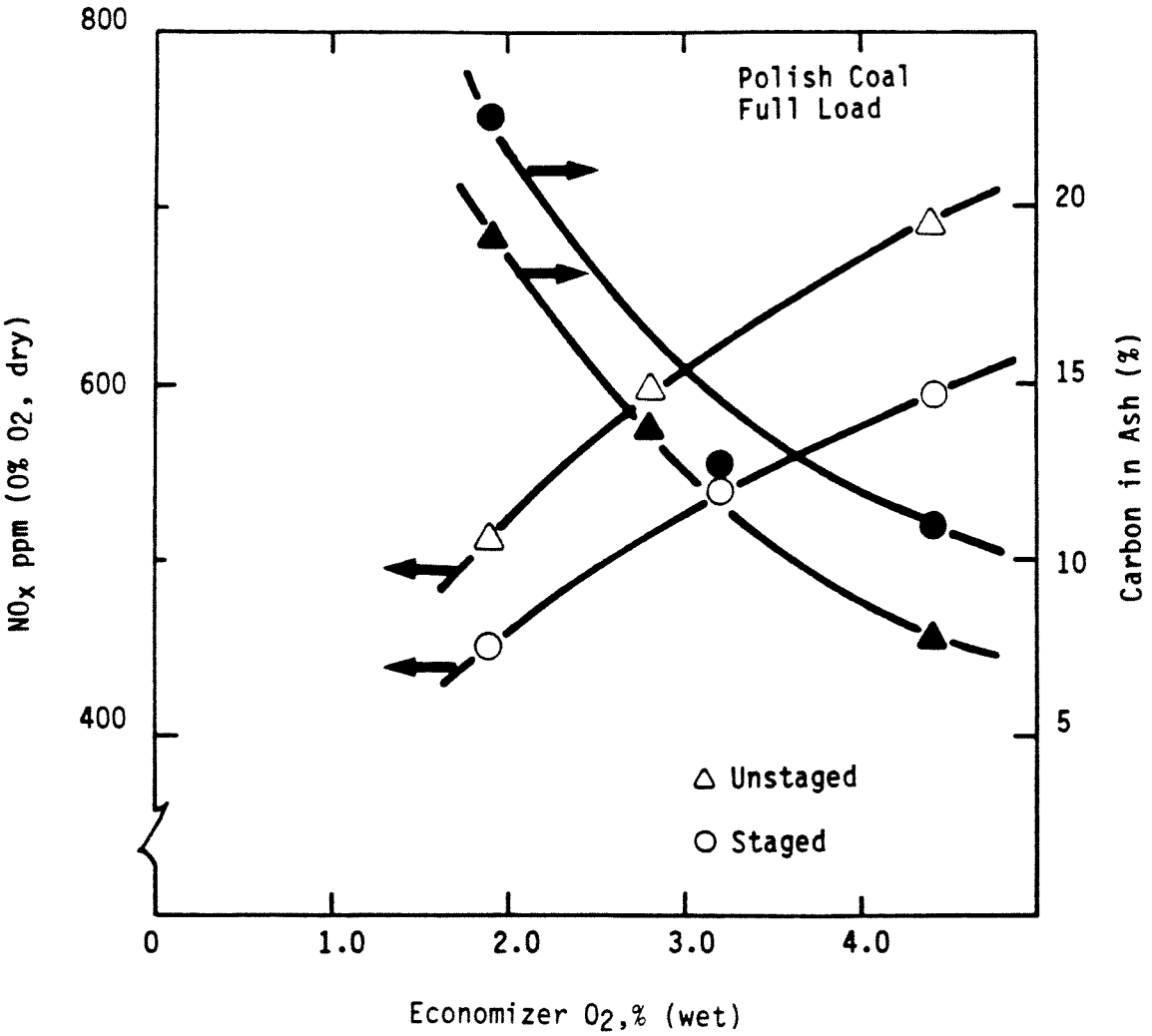


Figure 3-8. NO_x emission data - Hasselby.

carbon in ash when firing Polish coal. In the unstaged position, secondary air dampers are fully open and the tertiary dampers 22 percent open, while under staged conditions the damper positions are reversed. The test results presented in Figure 3-8 show, somewhat surprisingly, that the application of staged air addition had only a moderate effect on NO_x, reducing emissions by 14 percent (from 689-595 ppm at 4.4 percent O_2). This was found to be true for the other burner variables, swirl and impeller position, which also had negligible impact. The level of excess air employed was however found to have a more significant effect under both staged and unstaged conditions, reducing NO_x emissions by 24 percent and 26 percent respectively for O_2 levels down to 1.9 percent. This level of reduction is however believed to be commensurate with other experience and with literature values, where reducing excess O_2 by 1 percent will typically reduce NO_x by 60-100 ppm.

Perhaps the most significant feature of the Hasselby data was that all measures taken to reduce NO_x resulted in an increase in carbon in ash. This effect is also shown in Figure 3-8, where the maximum NO_x reduction of 34 percent (689 ppm with 4.4% O_2 unstaged, to 452 ppm with 1.9% O_2 staged) resulted in an increase in carbon in ash from approximately 8 percent to 22.5 percent. It should be noted, however, that CO levels remained relatively unchanged and varied only between 20 and 30 ppm (0 percent O_2) throughout this range. While some sensitivity to excess O_2 is to be expected, the observed trends may indicate an imbalance of flows between burners, or a reduced reactivity of the residual char in the lower temperature regions of the upper furnace. Heat transfer and combustion modeling work carried out in conjunction with this test program predicted comparatively high carbon in ash values with coal reactivity parameters that would be expected to yield good conversion in other boilers. This would suggest that the furnace thermal conditions might also have an impact on carbon in ash, making the system relatively sensitive to small changes in the mode of operation. The modeling study also showed a strong dependence of carbon burn-out on coal fineness.

Somewhat lower NO_x emissions had originally been expected from the Hasselby boiler, and the reasons why this was not achieved is not immediately apparent from the test data or from boiler operating conditions. One

possibility is that the Polish coal is less amenable to NO_x reduction by combustion staging than its composition would suggest. Other tests with Polish coals (e.g. at Stigsnaes) have indicated that, under some conditions this coal can give approximately 10 percent higher NO_x than comparable coals using similar burner settings. Also, the lack of sensitivity to adjustments in burner parameters (impeller position, swirl and air distribution) may suggest that flame conditions are still dominated by the coal impeller, or by the impeller in combination with high secondary swirl, in spite of the narrower coal spreading angle. Certainly, any future burner modifications should focus on the geometry of the interface between the primary and secondary streams. Additionally, the amount of combustion air which is diverted to the tertiary passage during staging is not known, since direct measurements of this parameter were not possible. Sliding-sleeve dampers of the type employed are know to be comparatively poor control devices, and it is possible that the tertiary air fraction may have been less than desirable.

Stigsnaes

Similar to the previous boiler, Stigsnaes unit number 1 was already equipped with low NO_x burners of the internally staged type with separate secondary and tertiary combustion air registers. While these burners had shown an ability to produce moderate reductions in NO_x, by diverting air to the tertiary passage, long term operation under low NO_x conditions had not been possible. This was due to reduced flame stability and to a maldistribution of gas temperatures in the upper furnace with a resultant impact on boiler steam temperatures. In order to correct these problems a number of modifications to the burner were carried out in preparation for the tests, namely:

- Modification to the coal pipe geometry to improve flame stability.
- Installation of fixed swirl vanes in the tertiary passage.
- Additional secondary air dampers to bias more combustion air to the tertiary passage.

During the test program the major burner variable available was the adjustment of air dampers to bias air to the tertiary passage. With the burners in the low NO_x setting, with tertiary dampers fully open, the combustion air was divided approximately 1/3 and 2/3 between tertiary and secondary air, yielding an inner burner stoichiometry (primary plus secondary) of approximately 0.8. Additionally, on the Stigsnaes boiler, full load operation is achievable with either two or three elevations of burners. This yields an important variable parameter which permits the testing of key premises concerning the influence of burner and boiler effects on NO_x emission. Switching from operation on two elevations (8 burners) to operation on three elevations (12 burners) at constant boiler load is expected to reduce NO_x emissions and improve performance because:

- Individual burner loads and velocities are reduced
- The heat release is spread over a greater furnace volume.
- Pulverizer loading is reduced, improving coal fineness.

The majority of the testing conducted at Stigsnaes was at 95 percent boiler load (142 MW_e) and with the U.S. coal. The highest NO_x emissions were recorded with two burner levels in operation and generally ranged from 650 - 700 ppm, independently of which combination of the three elevations were in service. When operation was switched to three elevations NO_x emissions were reduced to 550-600 ppm. The adjustment of air dampers for low NO_x operation was found to be effective for all firing configurations, and resulted in an NO_x emission reduction up to approximately 25 percent. With the U.S. coal, the lowest NO_x level recorded was 425 ppm (low NO_x, three elevations), representing a reduction of 40 percent relative to the highest NO_x configuration (unstaged, two elevations). It should be noted however, that actual reductions in NO_x relative to original levels may possibly be higher than those reported since pre burner modification emissions are not available. A series of earlier measurements had indicated baseline NO_x emissions up to 860 ppm, although this was with a different coal which was no longer available to the plant, and a direct comparison between the two test series is not considered reliable.

A limited amount of testing was additionally carried out with three different coal types, a Colombian coal, a blended Australian/Colombian coal, and a Polish coal. Results from these tests are summarized in Figure 3-9 together with the U.S. coal, indicating the impacts of low NO_x operation and burner levels in service. These results show similar trends in NO_x to those observed with the U.S. coal. It may, however, be significant to the Hasselby results that percentage NO_x reductions were lower with the Polish coal. The lowest emissions (400 ppm) were recorded with the Colombian coal which has a low ash content (6 percent) and consequently runs with a much clearer furnace. It is also noteworthy that, with all the coals, NO_x emission levels could vary by up to 50 ppm due to furnace cleanliness, and to the proximity of a given test series to sootblowing or a period of non-routine boiler operation. In this instance it appears as though furnace cleanliness effects are at least as important as the chemical differences in coal type.

General operation of the furnace under low NO_x conditions appeared to be satisfactory during the test program. Earlier problems with flame stability were not apparent and temperature distributions in the upper furnace remained uniform. Low NO_x operation was however found to result in a 1.0 to 1.5 percentage point increase in carbon in ash, though absolute values exceeded 5 percent only for the low ash Colombian coal.

Lakeview/Nanticoke

Low NO_x combustion modifications were not carried out on the Lakeview boiler, although Ontario Hydro had previously reported a comprehensive low NO_x burner retrofit and development study[4] in two of the larger (512 MW) Nanticoke station boilers. It was of particular interest to incorporate the results of this study into the IEA project because the original burners were of similar design to those in the Lakeview unit, and also in the Edgewater and Hasselby boilers.

The original burners installed in the Nanticoke boilers were standard circular burners with a single secondary air register with variable swirl, and a wide angle coal impeller. The basic concept employed initially in the

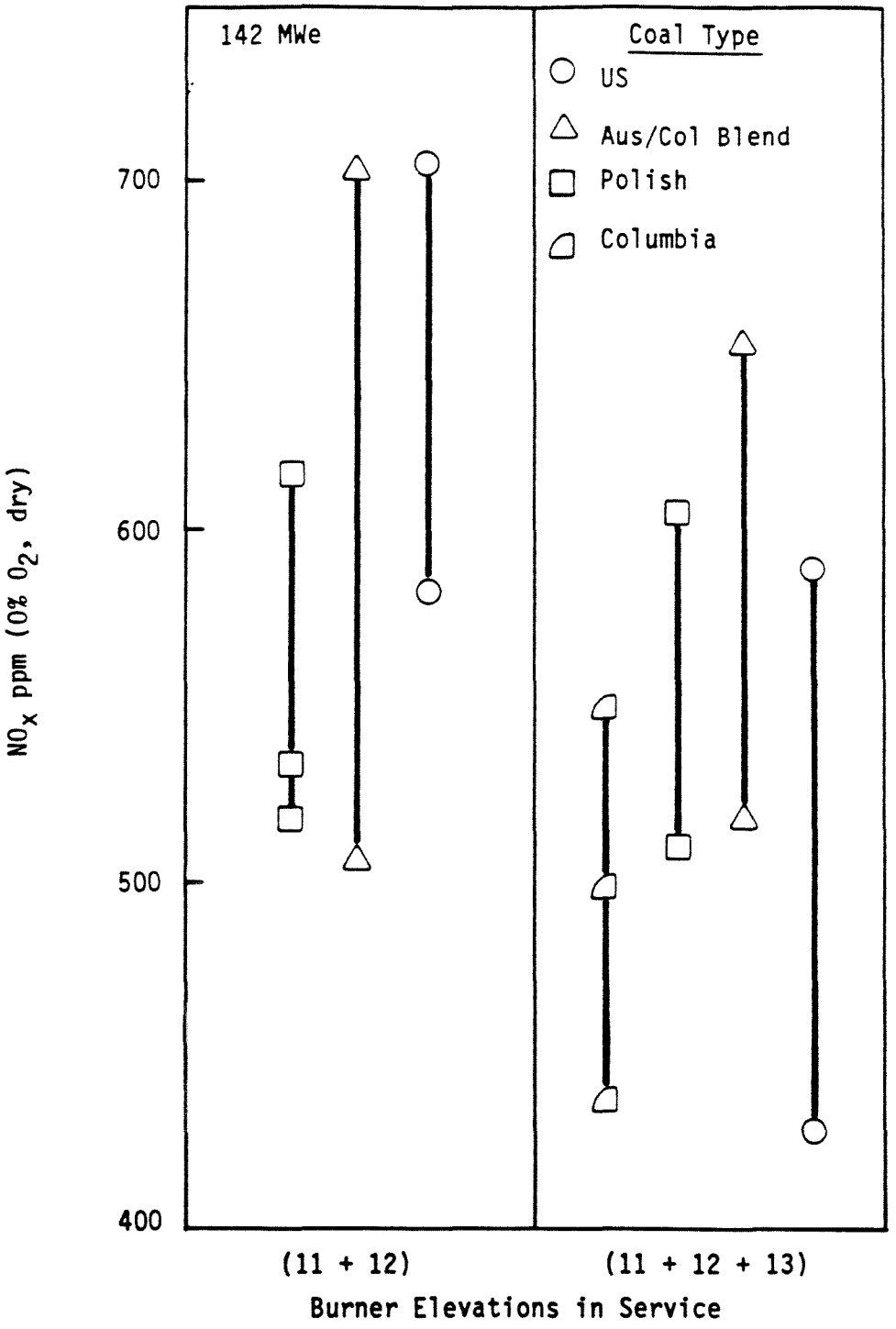


Figure 3-9. Stigsnaes - effect of burner staging on NO_x reduction for different coal types.

design and retrofit of low NO_x burners was that of conversion to a standard dual register burner, and included the following modifications:

- Replacing the existing coal impeller with a wedge and diffuser arrangement to reduce mixing while maintaining uniform coal flow.

- Enlarging the existing burner throat from 838 mm to 890 mm.

- Dividing the air register into secondary and tertiary streams, each with independent swirl control.

The first retrofit was conducted in 1982 on unit number 5, where baseline NO_x emissions had been measured at 1000 ppm (0% O_2) with a high efficiency impeller, and 840 ppm with a standard impeller. These values are comparable with reported values of approximately 805 ppm at Lakeview for operation at 78 percent load (235 MW). Following conversion to low NO_x burners, measurements showed that NO_x emissions had reduced to 515 ppm for full load operation at 512 MW. However, the boiler could not operate at normal O_2 levels due to an increase in CO levels (150 ppm) and high carbon in ash (above 12 percent). Although the problem was partly traced to poor pulverizer performance it was necessary to continue operation at elevated O_2 levels to improve carbon in ash and to mitigate opacity problems.

In a subsequent test series Nanticoke Unit 6 was modified with low NO_x burners of a similar design but without secondary air swirl. This version was referred to as the Mark 1 burner, and resulted in NO_x reduction of over 50 percent to levels of 415 ppm. However, unburned carbon remained high, resulting in low fly ash resistivity, reduced precipitator performance and high opacity. As a result of these tests a Mark II burner was developed, in which a small, variable position spreader was installed in the coal pipe. This burner proved capable of achieving NO_x emission reductions of 35 percent (down to 535 ppm), without increasing CO and with acceptable increases in carbon in ash (9.5 percent) relative to pre modification baseline levels (6 percent).

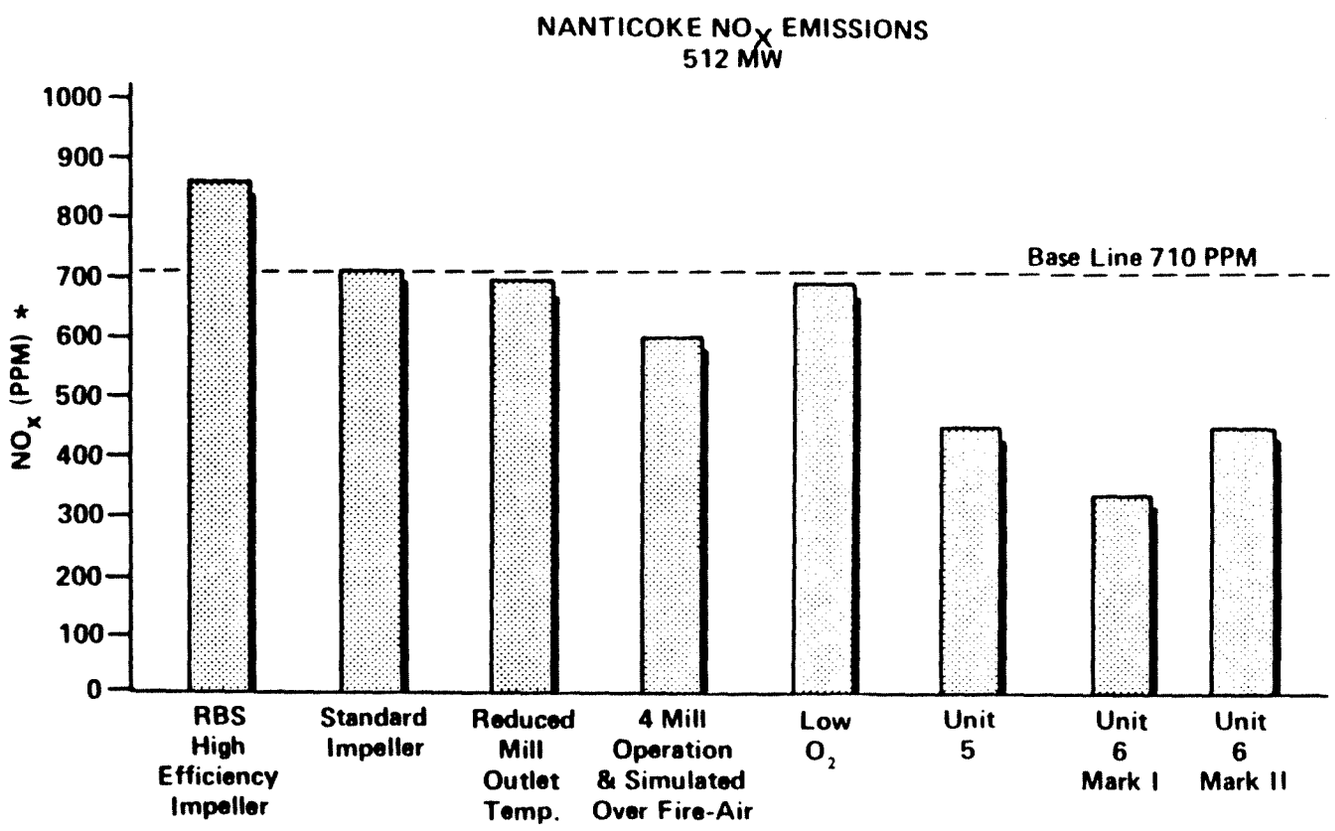
The results of Ontario Hydro's low NO_x retrofit program at Nanticoke[4] are summarized in Figure 3-10. This figure also shows the results of less successful operational changes to reduce NO_x emission prior to the burner retrofit.

Edgewater

As part of the U.S. EPA demonstration program, the existing circular burners on the Edgewater boiler were replaced by twelve XCL low NO_x burners recently developed B&W. This burner development was based on B&W's original Dual Register Burner, and was designed to achieve similar NO_x reductions but with a shorter, controllable flame shape.[6]

Prior to XCL burner installation, baseline tests were performed on the unit with the existing circular burners. After burner tuning, full load NO_x emissions were 755 ppm, with 20 ppm CO, 3 percent excess O_2 at the burners, and averaged 2.2 percent carbon in the ash. The XCL burners were installed during the fall of 1986 and, as installed, reduced NO_x to 450 ppm at full load and 3-3.5 percent excess O_2 at the burners, with 115 ppm CO and 2.8 percent carbon in the ash. Flame lengths were approximately 5 m, well short of the rear wall (6.7 m furnace depth). NO_x was reduced by 40 percent while maintaining high combustion efficiency. Subsequent impeller adjustments reduced NO_x to 290 to 340 ppm but CO and unburned carbon (UBC) increased unexpectedly to unacceptable values. Furnace probing measurements, and a series of subsequent burner adjustments ultimately attributed the source of the problems to an inability to adequately balance air and coal flows to individual burners, combined with low available windbox pressures (120 mm WC) in this retrofit situation.

Optimization work on the burners ultimately resulted in NO_x emission levels from the boiler being reduced to 395 ppm (0 percent O_2), with 6 percent carbon in ash and 60 ppm CO at full load and normal excess air levels.



(*at 3.3% O_2)

Figure 3-10. Summary of low NO_x retrofit program at Ontario Hydro's Nanticoke Station (Ref 4).

3.2.2 Impacts of Low NO_x Operation on Boiler Performance

Potential operational problems which are usually anticipated when boilers are modified for low NO_x operation include:

- Increased slag deposition and waterwall corrosion, due to increased flame length and the presence of local reducing zones.
- Difficulties with steam temperature control, due to increased furnace exit gas temperature, or to changes in temperature distribution in the upper furnace.
- Reduced boiler efficiency and increased stack opacity, due to higher carbon in ash.

While a number of problems have been experienced in the various demonstration projects as a result of low NO_x operation, these were surprisingly few. In most cases an increase in flame length was observed when switching from normal combustion to low NO_x conditions. In at least one instance (Gagetown) this was sufficient to result in significant flame impingement on the waterwall surfaces. Fortunately, this situation was recognized and burner adjustments were made to correct the situation. Usually, such adjustments result in higher NO_x emissions, and this is one of the compromises which must be faced in any retrofit situation.

For all of the demonstration projects there was no reported incidence of increased slagging or ash deposition on waterwall surfaces due to low NO_x operation. This suggests also that the low NO_x flames were well contained and that the envelope surrounding the flames was overall oxidizing. Individual test series were not run for sufficiently long periods to determine whether corrosion rates were a potential problem. For long duration operation under low NO_x conditions it will however be necessary to monitor conditions closely. Low-NO_x combustion systems are required to work to closer tolerances and are potentially less forgiving than high intensity

systems. Consequently the systems are expected to be more sensitive to operating conditions and changes, for example in the distribution of fuel and air to individual burners (due to pulverizer wear or other parameters), may lead to changes locally within the furnace.

In some low-NO_x combustion retrofit situations the resulting changes in flame characteristics and distribution of heat release have given rise to increased furnace exit temperatures or strongly biased temperature profiles. Such changes may in turn affect steam conditions or steam temperature control. Inspection of the available test data for the boilers incorporated into this study has however shown no evidence of any significant impacts of low-NO_x operation. Where upper furnace temperatures have been measured these have shown little change relative to baseline conditions, and there appears to have been little measurable impact on steam temperatures or attemperation spray requirements.

The most significant impact of low NO_x operation in each of the demonstration projects appears to have been in terms of increased carbon in ash. Any increase in the carbon content of the flyash is of concern for several reasons:

- It represents a loss in efficiency
- It may affect the sale, end-use, or disposal of the fly ash
- High carbon levels can reduce ash resistivity, thereby impacting precipitator performance and leading to increased opacity.

In each of the demonstration projects the carbon in ash levels were measured to increase as a result of low NO_x operation. As a minimum the increase was on the order of 1-2 percentage points, and up to several percentage points (to a maximum of 20 percent carbon in ash) for some units. Increased carbon appears to be an unavoidable and direct consequence of delayed mixing, and becomes more difficult to control as the lower limits of NO_x emission are approached. The only corrective measures appear to be

through an adjustment of burner parameters, usually at the expense of increased NO_x emission, or through reducing the fineness of the pulverized coal supplied to the burners. Improving coal fineness has some cost implications, due to increased mill power requirements or reduced mill capacity, but should be considered as an integral part of the low NO_x combustion system. On the Hasselby boiler, detailed efficiency calculations indicated that an increase in carbon in ash need not necessarily result in a loss in boiler efficiency relative to baseline levels. If low NO_x operation is accompanied by a decrease in excess air then reduced flue gas losses may compensate for the increased carbon loss.

3.3 Discussion of Results

The main results from the different boiler demonstration projects, as discussed in the previous sections, are summarized in Figure 3-11. This figure represents a very simplified picture of the large amounts of data that were obtained during parametric and optimization testing, and shows only baseline NO_x emissions, and NO_x levels under optimum low-NO_x conditions, to indicate the levels of reduction achieved during boiler operation under nominal full load conditions.

The presentation format selected in Figure 3-11 employs the burner zone heat liberation parameter discussed in Section 3.1 as a means of illustrating the impacts of burner and boiler design parameters on NO_x emissions. Upper and lower limit trend lines, determined from the data presented in Figure 3-6, are also carried over into the figure to illustrate where the present data lie in relation to the limits of previous boiler and experimental furnace experience. The lower limit line is established from boiler and furnace data which have resulted from extensive low-NO_x retrofit programs, and is considered to represent a limit of demonstrated performance on wall-fired boilers with otherwise satisfactory boiler operation. Results from the IEA project have indicated that the NO_x emission reductions achieved, relative to initial baseline values, have ranged from approximately 20 percent to greater than 40 percent. In some instances, as shown in the

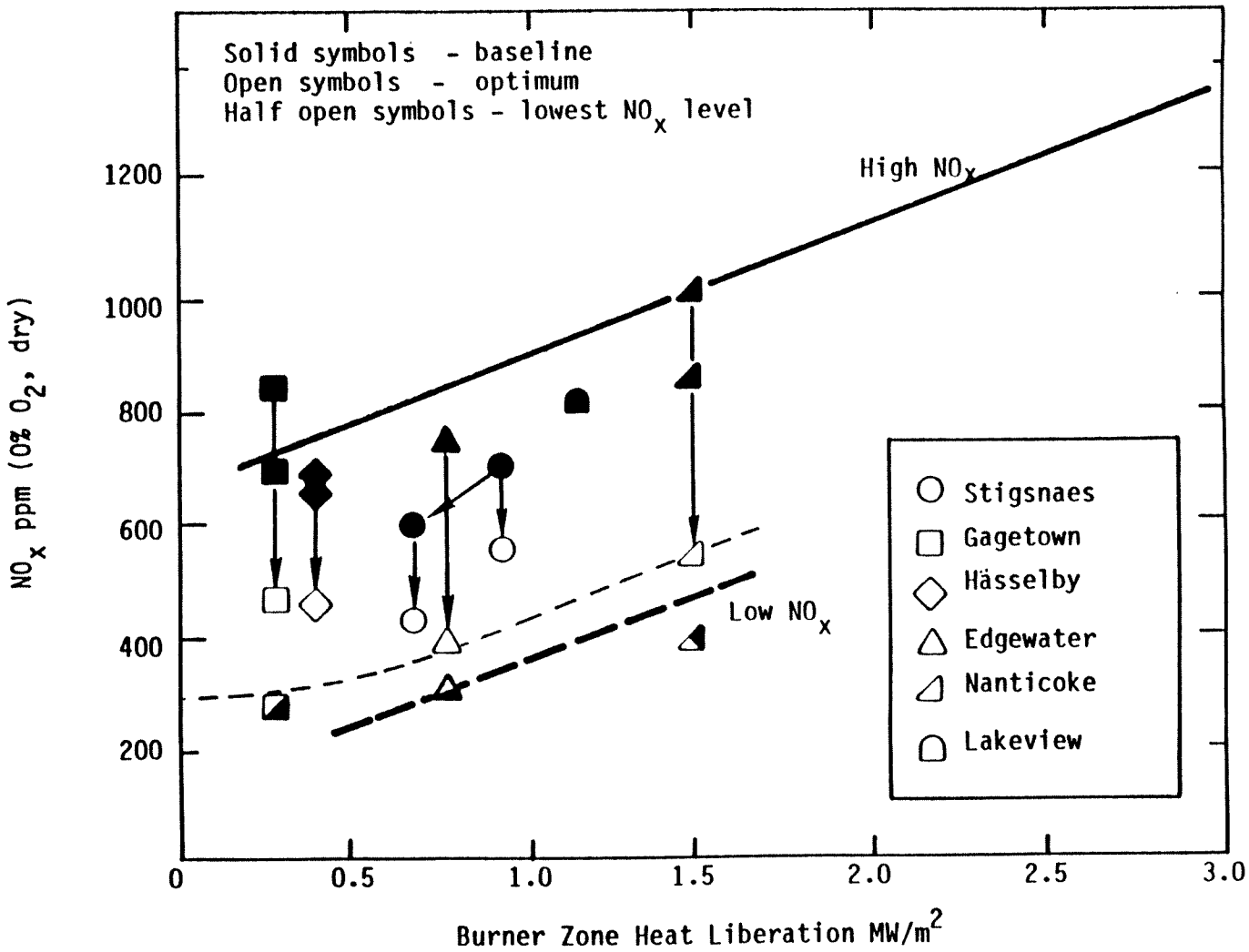


Figure 3-11. Summary of NO_x emission results - full load operation.

figure, considerably greater reductions were achieved, but only at conditions which were judged to be unsatisfactory for long term operation.

The burner zone heat liberation parameter does not however incorporate all the factors which contribute towards NO_x emission, although it does represent a useful vehicle for the interpretation and discussion of results. In this regard it was noted that the original burners installed in the Lakeview, Nanticoke and Edgewater boilers were all of similar design, in that these were single register circular burners with wide angle coal impellers. Under non-staged conditions the burners in the Hasselby boiler also had similar design parameters, and yielded emission levels comparable to values measured on adjacent units at the station prior to burner modification. Although individual burners in the above four units are of slightly different size, there is a good general correlation between uncontrolled N_{Ox} levels and burner zone heat liberation, as shown in Figure 3-11. This illustrates the utility of the burner zone parameter in accounting for certain boiler design features and their impact on NO_x emissions. Boilers with closely spaced burner arrangements tend to have higher burner zone heat liberation rates and consequently yield higher NO_x emissions, even though individual burner performance may be comparable to that in more lightly loaded units. The impact of coal type is not expressly taken into account, but is implied in that the correlation is only strictly valid when the same coal is used in different units. In this study, all the coals employed were high volatile bituminous coals, and were expected to yield comparable NO_x emissions levels based upon their composition.

In Figure 3-11, at the lower end of the burner zone heat liberation scale, it will be noted that some of the measured baseline NO_x emission data from Gagetown exceed the range for previous boilers of this general size. On this boiler, the use of oil co-firing as a precaution against boiler upset conditions due to excessively wet coal is believed to have complicated the situation somewhat.

For each of the different boiler situations, the data presented in Figure 3-11 shows a range of NO_x emission values, representing the extent of

NO_x emission reduction achieved, due primarily to burner modification. It is clear that, for a given firing arrangement and burner zone heat release rate, a wide range of NO_x emission levels and overall system performance are possible. As has been indicated in the discussion in previous sections, the most effective NO_x control techniques have been by staging the combustion process through modification at the burner, and by reducing the overall excess air. Within the total data set, the lowest overall NO_x emissions, relative to the initial baseline and the anticipated lower NO_x limit, were achieved on the Edgewater and Nanticoke boilers. On these boilers relatively extensive burner retrofit programs were carried out, rather than modifications to existing burners, such that considerable flexibility in selecting and optimizing burner parameters was afforded. The NO_x emission levels achieved on these boilers was close to that reported in other low NO_x burner retrofit programs, and are believed to be close to the lower limit of what is readily achievable by combustion modification. On both units, lower NO_x emission levels were reached but only with unacceptable performance in other respects; mainly due to high unburned carbon and excessive flame length. These observations are taken as further indications that the lower limit of NO_x emission had been reached with these burner arrangements, and that further gains may be achieved only through fine-tuning of burner parameters, and by greater attention to the overall firing system.

On Figure 3-11 two sets of data are presented for the Stigsnaes boiler, representing operation of the unit at full load on either two or three elevations of burners. Operation of the unit on four elevations of burners results in a lower burner zone heat liberation rate, since the total heat input is spread out over a much larger area of the boiler. As can be seen from the figure, this results in correspondingly lower emissions of NO_x under both baseline and low NO_x burner settings. However, with all burners in service the NO_x emission levels are considerably lower than would be expected by simply applying the general trend line to extrapolate burner performance to the lower burner zone liberation rate. For this particular configuration and coal type, the incremental gain in NO_x is believed to be due to the reduction in velocity as the firing rate at individual burners is reduced, which results in an improvement in low-NO_x performance. Although significant

NO_x reductions were achieved at Stigsnaes, it is clear from Figure 3-11 that the final emission levels are still considerably higher than would be expected in the limit, based upon the burner zone heat liberation rate and the performance achieved on the other units. It is possible that a further 100-150 ppm of NO_x emission reduction could be achieved on this unit by further adjustment and fine-tuning of the existing burners, or by more substantial modifications to improve staged combustion performance. This may also be supported by the fact that the reported performance was achieved without any marked impact on boiler performance (parameters such as unburned carbon, flame length, and temperature levels), relative to baseline conditions.

At the lower end of the burner zone heat liberation range, the two smaller boilers, Hasselby and Gagetown, did not achieve the NO_x emission levels which might have been expected based upon the unit size and firing characteristics. Emission levels on the order of 300 ppm are expected based on the correlation of Figure 3-11, while in practice values closer to 450 ppm were achieved. In both cases the primary limiting factor was a tendency towards high carbon in ash as burner and firing parameters were adjusted. Boiler heat transfer and combustion performance had indicated that both of these units might be susceptible to high carbon in ash because of their specific thermal characteristics. Nevertheless, based on experience with other units and with burners of similar designs, it is believed that further reductions in NO_x emissions should be possible on both of these boilers, although this could require further hardware changes and in-situ optimization.

From the burner retrofit results presented in previous sections, and as summarized in Figure 3-11, it is apparent that low NO_x burners should not be considered to be capable of achieving a fixed percentage reduction in emissions, or of achieving a constant minimum NO_x level for every application. When burners are applied under retrofit conditions to existing boilers, the degree of NO_x emission control will tend to be site specific, depending not only on burner design parameters, but also on boiler design characteristics such as burner spacing and firing depth, and any constraints

which may be imposed on burner design and operational features due to site specific conditions. Indeed, it can be implied from Figure 3-11 that there will be a lower limit in NO_x emission which is achievable independently of burner design. This lower limit is higher for higher firing densities, although for a given burner zone heat liberation rate other geometrical factors, such as available firing depth, may be more or less important. In this regard, boilers with an opposed-fired burner arrangement may offer more flexibility, since longer flames can be tolerated without risk of impingement on the boiler rear wall. On the other hand, smaller boilers with low burner zone heat liberation, are likely to be more constrained due to the somewhat cooler furnace environment and difficulties in ensuring high carbon burn out.

From this discussion it may be concluded that the ability to reduce NO_x emission in an existing boiler is clearly dependent upon many factors which relate not only to burner design but also to the boiler. The approach to burner design, and the design parameters employed, are of course of paramount importance, but these may also be constrained by the flexibility afforded by the specific retrofit situation. For example, of only simple modifications to an existing burner system are allowable, this gives less flexibility than if new burners are to be installed. Other parameters such as the available pressure drop, windbox space available, and ability to modify the firing wall, are all important.

Two of the main consequences of low NO_x operation have been shown to be an increase in flame volume, and a tendency towards increased carbon in ash. Changes in flame characteristics are usually manifested as increased flame length, with the possibility of flame impingement directly on water wall surfaces. For boilers with limited firing depth or a closely spaced burner zone this can in itself directly limit the NO_x reductions which are possible without operational risks. To some extent geometric limitations in the firing zone are reflected in the burner zone heat liberation parameter which has been used for NO_x correlation. Increased carbon loss is a direct consequence of the delayed mixing process used to control NO_x, and is often one of the main factors affecting the lowest NO_x levels achievable. Carbon burnout can be improved by mill adjustments to increase fineness, and by

careful attention to balancing air and coal flows for greater control over local stoichiometry. In approaching the lower limit of NO_x control it is therefore important to consider the combustion system as a whole, and not just the burners in isolation. Mill performance, provision for balancing air and coal flows, and improved burner management systems are all elements of the combustion system which need to be evaluated and possibly upgraded as a part of the NO_x control strategy.

For each boiler therefore it seems likely that there will be a lower limit on NO_x emission which will be achievable, which will be determined by boiler (and coal) specific parameters. The extent to which this level may be reached will depend upon the flexibility afforded to the burner designer, such that the final result will be a compromise between many factors which must be judged and handled on an individual basis.

4.0 SO_2 CONTROL BY SORBENT INJECTION

4.1 Parameters Affecting SO_2 Emission Reduction During Furnace Sorbent Injection

The upper-furnace injection of calcium-based sorbents for SO_2 control has been intensely studied. This process is attractive because of its simplicity and low capital cost requirements, but typically has the disadvantage that sorbent utilization is low compared to wet flue gas scrubbing systems. This has motivated much work on the factors which control conversion, and has led to a good understanding of both the global parameters that influence conversion, and the underlying fundamental processes. This section outlines this understanding.

4.1.1 Overview of Furnace Injection

When calcium-based sorbents, either $CaCO_3$ or $Ca(OH)_2$, are injected into a furnace, two chemical steps govern SO_2 capture. The first is the sorbent activation step (either calcination or dehydration) which prepares the active CaO:

$$CaCO_3 \rightarrow CaO + CO_2$$
$$Ca(OH)_2 \rightarrow CaO + H_2O \quad .$$

This is followed by the sulfation reaction:

$$CaO + SO_2 + 1/2\ O_2 \rightarrow CaSO_4 \quad .$$

The molar volume of the CaO is smaller than that of either of the original sorbents. The CaO, therefore, develops a high internal porosity during the activation reaction. Theoretical porosities for each of the two sorbents, assuming no shrinkage, swelling, or porosity in the original sorbent, are as follows:

$CaCO_3$ - 50.6

$Ca(OH)_2$ - 49.2

Note that $Ca(OH)_2$ typically has significant porosity before dehydration, as demonstrated by the high BET surface areas measured for the raw material (typically 5-20 m^2/gm).

This internal structure is typically held in pores that range form 0.01-0.05 microns. As such, the internal structure represents the vast majority of the surface that is available for reaction, and the contribution of the external particle surface can be neglected.

The sulfate product has a higher molar volume than CaO, or either of the raw materials. Thus, all of the internal porosity can become filled with product before the particle reaches 100 percent conversion. Ratioing of molar volumes allows the calculation of the amount of sulfation that would fully plug the internal structure of CaO:

	Percent Sulfated
CaO at theoretical porosity from $CaCO_3$	59.3
CaO at theoretical porosity from $Ca(OH)_2$	55.5

There are two general reasons these high conversions are never achieved with practical sorbents. First, at the temperatures encountered in activation and sulfation, the CaO structure is prone to shrinkage and sintering. This can occur on the same time scale as the sulfation reaction. Second, as reaction proceeds, the pores near the particle surface can become plugged with product, which can shield the interior from SO_2. Both of these processes act to reduce the surface area available for reaction.

An additional constraint on conversion is the reaction rate per unit surface area. Under some conditions this can act to limit reaction even in the absence of the desurfacing just described. At a very early time in the sulfation reaction, the surface of the CaO becomes coated with sulfate product. For subsequent reaction to occur the SO_2 and O_2 (or SO^{2-} must

diffuse across this product barrier. The actual surface-specific rate of sulfation is thought to be governed by this solid state diffusion process. The exact nature of the product layer diffusion resistance is not well know, but its global value has been well characterized, as shown in Figure 4-1. This means that the instantaneous rate of sulfation will be governed by the combination of all the mass transfer resistances which hinder the arrival of SO_2 at the CaO surface:

- Diffusion of SO_2 from the free stream to the particle surface
- Diffusion of SO_2 through the pore structure within the particle
- Product layer diffusion, as described above.

Above about 1300°C, $CaSO_4$ becomes thermodynamically unstable (see Figure 4-2). Below 900°C, the product layer diffusion becomes so slow that significant sulfation cannot proceed. This defines the "sulfation temperature window" outside of which significant sulfation cannot occur under practical conditions.

In summary, the sulfation process is governed by the coupling of complex phenomena. These include:

- A diffusion limited sulfation rate that acts to limit reaction at low temperatures.

- A thermochemical equilibrium limit that prevents sulfur capture above about 1300°C.

- A sorbent structure that is rapidly degrading on the same time-scale as the sulfation reaction.

Within the sulfation window where the inherent sulfur capture processes are fastest, it appears to be the loss of reactive surface (i.e., sintering, shrinkage, and plugging) that ultimately limits practical sulfur capture.

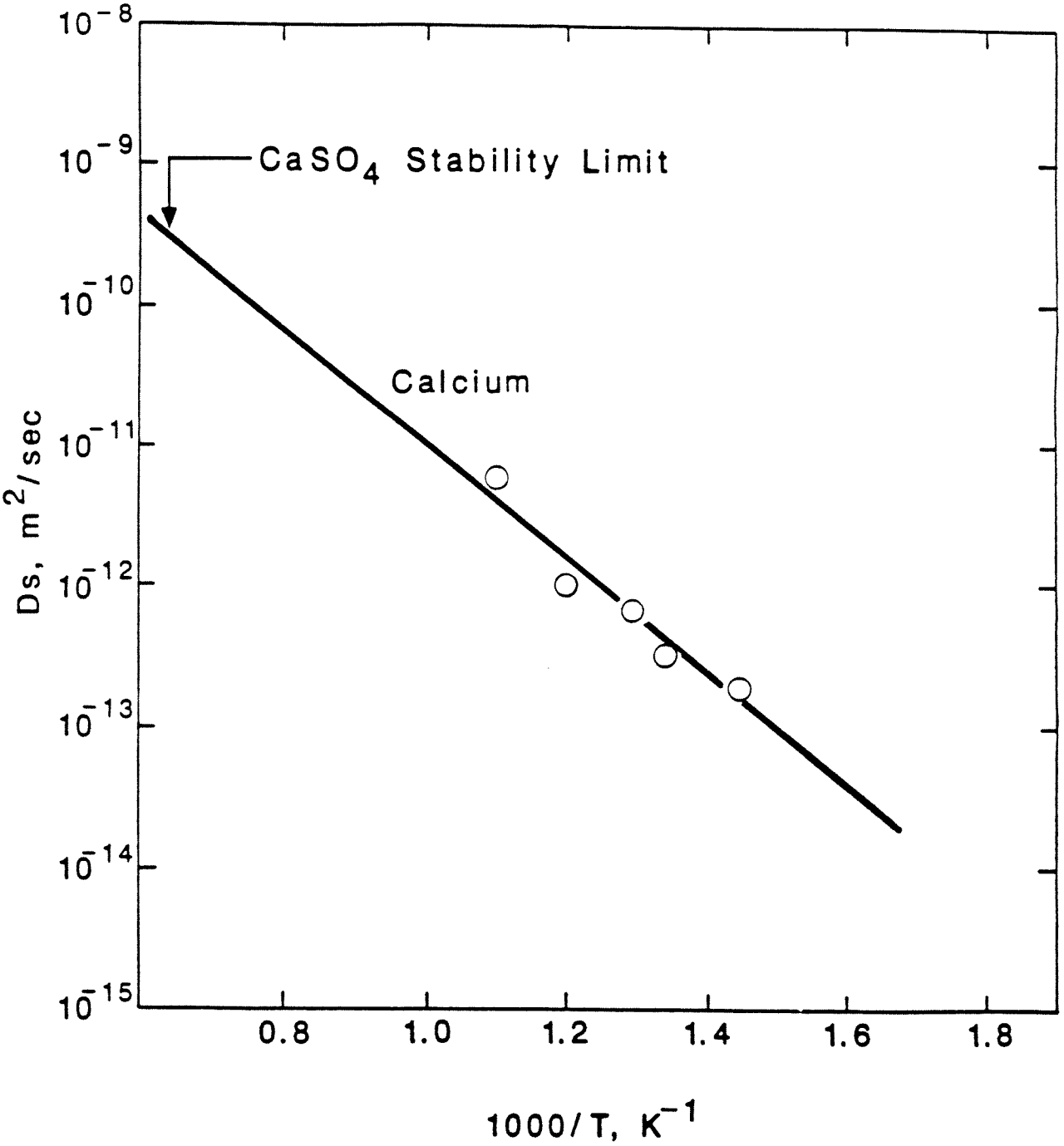


Figure 4-1. Diffusion coefficients for sulfur oxides through calcium sulfate.

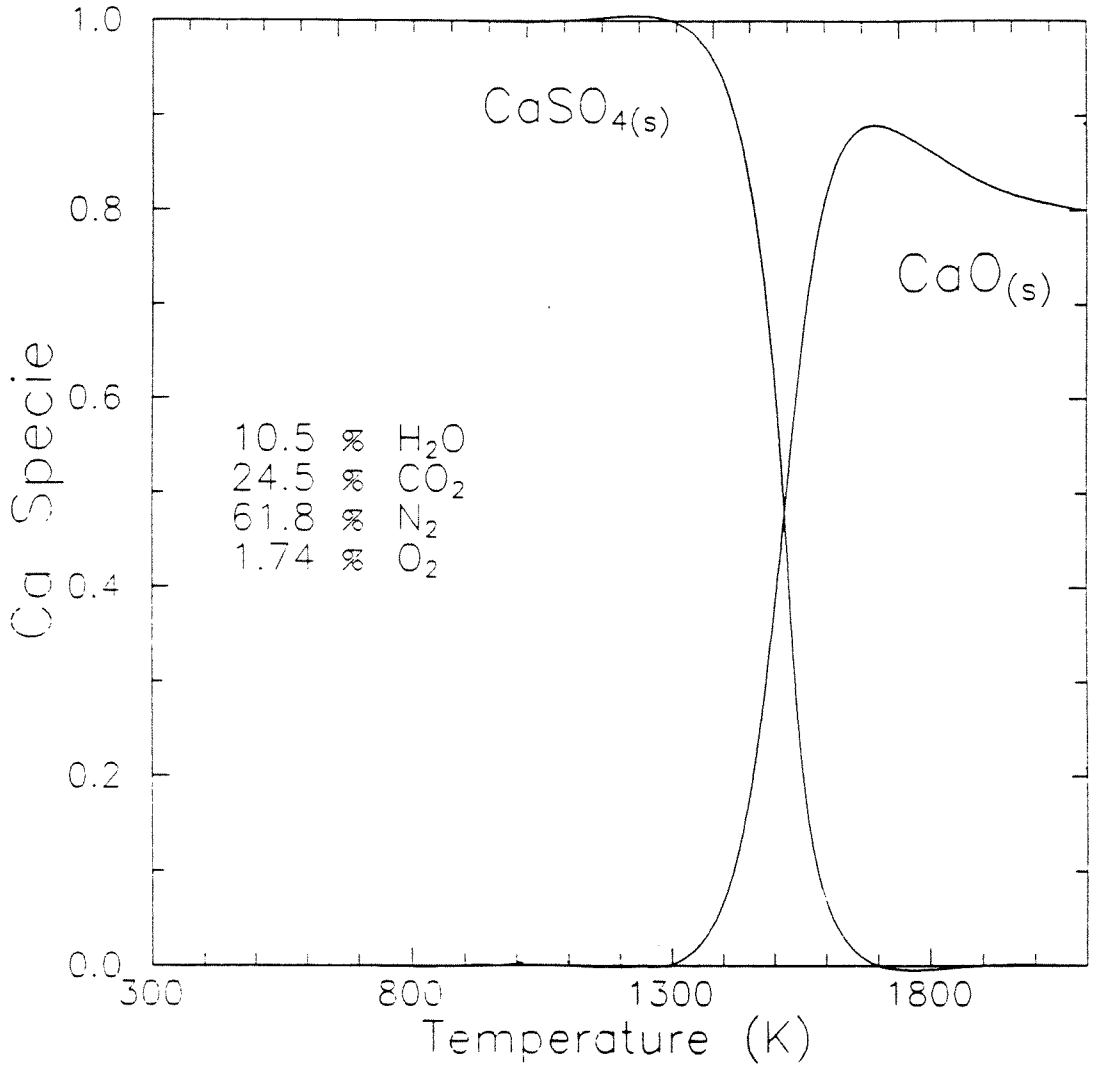


Figure 4-2. Equilibrium distribution for the calcium/sulfur system.

The following section details our understanding of how sorbent structure acts to limit sulfur capture under realistic conditions. This understanding has been key to explaining how the various application parameters influence performance. Finally, Section 4.1.3 reviews the influence of these various application parameters on sulfation, along with the mechanistic reasons for why the data are thought to behave as they do.

4.1.2 Relationship between Structure and Sulfation

One of the most important tools for understanding high temperature sulfation was the development of short residence time data (i.e., less than 100 ms). This was a consequence of the development of high mixing rate bench-scale sorbent injectors that allowed meaningful data to be collected at these short times.

Figure 4-3 shows what was found when these injectors were first applied. Within the middle of the sulfation window, at 1180°C, a large amount of sulfur capture occurred under very short times. This has been termed "prompt capture," and it is followed by a much slower capture rate. One hypothesis stated that a high surface area "bloom" would occur during sorbent dehydration, followed by rapid sintering. The prompt capture would correspond to the "bloom." To investigate this, sorbent samples were collected with and without sulfur, and these were characterized for structure-dependent properties. No surface bloom was noted.

Pore size distributions of these solids were also measured and their porosities calculated. (Although these porosities were calculated from the distributions, they will be referred to in the remainder of this section as the measured porosities.) The measured porosities are plotted in Figure 4-4 as a function of time. The porosities of solids sampled both with and without SO_2 present in the reactor were also approximately constant with time. All of these measured porosities are significantly lower than the porosity which is theoretically possible from calcium hydroxide (0.49). The sorbents samples without SO_2 present in the reactor have therefore experienced a greater than 50 percent loss in porosity.

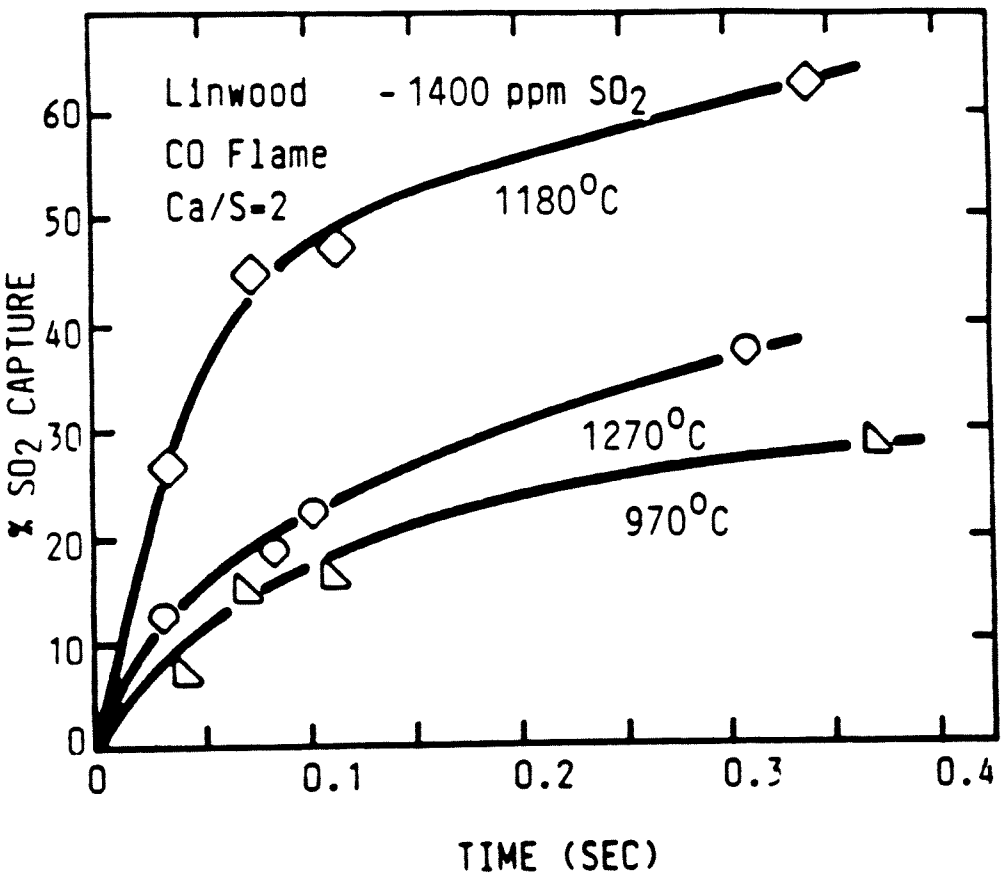


Figure 4-3. Influence of time and temperature on sulfur capture by a Linwood hydroxide.

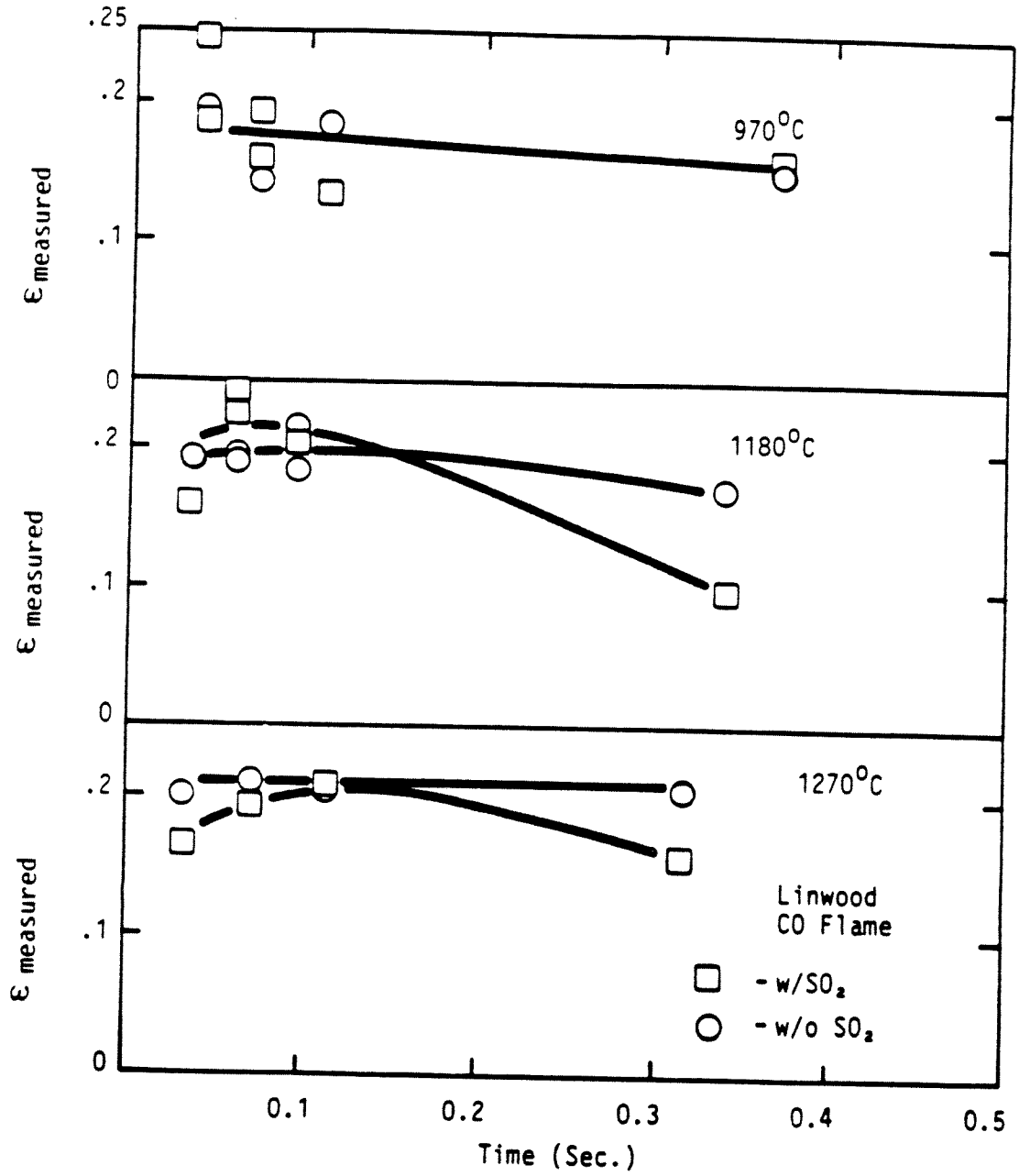


Figure 4-4. Measured porosities of sorbent sampled from the STR.

The porosities of sorbents sampled with SO_2 present in the reactor reflect the presence of the product of the sulfation reaction, $CaSO_4$. The porosities of these sorbents prior to sulfation (But after calcination) must originally have been larger. This original porosity can be calculated from the measured porosity and the measured calcium utilization by the equation:

$$o = m + X(-1))/(1 + X(-1))$$

where Σ_o = calculated original porosity
Σ_m = measured porosity with SO_2
X = calcium utilization
= molar volume of $CaSO_4$/molar volume of CaO = 3.107.

The results of this calculation are plotted as a function of temperature in Figure 4-5 along with the measured porosities of the solids sampled without SO_2 in the reactor. These calculated original porosities exhibit a strong dependence on temperature. At the lowest temperature shown, 970°C, a significant loss in porosity from that theoretically possible still occurs although the extent of the loss is not as great as that in sorbent sampled without SO_2 present in the reactor. At 1180°C the calculated original porosity is close to the theoretical porosity of a calcined calcium hydroxide, 0.49, and at 1270°C a large loss in porosity again occurs. Sulfation therefore appears to hinge or, at the optimum sulfation temperature, prevent this loss in porosity. This dependency of the calculated original porosity on temperature and the presence of SO_2 allows a new hypothesis to be proposed:

> The process which causes this porosity loss (sintering) occurs at approximately the same temperature as the sulfation reaction. Porosity loss and sulfation may therefore be viewed as processes which compete for available sulfation sites. When the mechanism which causes porosity loss is fast compared to sulfation, the loss in porosity results in low sorbent utilization. When sulfation is fast, porosity loss does not occur and greater levels of sorbent utilization result.

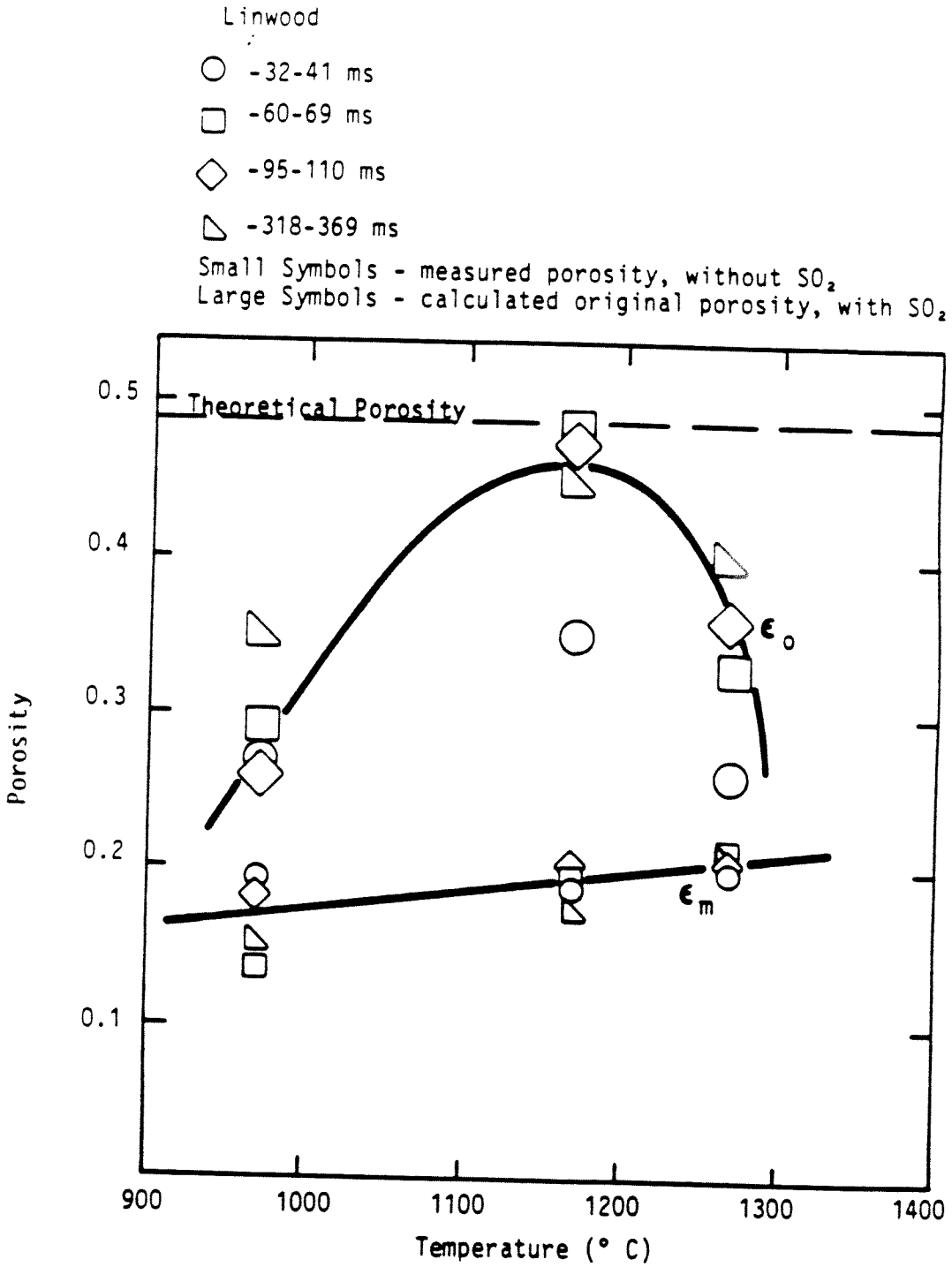


Figure 4-5. Measured porosities and calculated original porosities.

The most likely mechanism responsible for this porosity loss is sintering caused either by the high temperatures typical of a combustion environment or sintering activated by CO_2 from the combustion process.

The implication of Figure 4-5 is that an unstable, high reactivity material exists immediately following activation. If not used immediately, porosity loss causes the material to experience a lower level of "prompt" capture, although the long-term capture is unimpaired.

There are two general hypotheses concerning the ability of the sulfation to prevent porosity loss. These are:

1. At the optimum temperature, the rapid initial formation of a product layer minimizes the mobility of the CaO surface. This could be through shielding it from CO_2. Thus, the particle becomes more resistant to shrinkage, and the sulfation can occur in due course.

2. At the optimum temperature, the sulfation reaction is sufficiently fast to allow prompt sulfation before significant shrinkage has occurred. In this scenario the shrinkage rate is not modified by the sulfation, but rather the sulfation fills the pores before shrinkage can close them.

It is entirely possible that the actual process lies between these two extremes, i.e., the inherent shrinkage rate is reduced, which gives more time for sulfation to fill the pores.

The key idea is that maximum utilization occurs if the sorbent is rapidly brought to the optimum temperature at the same time it is exposed to SO_2. Many of the practical injection parameters appear to act through modifying this scenario.

4.1.3 Influence of Process Parameters

Injection Temperature. Before discussing the effects of injection temperature it is important to clearly understand what is meant by this term. Confusion arises because the air used to convey the sorbent into reactors and furnaces is typically at room temperature. The amount of conveying air used at bench scale is generally from 10 to 15 percent of the total air added, while for furnaces a value of 2 to 4 percent is more typical. A simple energy balance reveal that using such large amounts of conveying air can significantly reduce the reactor gas temperature. Table 4-1 summarizes energy balance calculations based on an initial reactor gas temperature of 2250°F and a conveying air temperature of 80°F. Two ways of defining injection temperature are possible. The first involves measuring the gas temperature at the injection point in the absence of conveying air and sorbent. The second involves measurement in the presence of conveying air and sorbent after the two streams have mixed. This second approach much more closely approximates the peak temperature experienced by the sorbent, and it has been found to be much more successful at correlating injection temperature results from a wide range of facilities.

TABLE 4-1. THE EFFECT OF CONVEYING AIR ON REACTANT GAS TEMPERATURE

Initial T, °F (°C)	Fraction Added, 80°F (27°C)	Mixed T, °F (°C)
2250 (1232)	.05	2140 (1171)
2250 (1232)	.10	2030 (1110)
2250 (1232)	.15	1925 (1052)

The effect of injection temperature on SO_2 capture for hydrated limes is shown in Figure 4-6 and the plotting symbols are explained in Table 4-2. Observed capture levels range from 25 to 65 percent. An absolutely critical point in resolving the optimum injection temperature from the various experiments is evaluating the peak temperature experienced by the sorbent. Plotted on this basis, the maximum utilization occurs at about 2100°F. The

TABLE 4-2. SYMBOL KEY FOR FIGURE 4-6

1. ▲ Teixeira, et al. (1986) 1 x 10^5 Btu/hr, gas fired, -450°F/s, 2500 ppm SO_2, 0.35 s, pressure hydrated dolomitic lime.

2. □ Muzio, et al. (1986) 1 x 10^5 Btu/hr, gas fired, -450°F/s, 2500 ppm SO_2, 0.35 s, Colton atmospheric hydrate, 5 μm.

3. ◇ Muzio, et al. (1986), atmospheric, alcohol-water hydrate, 2 μm.

4. ● Beittel, et al. (1986), 1 x 10^6 Btu/hr, Hallmark coal, -3600°F/s, 2200-3200 ppm SO_2, Longview atmospheric hydrate, 2 μm.

5. ◺ Newton (1986), 2.2 x 10^5 Btu/hr, gas fired, -870°F/s, 2000 ppm SO_2, 0.5 s, Linwood atmospheric hydrates, 2 μm.

6. ◗ EER-CTT, 9 x 10^4 Btu/hr, gas fired, -1000°F/s, 2000 ppm SO_2, Linwood atmospheric hydrate, 2 μm (data generated under EPA Contract 68-02-3633).

7. ○ EER-BSF, 1 x 10^6 Btu/hr, gas fired, -250°F/s, 1800 ppm SO_2, Linwood atmospheric hydrate, 2 μm (data generated under EPA Contract 68-02-3633).

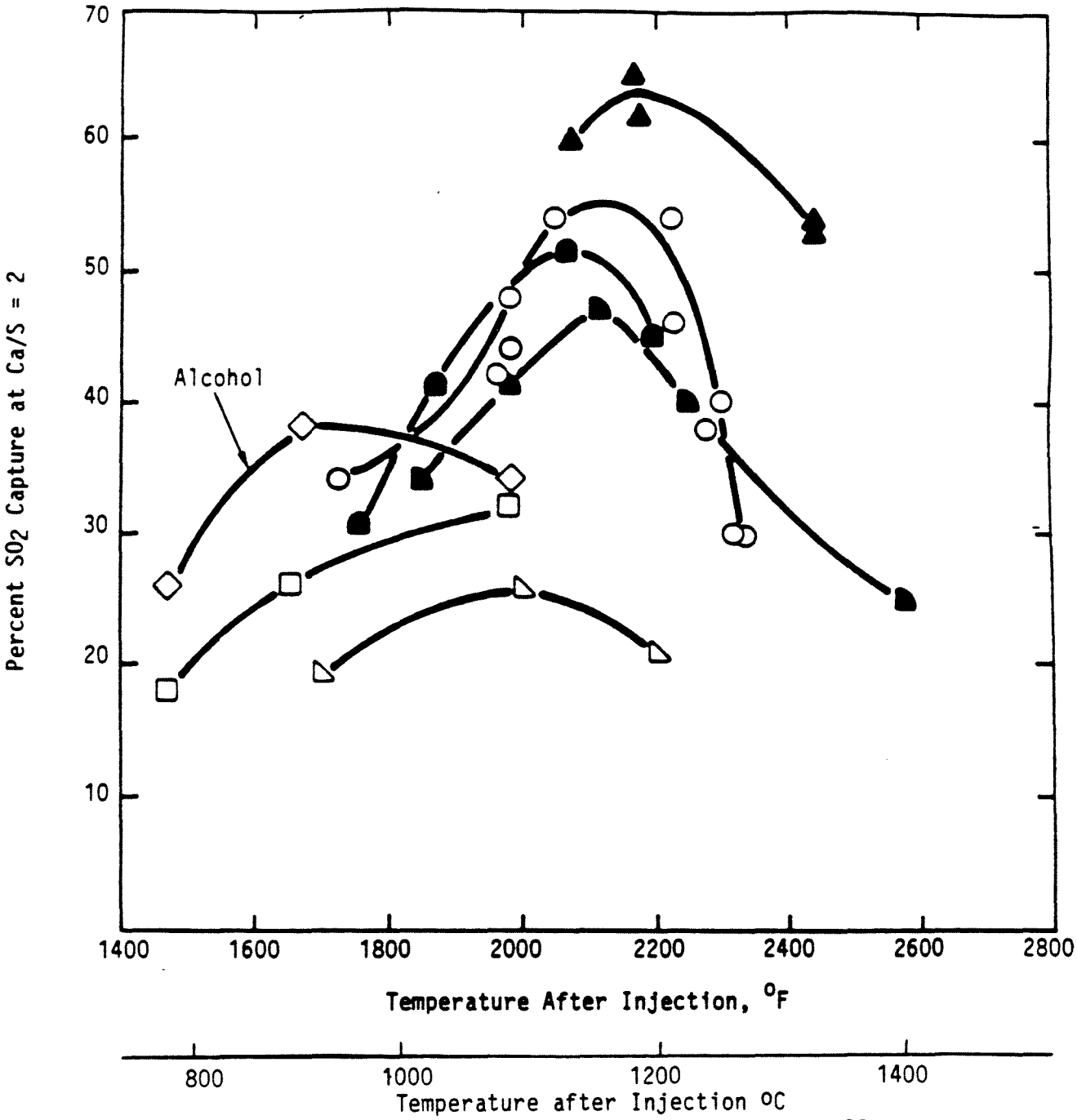


Figure 4-6. The effect of injection temperature on SO_2 capture at Ca/S = 2 for hydrated limes. See Table 4-2 for an explanation of the plotting symbols.

only sorbent which shows a markedly different optimum is an alcohol hydrate; these sorbents are thought to have an additional advantage at lower temperatures due to their high surface area, but they lose this advantage at higher temperatures due to accelerated sintering.

Section 4.1.2 described the mechanistic reasons for the existence of the 2050°F temperature peak.

Mixing Rate. The rate at which a sorbent mixes with combustion gases is known to influence SO_2 capture. This is shown in Figure 4-7 for capture in and isothermal reactor. Estimated mixing times and free stream Reynolds numbers are given for these three mixing systems in the figure. Note that in each case the final sorbent temperature is the same. Thus, the only variable is the rate at which the sorbent is mixed with the furnace gases. Here, the higher mixing rates lead to more "prompt" capture and higher final utilizations.

In an isothermal system the mixing rate can influence SO_2 capture in two ways. The first would be delaying the sulfation reaction. This can be seen in Figure 4-7 for capture by the Linwood hydroxide in the STR (Short Time Reactor). The overall mixing rate is approximately three times longer than in the ITR (Isothermal Reactor). The initial rate of capture is slower than in the ITR but reaches the same level of capture within ~0.3 s.

The second manner in which mixing rate can influence SO_2 capture in two ways. Heating of a sorbent injected into a hot environment is primarily by convection. The rate of sorbent heatup therefore occurs at the same rate as mixing does. Thus, lower heating rates require the sorbent to experience sub-sulfation temperatures for longer times. Figure 4-5 shows that exposure to cooler sulfation temperatures leads to porosity loss and reduced performance.

Figure 4-8 shows that mixing rate also influences the location of the sulfation window within isothermal systems. (The University of Utah (UOU)

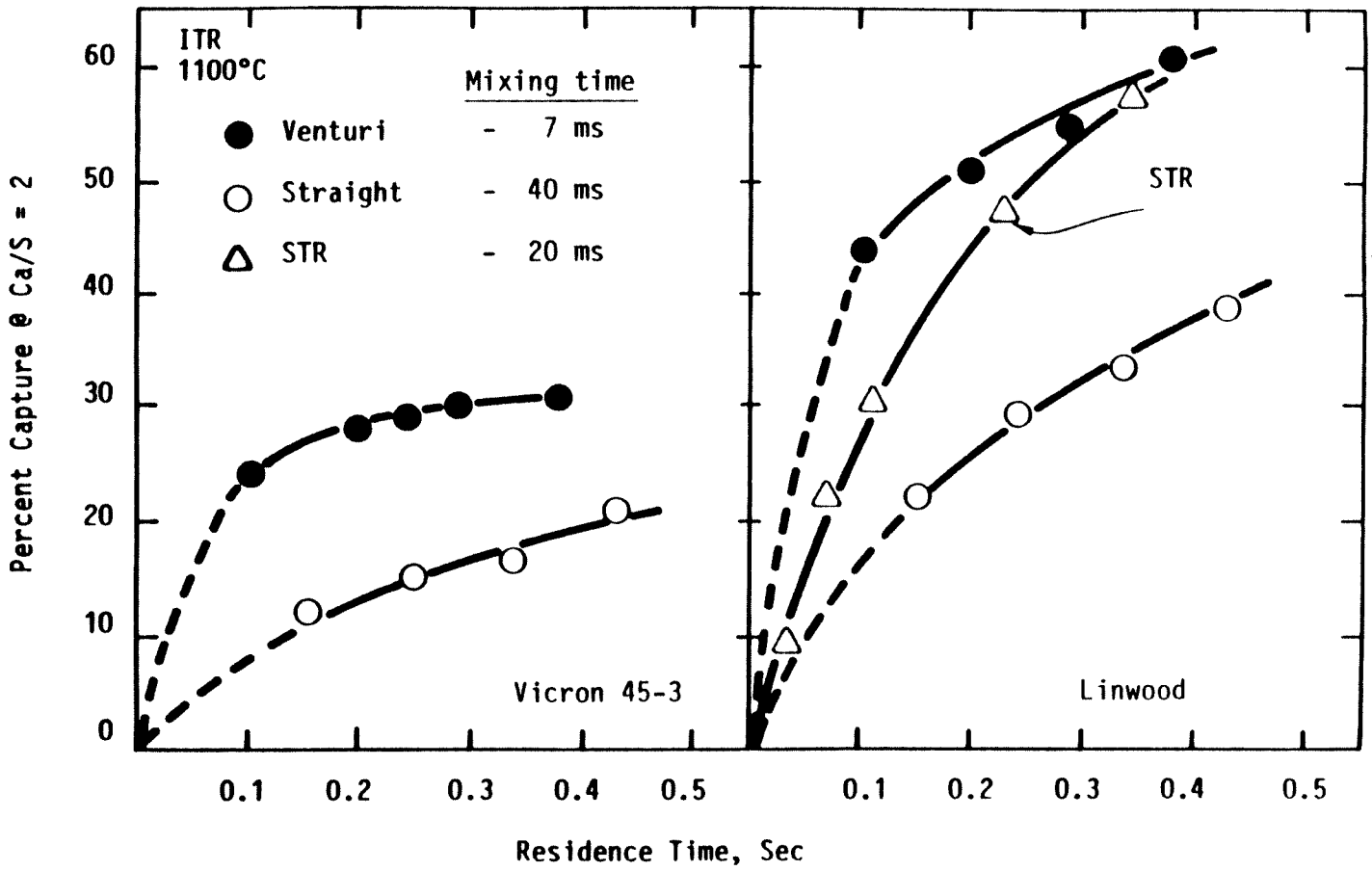


Figure 4-7. Influence of mixing rate on SO_2 capture by Vicron 45-3 and Linwood atmospheric hydrate. ITR is isothermal reactor, and STR is short-time reactor. Mixing rates are identified in Table 4-3.

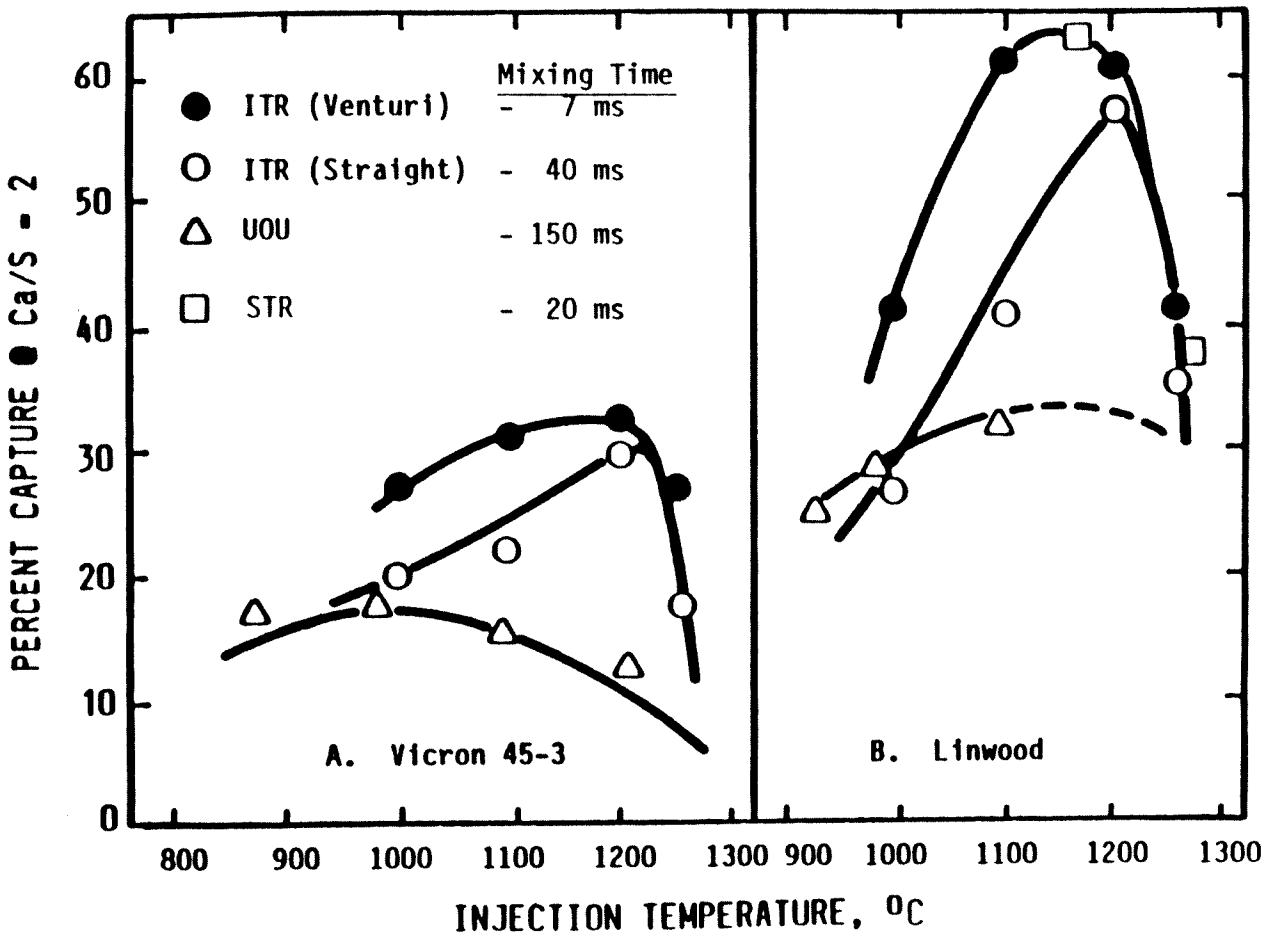


Figure 4-8 . Isothermal data demonstrating the influence of mixing in different furnaces.

data are for an extremely slow mixing time of 150 msec.) The tendency is for slower mixing rates to more severely affect the low-temperature side of the sulfation window. This is probably due to increasing the amount of time the sorbent spends at low sulfation temperatures; with higher injection temperatures the sorbent is moved through this low-temperature range with less damage.

Quench Rate. The quench rate in a furnace is also known to have a strong influence on SO_2 capture. Comparison of capture of a furnace with low and high quench rate environments (Figure 4-9) reveals that higher quench rates influence capture in two ways:

- The level of SO_2 capture is reduced and
- The temperature where maximum capture occurs is shifted to higher values.

A quenched thermal profile may be responsible for these trends in two ways. the first of these is that the slowing of kinetic and diffusional mechanisms in a high quench rate environment will "shut off" the sulfation process sooner. This type of effect explains the reductions in SO_2 capture observed but does not explain the shift in the temperature where maximum capture occurs.

The other manner in which quench rate can influence SO_2 capture is a result of the mixing process. Mixing of a cold jet in a hot environment does not always result in a steady increase in temperature. The various elements or eddies of the jet will retain their initial temperature until they encounter the hot gas stream where their temperature will rise abruptly to the ambient temperature. When injecting into a quenched environment eddies initially at the edge of the jet will mix immediately and attain the injection temperature. Eddies at the center of the jet will, however, make the transition from the jet temperature to the ambient temperature at a later time when, due to the quenched temperature profile, the ambient temperature is lower. Sorbent initially at the edge of the jet will therefore calcine at

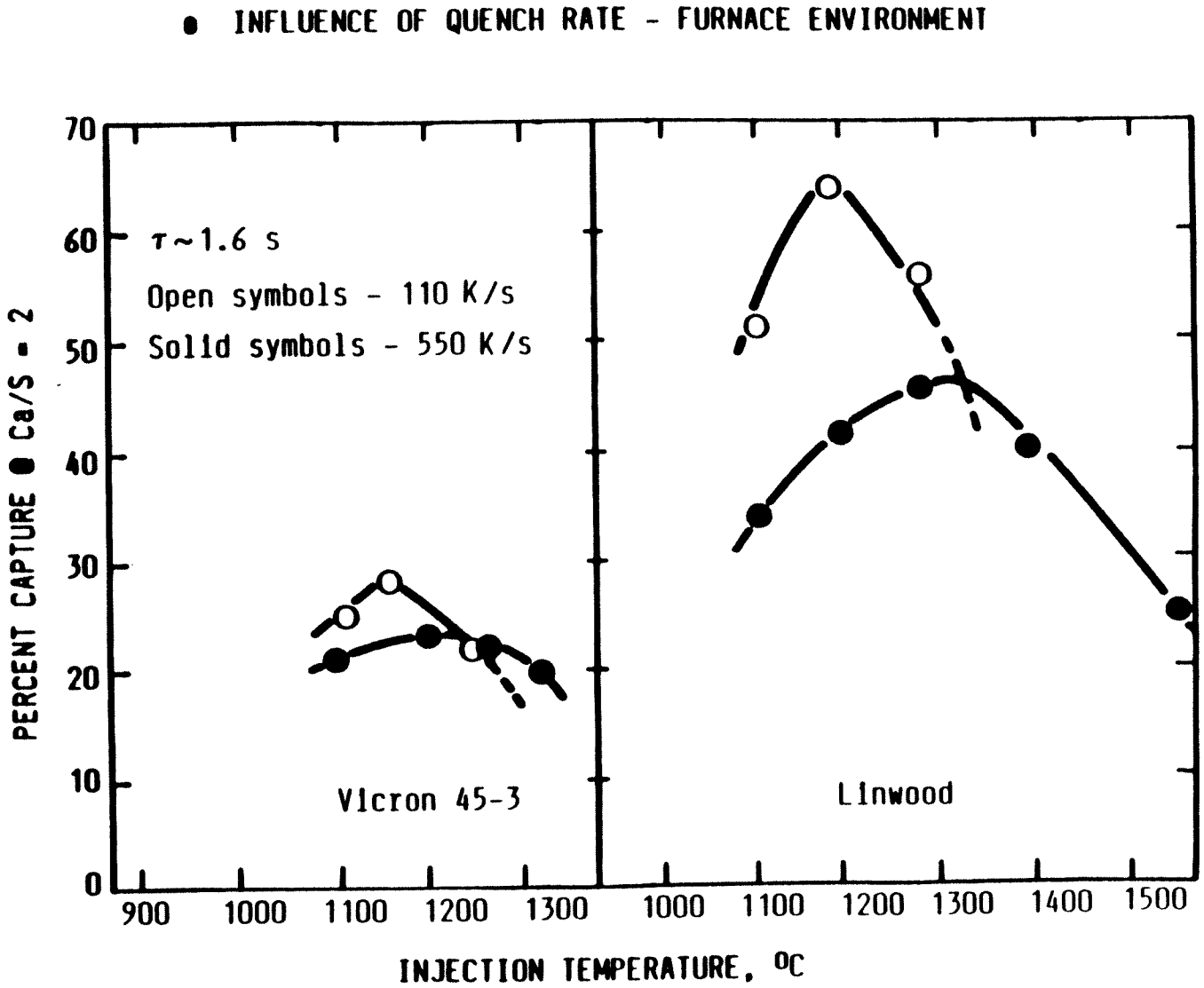


Figure 4-9. Influence of quench rate and injection temperature on SO_2 capture.

different temperatures than sorbent at the center of the jet. A distribution of sorbent porosities will result from a quenched environment.

This is illustrated in Figure 4-10. On the left SO_2 capture is plotted for three furnaces: the isothermal STR; the BSF, a furnace with a low quench rate; and the CTT with a high quench rate. All three furnaces have turbulent flow. On the right, mathematical fits of the calculated original porosities and tne measured porosities of sorbent sampled without SO_2 present from Figure 4-5 are plotted. In the isothermal case all of the sorbent is calcined at the same temperature and when injected at the optimum injection temperature it will have the maximum porosity obtainable. In the quench rate cases the sorbent sees a distribution of temperatures resulting in a distribution of porosities. In order to obtain the maximum average porosity possible it is necessary to inject at a temperature higher than the isothermal case. The injection temperature for a quenched furnace which yields the maximum possible porosity will be (assuming that mixing occurs evenly over the mixing period) that which yields an average sorbent mixed temperature equal to the optimum for an isothermal furnace, ~1180°C. For fixed mixing times, increasing quench rates will therefore require increasing sorbent injection temperatures. The distribution of porosities which occur in a quenched furnace will also result in an average porosity at the furnace's optimum injection temperature which is less than that possible in an isothermal furnace. Reduced capture levels will therefore occur. This explains (1) why the injection temperature for maximum performance shifts to a higher temperature, and (2) why the thermal window broadens.

Sorbent Type. Of the two general classes of sorbents, carbonates and hydroxides, the hydroxides have uniformly been the more reactive sorbents. Within each of these general classifications, there are also differences in reactivity between specific sorbents. The reasons for these differences are not yet fully understood.

One significant factor is particle size. Figure 4-11 shows that sorbent reactivity generally increases as particle size is reduced. This is generally considered to be a consequence of less sintering during activation

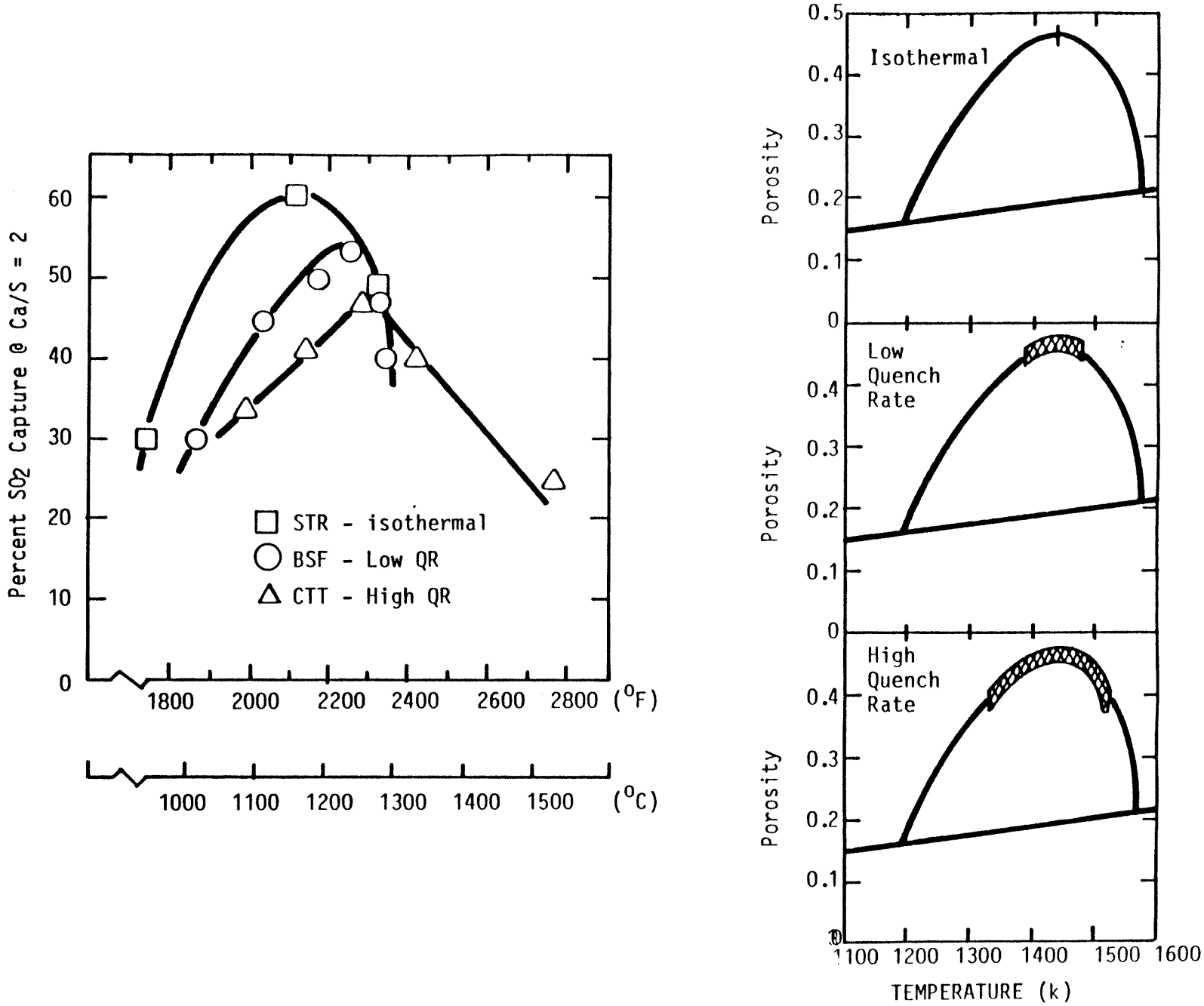


Figure **4-10.** Capture in differently quenched reactors. Data are from Silcox et al. (1987). Figures at right shows the calculated original porosity when SO_2 is present and the measured porosity when SO_2 is not present.

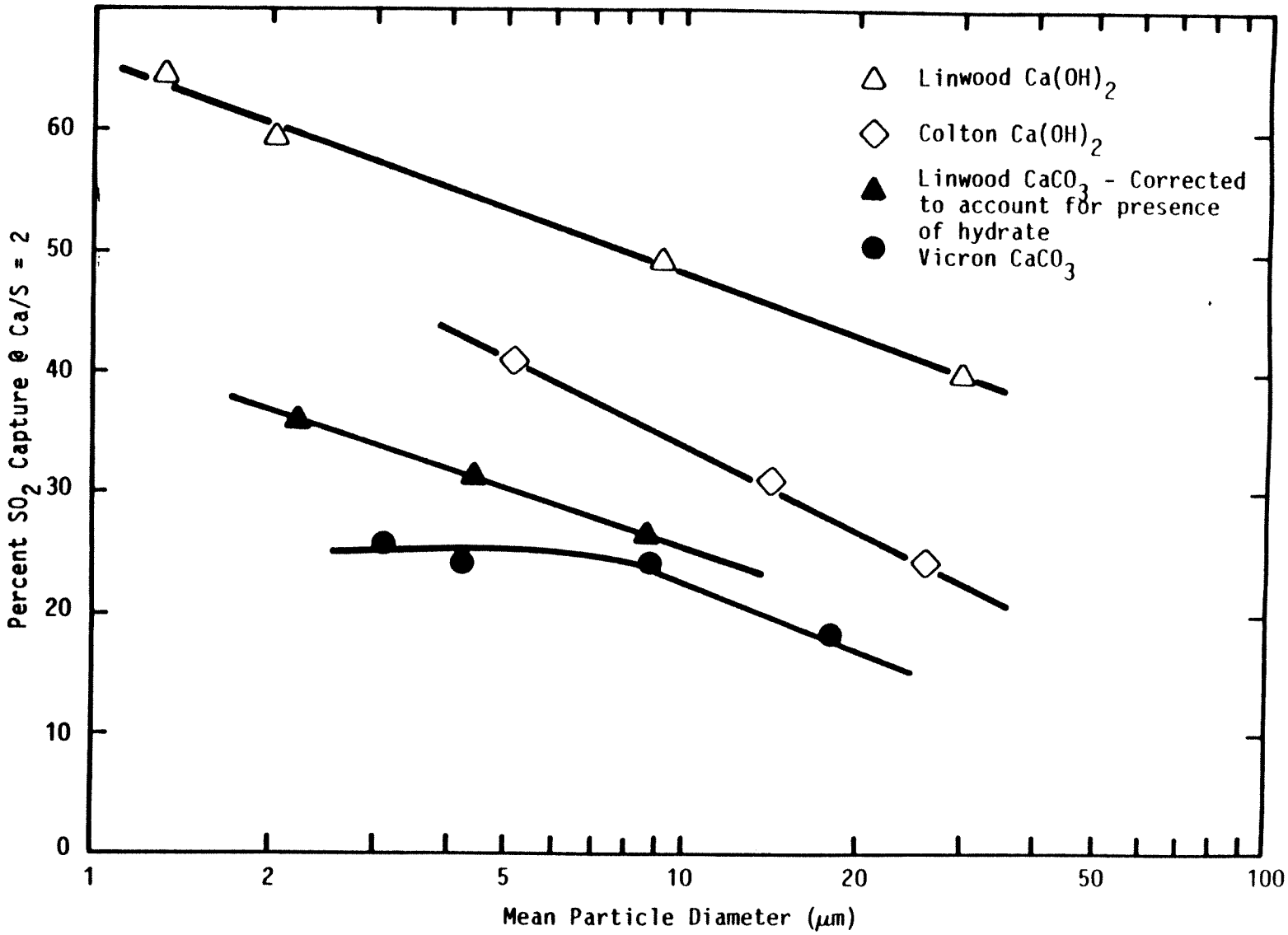


Figure 4-11. Comparison of sulfur capture for four different sorbents as particle size is varied.

(carbonates), and less pore diffusion resistance (all sorbents). Hydroxides are generally finer than carbonates, but Figure 4-11 shows that even on an equal size basis, the hydroxides are more reactive. Thus, particle size is an important parameter influencing reactivity, but it is not the only parameter.

Figure 4-12 presents the same capture data plotted against specific surface area for the raw materials. The trend is for carbonates as expected: the higher the raw surface area, the higher the measured SO_2 capture. This is due to the close correlation between particle size and specific surface area (which are correlated because most of the area is external). For hydrates, there is no clear correlation between raw surface area and sulfur capture. Potentially, good correlation could be achieved using surface areas of the calcined sorbent material, but reliable sampling and handling techniques have not yet been established for this measurement. At present, there is not a good understanding of what governs hydrate reactivity. It is known that raw hydrate particle size does not strongly correlate reactivity between different materials (note that Figure 4-11 was generated from a size fractionation of one sorbent). It is also known that hydration conditions can influence reactivity for the same starting CaO. for example, high-temperature hydration is generally detrimental. As stated above, attempts to correlate reactivity against the surface area of a low-temperature calcination product have not been conclusive. Some tests have indicated a positive correlation and some a negative. Thus, a major unexplored area remains the influence on reactivity of:

1. Raw material.
2. Calcination conditions (i.e., preparing the limestone in the kiln for hydration).
3. Hydration conditions.

4.1.4 Summary

At the fundamental level there are two general factors which are thought to govern sorbent performance. These are:

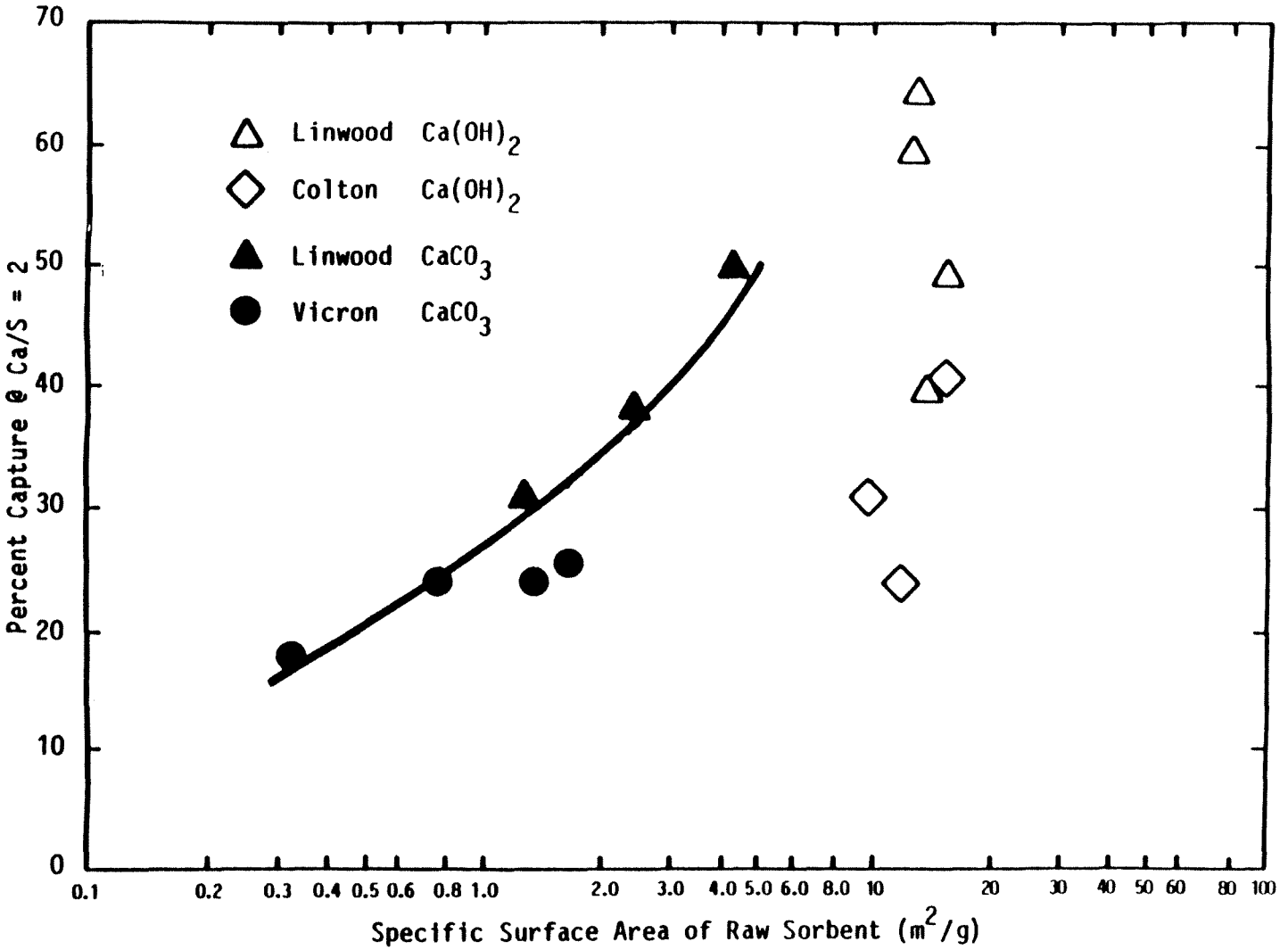


Figure 4-12. Comparison of sulfur capture for four different sorbents at varied specific surface areas.

1. Sorbent Reactivity. During calcination the sorbent particles develop a highly porous, reactive, and unstable CaO structure. To take full advantage of this structure, it must be immediately sulfated. This requires that the sorbent be rapidly brought to a temperature where the sulfation kinetics are rapid.

2. Sulfation Kinetics. Sorbent sulfation is primarily governed by the rate of SO_2 diffusion across the sulfate product layer that coats the CaO reagent. This diffusivity is strongly temperature dependent and it acts to limit the overall sulfation rate at low temperatures. At high temperatures (1300°C) sulfation becomes limited by the thermochemical stability of the sulfate.

The kinetics act to define the sulfation window. Within the window, it is largely the competition between reaction and desurfacing that determines capture.

From a practical point of view the various process parameters which act to control sulfur capture, principally through the above mechanisms, are:

- Injection Temperature. Where the appropriate temperature range is defined by the sulfation temperature window. Injection temperatures close to the upper limit of sulfation are generally more favorable, since these provide the fastest reaction rates. For most boilers the optimum temperature is on the order of 1200°C, though this will be influenced by quench rate, sorbent type, and injection parameters.

- Mixing. In large scale systems the ability to disperse the sorbent throughout the flue gases is important to ensure good contacting with the SO_2. Bench scale studies have also shown that mixing rate is important, where slower rates allow sorbents to calcine and sulfate under conditions which lead to porosity loss, and loss of reactivity. In full scale systems it is however seldom possible to

control mixing rate independently of requirements to achieve good penetration and dispersion across large boiler distances.

- Quench Rate. A high rate of temperature decay through the sulfation temperature window means that the injected sorbent will encounter a variety of thermal environments upon injection, and as a consequence utilization will suffer. Low quench rates are therefore beneficial for high sorbent utilization. Quench rate also impacts the optimum temperature for sorbent injection, higher temperatures being required at higher quench rates.

- Sorbent Type. Experience has shown that dolomitic sorbents are generally more reactive than calcitic hydrates, which are in turn more reactive than limestones. This is true even when particle size is identical. Although for limestone there is some correlation between particle size and reactivity, in general the factors that determine reactivity are poorly understood. There is no good correlation between readily measurable raw sorbent parameters, such as particle size, surface area and porosity, and a sorbent's ability to capture SO_2.

- SO_2 Concentration. Since sulfation is a kinetic process, sorbent utilization will depend upon the available SO_2 concentration driving force.

4.2 Comparison of Sorbent Injection SO_2 Removal Data

From the foregoing discussion of the parameters which impact SO_2 removal by injected sorbents, it can be seen that removal efficiency will depend upon a number of variables related to boiler design and operation, the injection system itself and the type of sorbent used in the particular application. Since the demonstration projects in this study were conducted on boilers of very different designs, using different coals and sorbent materials, substantially different SO_2 removal performance was to be expected. This potentially leads to difficulties in comparing test results from different

boilers on an equivalent basis. Prior to actual demonstration testing a number of pre-evaluation studies were carried out, to determine the reactivity of the sorbents used, and to predict SO_2 removal performance as a function of the different boiler designs and operational characteristics. This section of the report will briefly review the results of these evaluations and will summarize the main results of sorbent injection testing, in terms of SO_2 removal, the effects of major variable parameters, and impacts on boiler operation. A subsequent section will discuss the implications of the results.

4.2.1 Sorbent Reactivity Testing

As discussed in the preceding sections a key parameter in determining overall SO_2 removal is the reactivity of the sorbent materials used. Experience to date has shown that different sorbent materials (even when these are of the same basic sorbent type) exhibit differing levels of reactivity towards SO_2, and that reactivity cannot be determined directly from easily measurable sorbent properties. In this project, each of the various sorbent materials considered for use in the different demonstration projects was subjected to testing in a 15 kW bench scale experimental furnace, to determine relative reactivity from measurements of SO_2 removal as a function of added sorbent flow rate. The test furnace was operated under conditions which provided for sorbent injection at a point where the local gas temperature was approximately 1250°C, and where the temperature decay rate subsequent to injection was controlled to 240°C/second. Two kinds of tests were conducted: with the furnace fired on natural gas, doped to yield a constant flue gas emission of 2000 ppm SO_2; and with the furnace fired on corresponding coals which were used in each of the demonstration projects. The measurements under gas fired conditions provide for a carefully controlled environment where the SO_2 removal data may be used directly to compare sorbent materials and to rank them in terms of their relative reactivity. Measurements under coal fired conditions relate to an environment more directly comparable to that experienced in the actual boiler, and provide data from which reactivity parameters can be derived for the prediction of expected boiler performance.

A total of thirteen commercial sorbent materials have been evaluated in this project; these comprised nine limestones ($CaCO_3$), three hydrates ($Ca(OH)_2$), and one dolomite ($CaCO_3 \cdot MgCO_3$). Experimental screening results for natural gas fired conditions, 2000 ppm SO_2, and an injected calcium to sulfur molar ratio of 2 are presented in Figure 4-13. This figure identifies the different sorbents by sorbent type and by country of origin. Previous data for one of the sorbent materials used in the Edgewater project, and the range of measurements previously recorded by EER for different sorbent types, are also included in the figure for comparison. The results presented in Figure 4-13 confirm the generally accepted trend in reactivity with sorbent type, in that the dolomite shows the highest SO_2 removal, followed by hydrates and limestones. The data also show significant variations between sorbents of the same type, as evidenced by a difference of almost a factor of two between the best and worst Swedish limestones. Indeed, some of the limestones tested under this project have exhibited the highest reactivity ever recorded in this experimental furnace.

When the sorbents are subjected to a coal fired environment the SO_2 removal rate (sorbent reactivity) may vary for two main reasons; due to changes in the baseline SO_2 concentration; or due to changes in thermal conditions as a result of different combustion characteristics or ash deposition on heat transfer surfaces. In the experimental furnace, thermal conditions can be more closely controlled and performance was found to be dependent more on SO_2 concentration. This is illustrated in Figure 4-14 where experimental SO_2 removal rates are presented for all coal/sorbent tests, relative to data for natural gas and a constant 2000 ppm SO_2. These results indicate that all the sorbent materials follow a similar trend, and suggest a significant impact of SO_2 concentration when the initial value is below 1000 ppm, but a relative insensitivity when the initial SO_2 concentration is above 2000 ppm. This trend is comparable with previously reported data and is consistent with the sulfation kinetics.

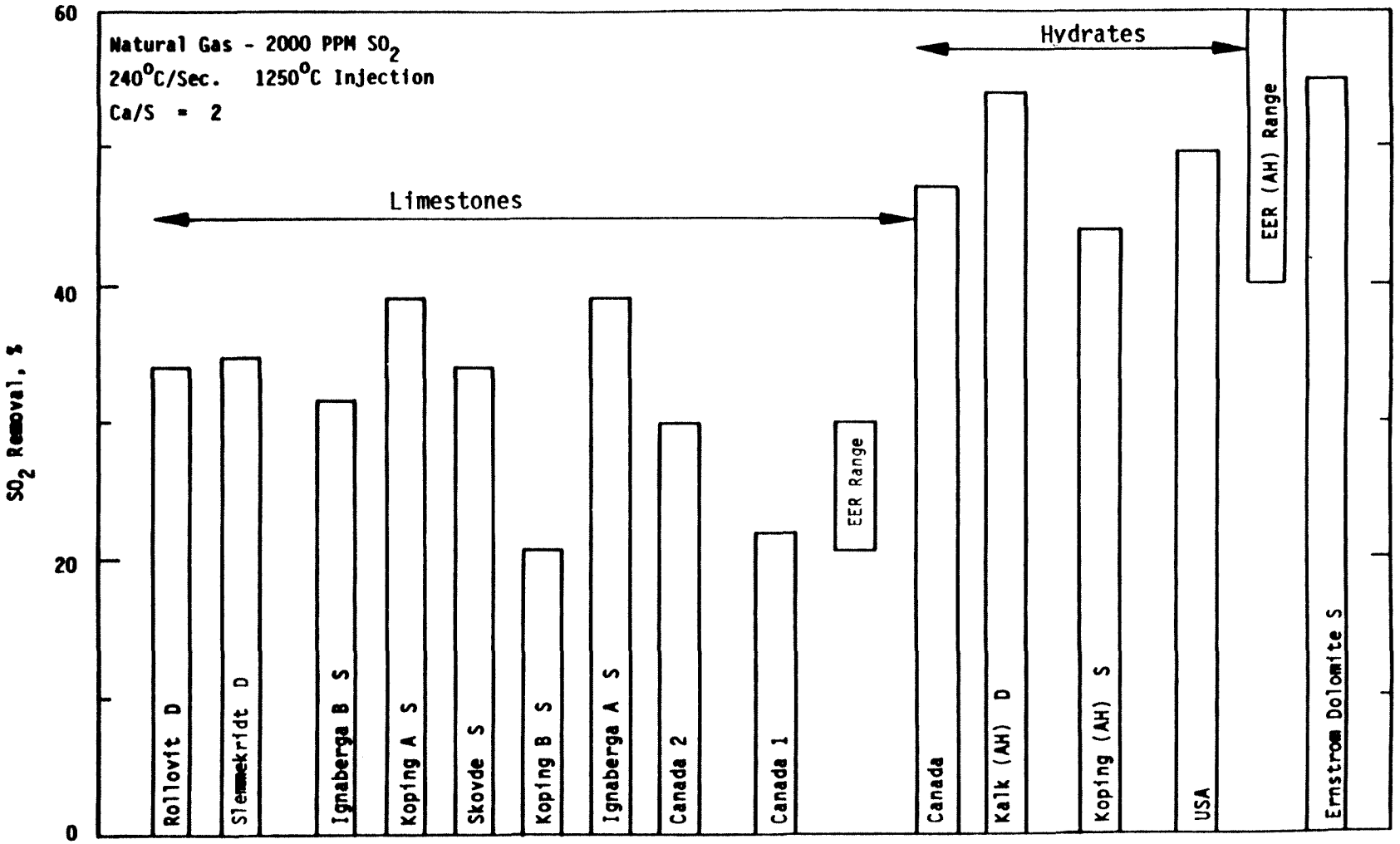


Figure 4-13. Relative SO_2 removal performance of different sorbents - bench scale data.

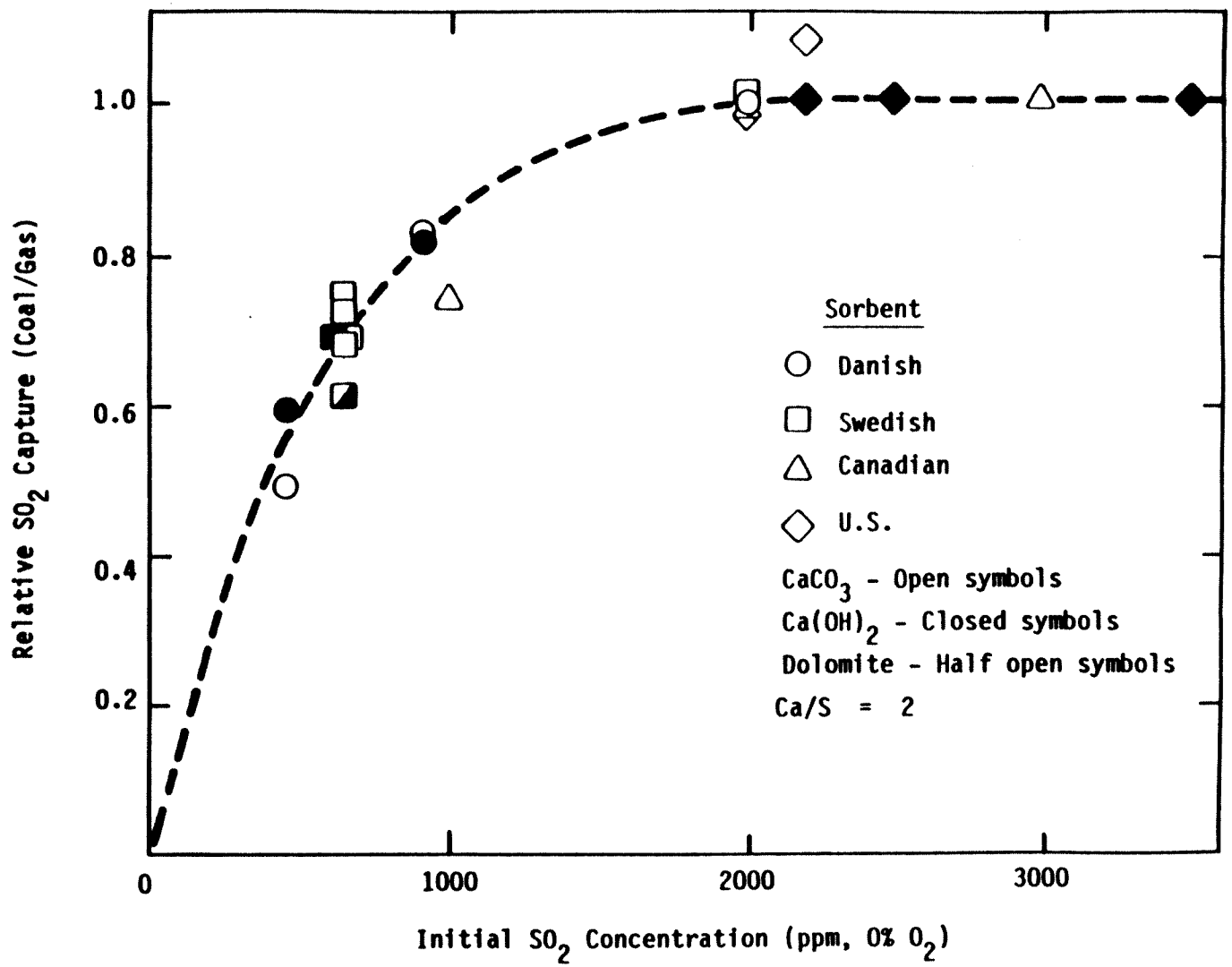


Figure 4-14. Effect of initial SO_2 concentration - relative SO_2 capture - experimental data.

4.2.2 Performance Prediction and Sorbent Injection System Design

The application of sorbent injection as an SO_2 control technology to specific full scale boiler systems requires an ability to predict performance. This is both to determine the level of SO_2 removal which can be expected under given circumstances, and to permit optimization of process variable parameters for maximum removal efficiency. In recent years EER has developed a methodology for performance prediction and system design which takes full account of the various process controlling parameters discussed in previous sections. The methodology employs a combination of heat transfer modeling, isothermal flow modeling and sorbent sulfation modeling, and has been applied to each of the boilers which have been incorporated into this IEA project.

The heart of the methodology is a model of the sorbent sulfation process. This model predicts sorbent utilization and SO_2 removal according to sorbent specific and application specific parameters. Typical model inputs required include: the initial temperature in the boiler at which the sorbent is injected; the subsequent temperature vs. time history of the sorbent; a mixing rate term which describes a characteristic of the injection system; flue gas composition, and sorbent specific reactivity parameters. The model uses these parameters, together with sulfation rate equations and a model of the sorbent activation process (according to the description in Section 4.1.2) to predict sorbent utilization. Here it should be noted that specific sorbent reactivity parameters cannot be determined fundamentally or directly from raw sorbent data. In this approach reactivity is back - calculated form measured SO_2 removal data for specific sorbents under well characterized conditions. This is usually obtained form bench scale experiments as described in the previous section. Boiler and injection system specific data such as temperature, temperature profile and mixing characteristics can be obtained from the interpolation of measurement data or from appropriate models.

For a boiler application where little information is available the initial the approach to sorbent injection system design and performance

prediction involves three main elements: boiler heat transfer modeling, sorbent sulfation modeling, and isothermal physical flow modeling.

In the first instance a heat transfer model is set up for the specific boiler design and operating conditions, and is used to predict temperature profiles and temperature/time characteristics for the boiler under a range of relevant boiler loads. This information is used to identify elevations in the boiler which are expected to be favorable for sorbent injection. Calculated temperature profiles for the five boilers in this study have been presented in Figure 2-13.

A reduced scale plexiglass model is then constructed to permit evaluation of the flow field and injection characteristics. The approach to sorbent injection design is usually relatively empirical, where injector characteristics are tailored to the specific flow field and injection elevations by using a variety of tracer techniques to evaluate mixing as a function of the variable injection parameters. This information is then used to specify design parameters for the full scale system in terms of the number of injection nozzles, nozzle placement, size and velocity, tilt, etc.

In a final element of the procedure, sorbent injection parameters are used to readjust the calculated temperature profiles to allow for the impact sorbent injection on temperature vs. time characteristics. Sulfation modeling is then applied to predict SO_2 removal based upon the specific boiler thermal characteristics and sorbent reactivity data derived from a bench scale evaluation. Sensitivity studies may then be conducted to permit optimization of injection parameters, (e.g. injection elevation) for maximum anticipated SO_2 removal.

The above procedures have been applied to each of the five boilers on which sorbent injection testing has been carried out. Boiler temperature profiles were determined from heat transfer modeling studies as shown in Figure 2-13, injection parameters were determined in isothermal flow models, and respective sorbent reactivity was determined in the experimental furnace as shown in Figure 4-13. Results for the prediction of SO_2 removal

performance for the different boilers are presented in Figure 4-15, for limestone and $Ca(OH)_2$ sorbents at an injected Ca/S molar ratio of 2.0. The variable parameter on this figure is the mean gas temperature at the sorbent injection plane. This can vary if the injection elevation is changed, or for a fixed injection location the injection temperature may change as a function of boiler load or as a result of other operating variables. It can be seen from Figure 4-15 that the maximum SO_2 removal expected in each of the boilers is different due to unique combinations of the parameters:

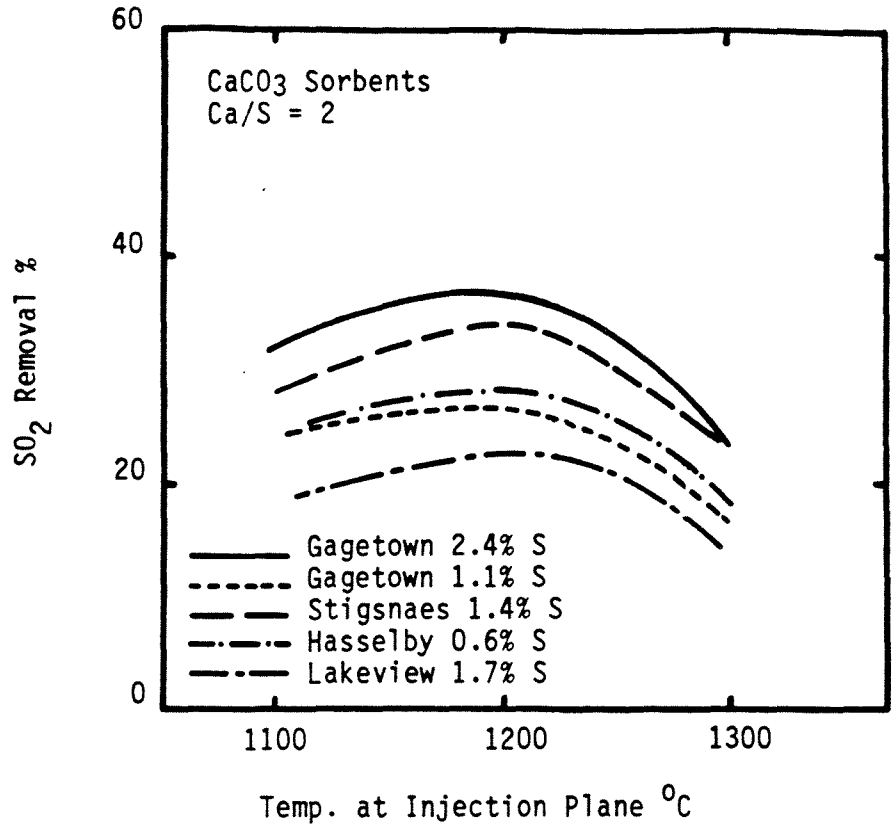
- Boiler temperature profile
- Sorbent characteristics
- Coal sulfur content.

4.2.3 Summary of SO_2 Capture Data

This section of the report will present brief summaries of the sorbent injection testing carried out at each of the boiler demonstration sites. The main emphasis will be on SO_2 capture and the effects of major test variable parameters.

Gagetown

The method of sorbent injection employed at Gagetown was different from the other boilers in this project, in that sorbent injectors were located on the axes of the tertiary air ports around each of the low-NO_x burners. Although this injection method provides good mixing of the sorbent with the flue gases, in most boilers the sorbent will see excessive temperatures when injected in the burner zone and will therefore lose reactivity. However, the moderate bulk temperature levels which characterize the Gagetown boiler (Figure 2-2) were considered to be most favorable, since peak temperatures outside of the main flame zones were predicted not to exceed 1550°K. Moreover, the flow field is characterized by large recirculation zones above and below the burners, and the mean temperature quench rate (250°C) is quite moderate, both of which are expected to advantageous to good sorbent utilization.



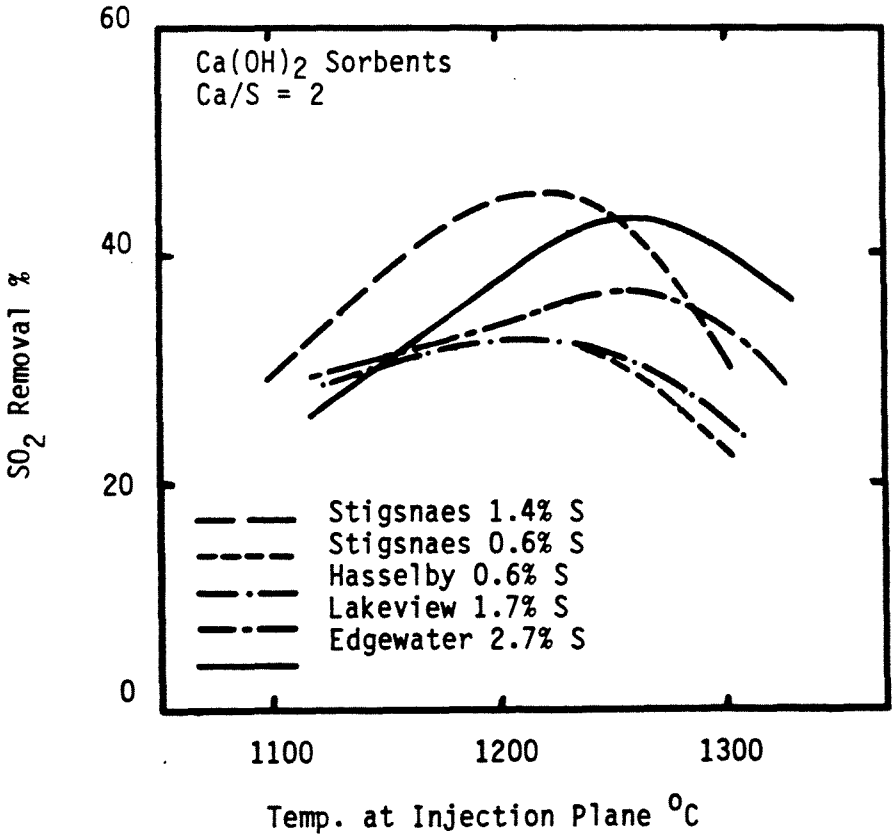


Figure 4-15. Predicted SO_2 Removal.

Testing at Gagetown was carried out exclusively with a limestone sorbent. Experimental evaluation of this material had shown it to be of comparatively low reactivity (Figure 4-13, Canada 1) probably due to a relatively coarse particle size. SO_2 removal data obtained during the Gagetown sorbent injection tests are summarized in Figure 4-16, which shows capture as a function of the added limestone rate. Date are presented for high and low sulfur coals, and show a substantial impact of coal sulfur content, reducing SO_2 capture from about 40 percent to 20 percent at Ca/S = 2 for 2.4 percent and 1.2 percent sulfur coals respectively. These data are generally commensurate with expectations based on temperature levels and sorbent reactivity. Also shown on Figure 4-16 is one data set where the limestone sorbent was blended with the raw coal and passed through the coal pulverizer. This method of sorbent injection results in a significant reduction in SO_2 removal, since the sorbent is now exposed to full peak flame temperatures in the combustion zone.

Hasselby

As discussed earlier, sorbent injection at Hasselby was accomplished through a series of six ports located at the 19.3 m elevation in the boiler. This elevation had been selected as the optimum location based on earlier heat transfer analyses where a mean temperature of approximately 1220°C was expected. The injection system provided for variable injection velocity (30-60 m/s) and injector tilt over the range -15° to +15°. Testing was carried out with four different sorbent materials:

- Limestone (Koping, 0-50 microns)
- Hydrated Lime (Koping)
- Dolomite (Glanshammer, 0-80 microns)
- Dolomite (Glanshammer, 0-10 microns)

Polish coal with mean sulfur content of 0.5-0.7 percent was used throughout the tests, and other variables tested included boiler load, and low or high - NO_x settings at the burner.

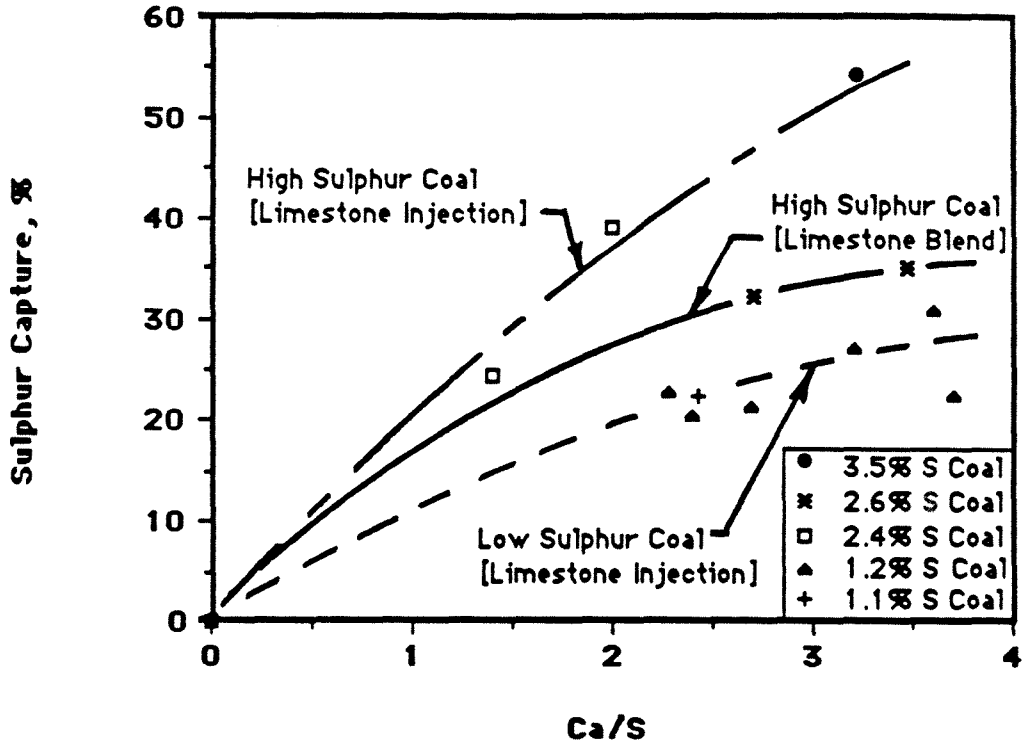


Figure 4-16. Summary of Gagetown sorbent injection data.

For each sorbent type, three different test series were conducted. Namely, initial function tests, parameter optimization tests, and finally long term tests at fixed conditions to determine impacts on plant operation. The results of SO_2 removal data generated in these tests are presented in Figure 4-17, 4-18 and 4-19, for each of the main sorbent types and for full and reduced boiler loads. In spite of high sorbent reactivity, comparatively low SO_2 removal rates had been expected for this boiler, primarily because of the low sulfur content of the Polish coal. However, under full load conditions, measured SO_2 removal rates were some5-10 percentage points lower than had been predicted under optimum conditions. Subsequent temperature measurements at the injection elevation indicated temperature levels up to 1300°C, suggesting that the boiler was operating hotter than had originally been anticipated and that injectors were too low in the furnace. Support for this premise was found in the effects of varying injector tilt. At full load changing the tilt from -15° to +15° increased capture from 17 percent to 23 percent, while at low load there was no impact. From the estimated temperature profiles these observations would suggest that the injectors are located at least one meter too low in the furnace to achieve optimum SO_2 capture for the nominal load range. All subsequent tests were run with +15° tilt at full load and zero tilt at low load. The other variable parameters, injection velocity and burner settings, were found to have relatively minor effects on overall SO_2 removal.

The main results of the Hasselby sorbent injection tests are summarized in Table 4-3 below which shows nominal SO_2 removal rates for sorbent injection at Ca/S = 2.

TABLE 4-3. SUMMARY OF HASSELBY SO_2 REMOVAL DATA

SORBENT	SO_2 Removal % (Ca/s = 2)	
	Full Load	Reduced Load
Limestone	15	28
Hydrated Lime	20	30
Dolomite 0-80 Microns	30	34
Dolomite 0-10 Microns	47	-

From these results the relative ranking of the different sorbent material is readily seen, and the superiority of the fine Dolomite (0-10 microns) is apparent. For the limestone sorbent, and from the data presented in Figure 4-17, it will be noted that SO_2 removal rates obtained during the long term tests were substantially better than in other test periods. The reasons for this were extensively evaluated but satisfactory explanations could not be found in any of the boiler data, operating conditions, or analytical equipment performance. Similar trends were not observed for the hydrate and dolomite during the same testing period.

Stigsnaes

On the Stigsnaes boiler, sorbent was injected into the furnace through eight injection nozzles on the boiler front wall, located at an elevation just above the boiler nose plane. The majority of the testing was conducted at 95 percent boiler load (142 MWe) with the U.S. coal (1.4 percent S) and limestone sorbent. Initial testing carried out at Stigsnaes was in the nature of parameter screening tests, designed to optimize injection and operational variables for SO_2 removal. The results of the parametric tests were:

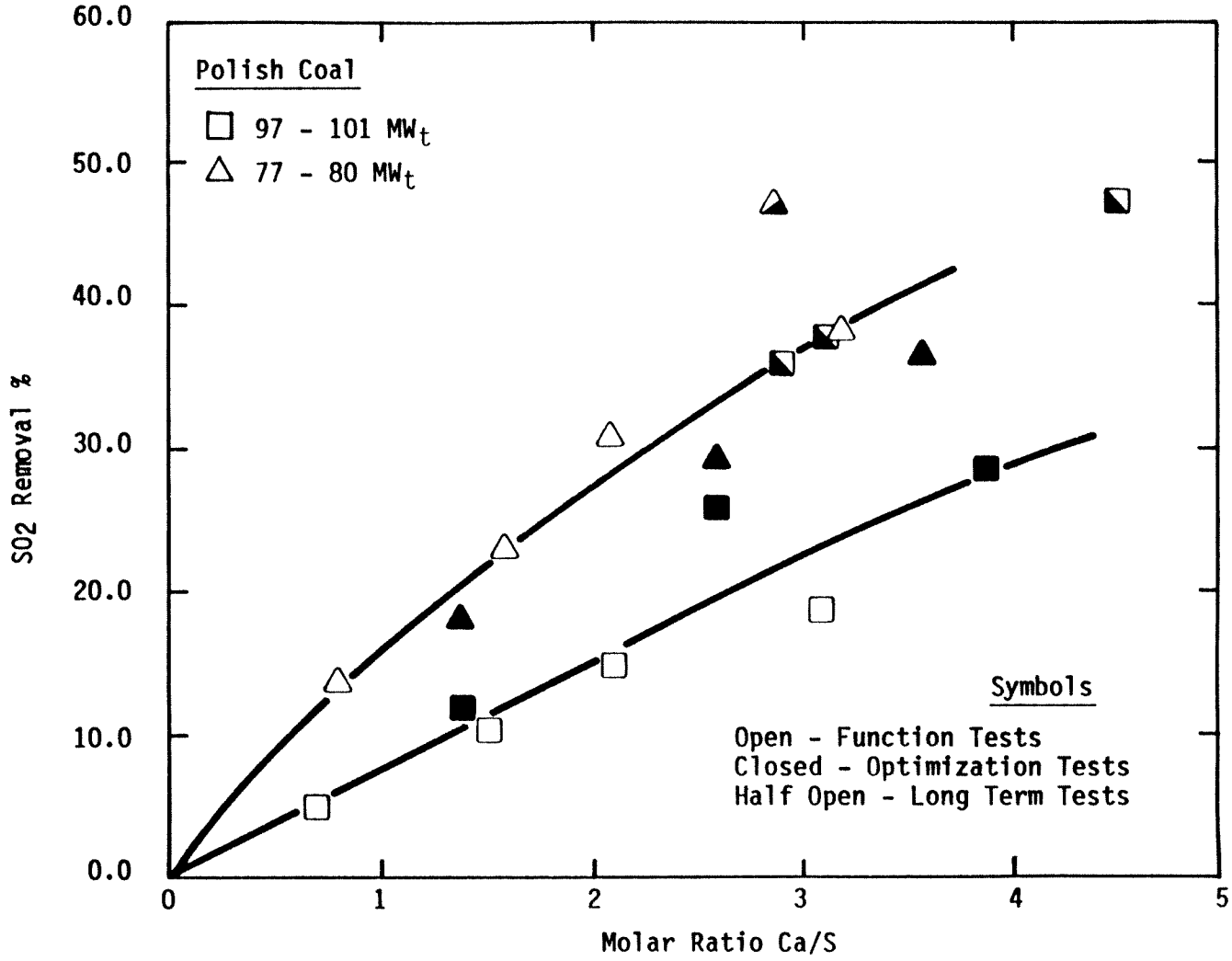


Figure 4-17. Hasselby SO_2 removal data - limestone.

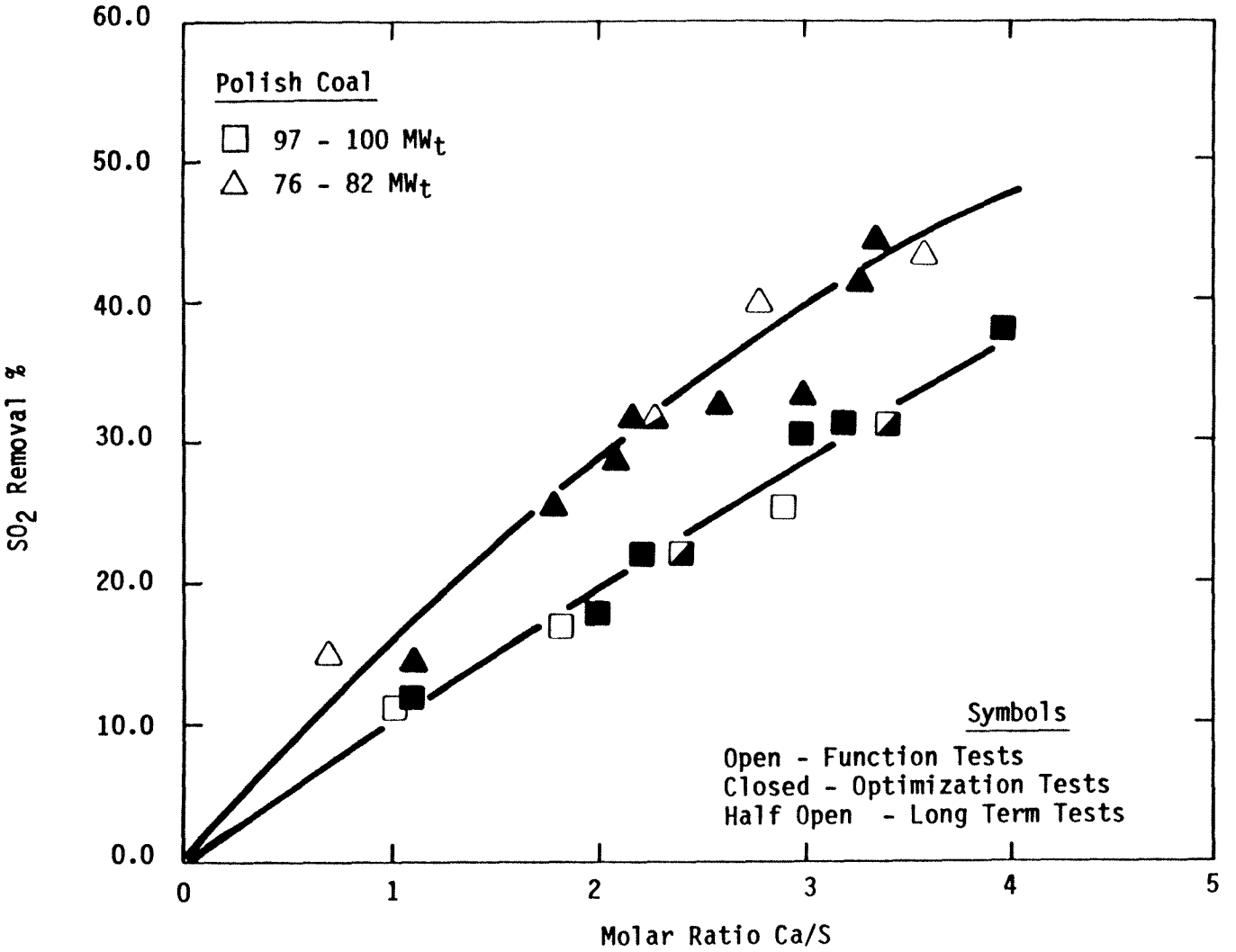


Figure 4-18. Hasselby SO_2 removal data - hydrated lime.

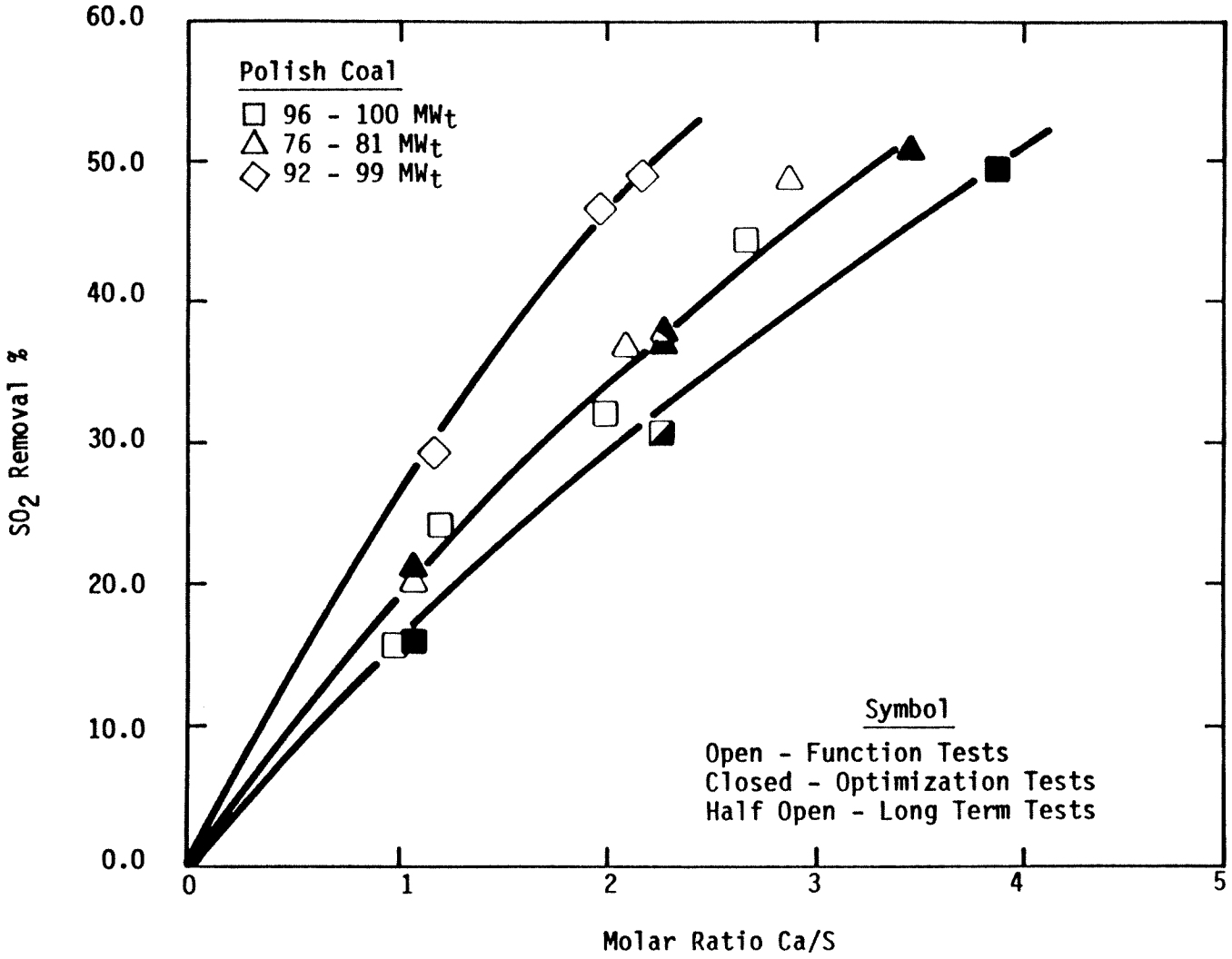


Figure 4-19. Hasselby SO_2 removal data - dolomite (◇, 0-10 microns, △ □, 0-80 microns).

Injection Velocity and Injection Angle. Injection velocity was varied over the range 50-115 m/s, and injection angle from 0 to -45°. At full load operation neither of these parameters was observed to have a significant impact on SO_2 removal performance. However, at low load (66 percent) the best performance was found with high velocity and maximum downwards tilt. These observations suggest that the selected injection location is close to optimum for full load operation. At low load, local temperatures are perhaps too low, and downwards tilt helps to place the sorbent in a more favorable temperature regime.

Number of Injectors. Tests were conducted using all eight of the installed injectors, four center injectors and four wing injectors. These various combinations were found to have only a small impact on the SO_2 removal levels measured.

Burner Settings. When changing from high-NO_x to low-NO_x burner settings little difference in SO_2 capture was noted, confirming earlier observations of no measurable impact on upper furnace temperatures.

Burner Levels in Operation. The SO_2 capture was found to be more dependent on which elevations of burners were in service, due to variations in mean furnace exit temperature. Higher SO_2 removal rates were generally observed when the upper and lower burner elevations were in service, with lower removal rates when the two upper elevations were in service. Results with all three and the two lower elevations were generally comparable and intermediate.

Test results for U.S. coal, limestone injection and three burner elevations in service are presented in Figure 4-20 and show sulfur capture as a function of injected Ca/S ratio. During the long term (50 hours) test SO_2 capture data were observed to be higher than in earlier parametric tests, and ranged from 35 - 43 percent removal at an average Ca/S of 2.15. In this period SO_2 capture values were observed to be highest immediately after

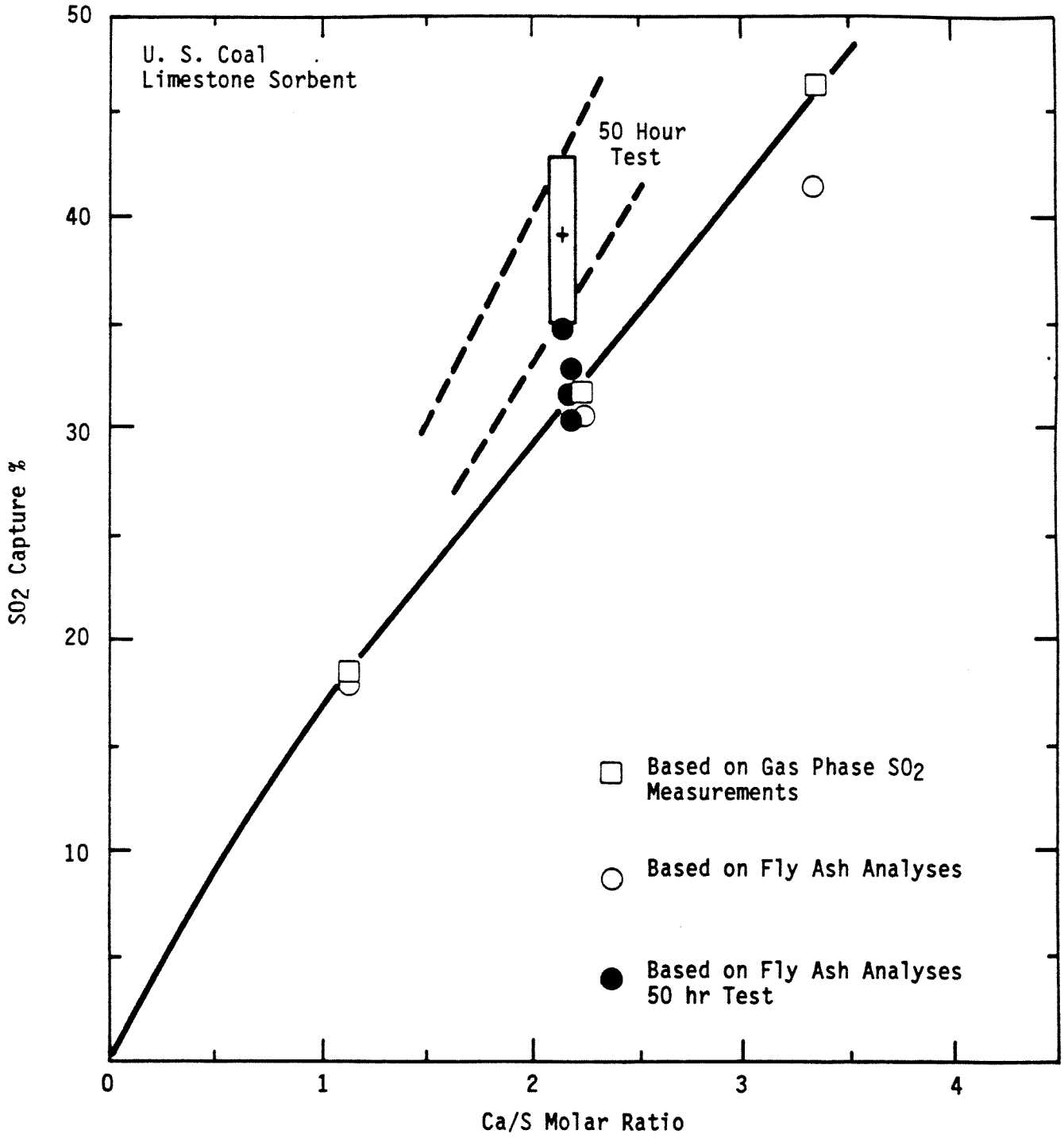


Figure 4-20. Stigsnaes data - SO_2 capture with U.S. coal - parametric and 50 hour tests.

furnace soot blowing, when upper furnace temperatures are lowest. Superimposed on the gas phase data of Figure 4-20 are SO_2 removal rates calculated from analysis of fly ash samples obtained during the respective test periods. These values are in generally good agreement with data obtained during parametric testing, but are somewhat lower than the average of the 50 hour test. This potentially implies that incremental SO_2 capture may occur on sorbent material which is deposited on tube surfaces over long periods of time. Indeed, a limited number of ash samples taken from tube surfaces during the 50 hour test showed high levels of sulfation (up to approximately 14% sulfur), which would tend to support this possibility.

Limited sorbent injection testing was also carried out with the other coal types fired at the Stigsnaes plant. The results of these tests for full load operation are summarized on Figure 4-21, where SO_2 removal is plotted as a function of the baseline SO_2 concentration. These data show a strong correlation with SO_2 concentration, which is in good agreement with that obtained during bench scale characterization of the different sorbents (Figure 4-14). Only the Polish coal falls significantly outside the expected trend.

Only one data point was obtained at Stigsnaes with an alternate sorbent which was a hydrated lime. This was with Polish coal and an injection rate of Ca/S = 3.8, where SO_2 removal was improved to 44 percent compared to 33 percent with limestone.

Lakeview

Sorbent injection at Lakeview was carried out through six injection nozzles located on the boiler at the 360 ft (109.7 m) elevation. All testing was carried out at a boiler load of approximately 235 MWe, which represents 78 percent of the nominal MCR for this unit. At 235 MW, heat transfer modeling, supported by temperature measurements on the boiler, indicated a mean temperature of approximately 1230°C at the 360 ft elevation, which is considered to be close to the optimum for sorbent injection. At an MCR of 300 MWe however, predicted mean temperatures were close to 1310°C which would

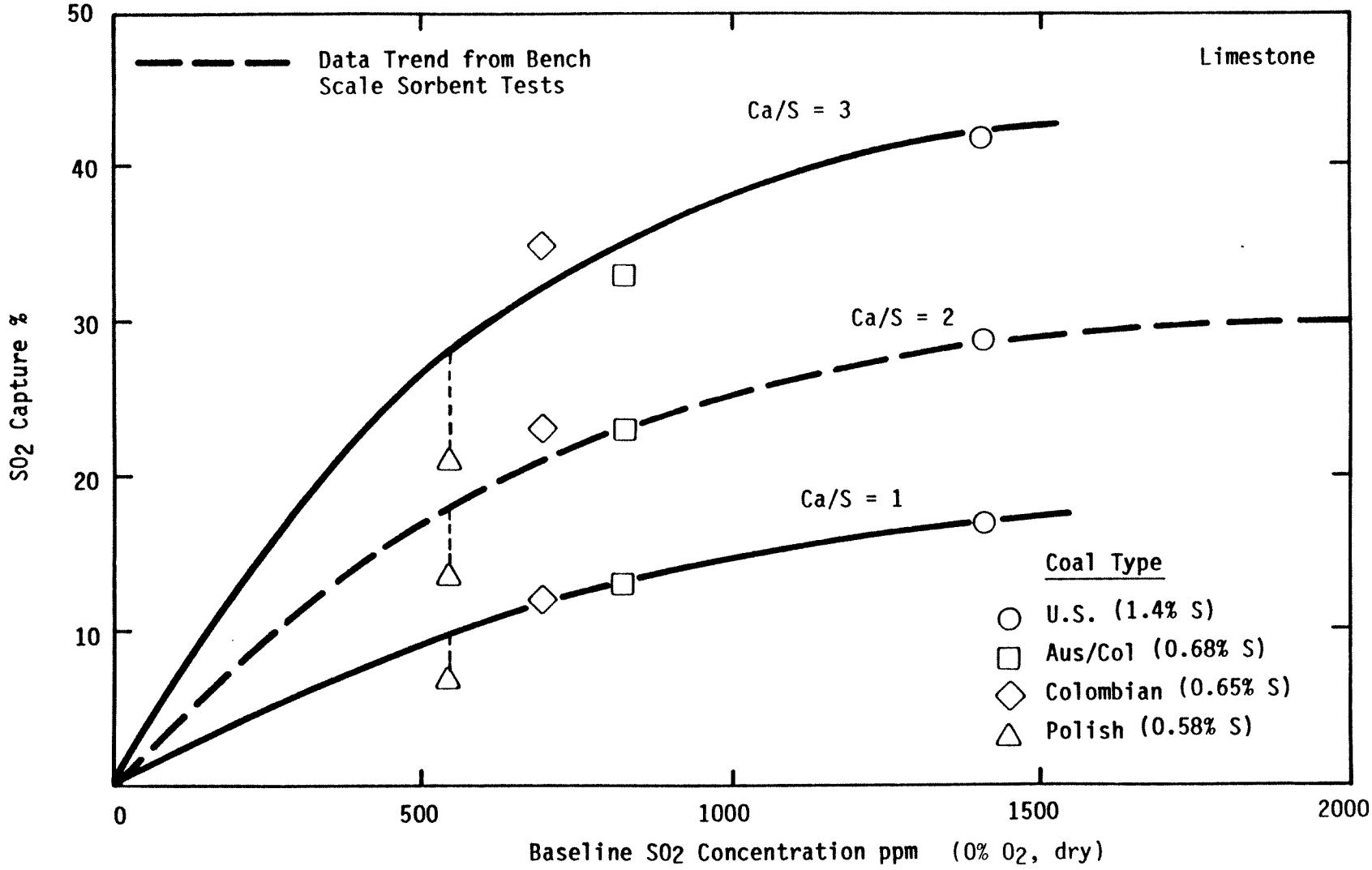


Figure 4-21. Stigsnaes data - effect of coal type (SO_2) on sulfur capture - 142 MWe.

be expected to result in significant deactivation of the sorbent. Injection at higher elevations in the boiler would probably not be effective because of the proximity of the superheater tubes.

Sorbent injection testing at Lakeview was carried out using both a limestone sorbent and a hydrated lime. During limestone injection testing the sulfur content of the coal varied dramatically over the range from 1.2 to 2.2 percent. A summary of the large amount of data generated during this period is presented in Figure 4-22, where a trend line indicates the mean of the individual data points. This shows SO_2 reduction levels of 40 percent and 27 percent at Ca/S = 3.0 and 2.0 respectively, and is well supported by analyses of fly ash samples taken selectively during the tests. The impact of coal sulfur content is illustrated in Figure 4-23, where the slope is somewhat steeper than would have been expected from the bench scale experimental data (Figure 4-14). It was also observed that the amount of SO_2 capture increased slightly with the amount of time that sorbent was injected. However, operational problems prevented very long term tests, so that actual SO_2 removal which would be achieved when the boiler was fully seasoned with sorbent were not determined.

Limited testing was also carried out using straight nozzles and fan-tip nozzles designed to provide improved lateral coverage. These tests were not conclusive although, in general those tests performed with the straight nozzles had a higher SO_2 reduction than the fan tip nozzles. Visual observations indicated that the sorbent in the straight nozzle tests had greater penetration of the flue gas stream than the fan-tip nozzles. As the relative SO_2 concentration and flue gas mass flow rate is greater away from the front wall and sides on a front-wall fired boiler, it is possible that the fan tip nozzles resulted in poorer flue gas-sorbent mixing.

Flue gas recirculation was also used during several tests runs to determine the effect on SO_2 capture. The gas recirculation fan draws the flue gas from before the economizer section and reintroduces it at the boiler back wall below the burners. Using the gas recirculation generally seemed to improve SO_2 capture but the improvement was within the limits of measurement

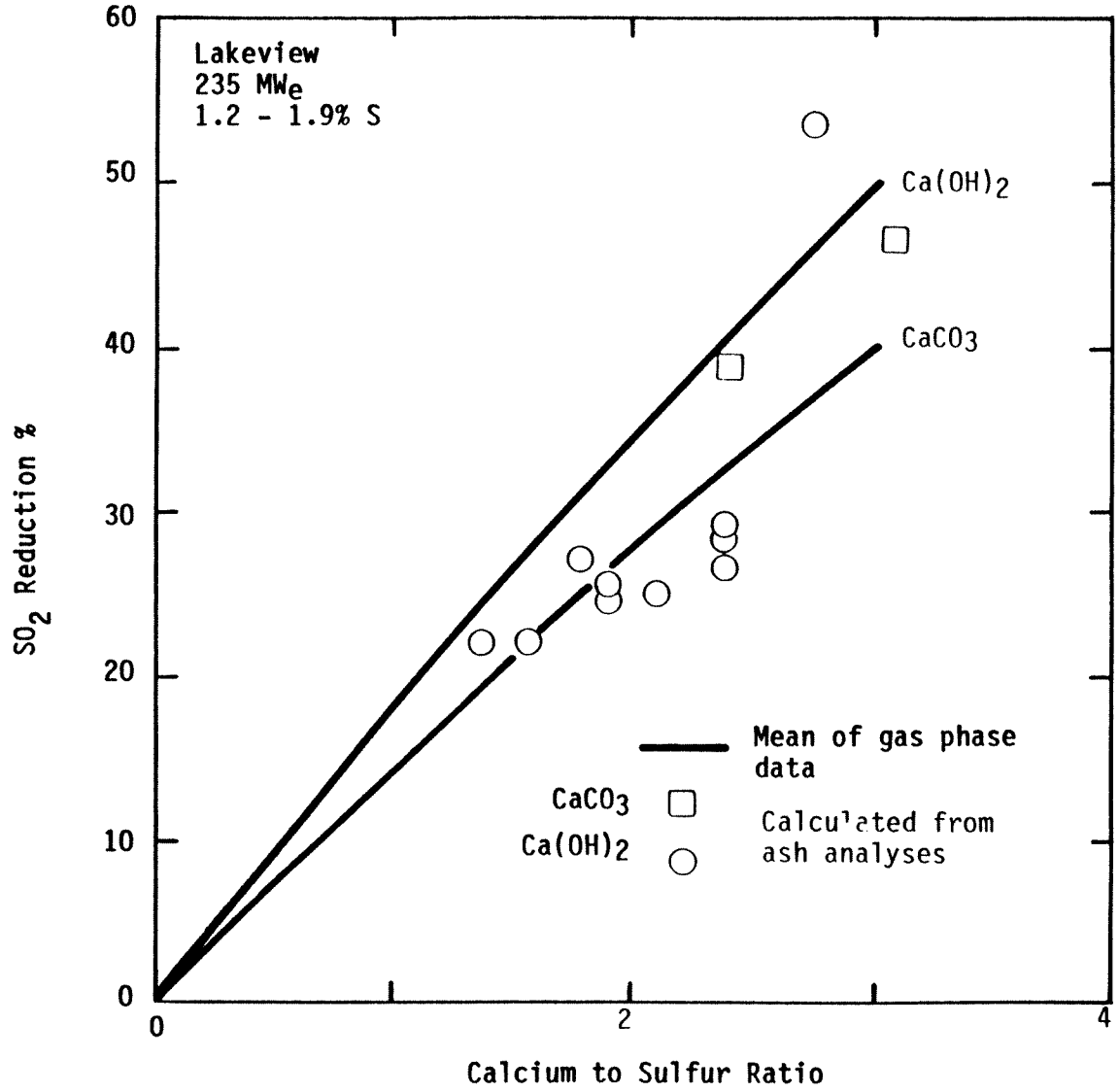


Figure 4-22. Lakeview - Summary of SO_2 removal data.

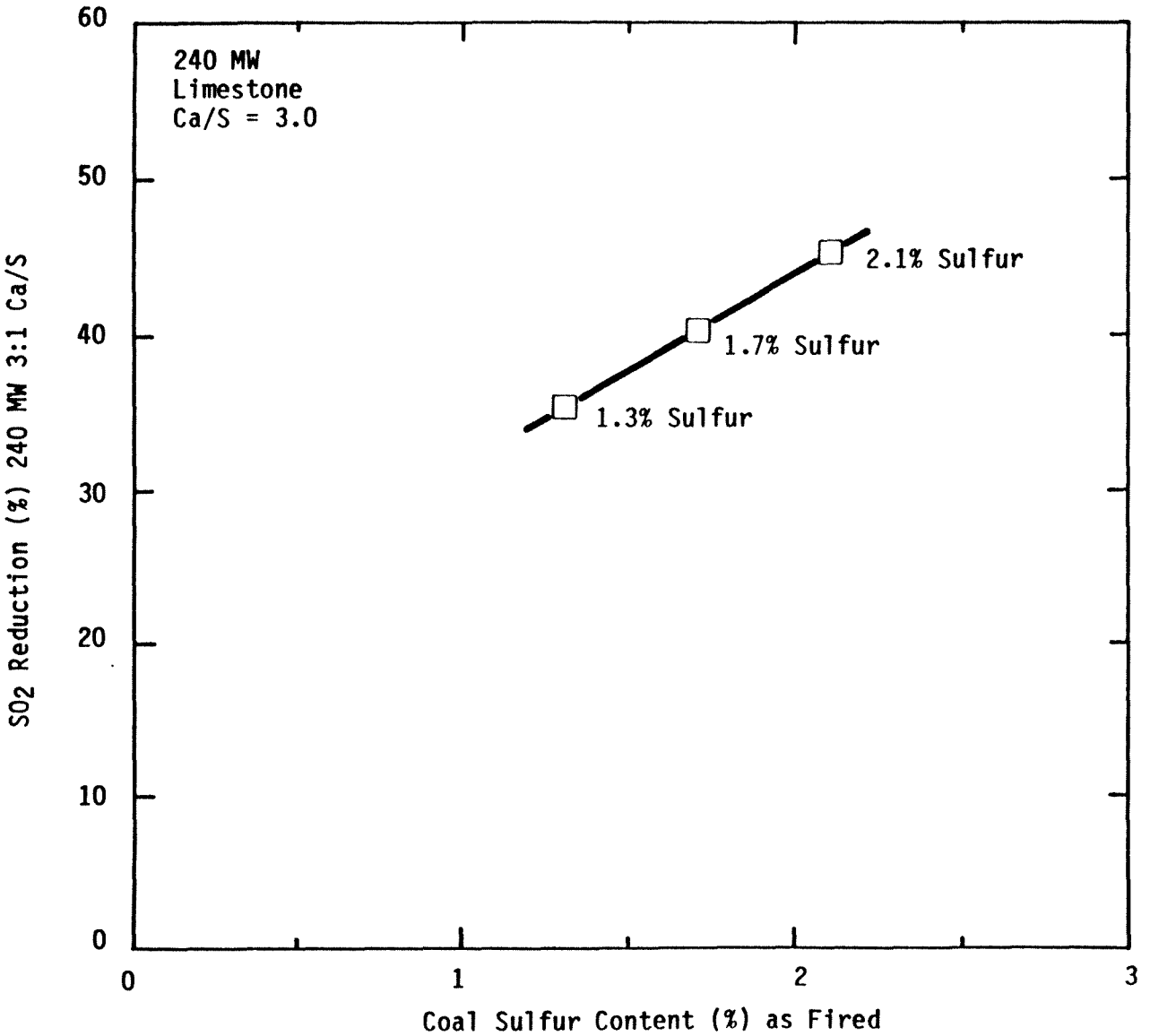


Figure 4-23. Lakeview - effect of coal sulfur content on SO_2 capture.

capability. Further, at 235 MW the use of gas recirculation amplified existing problems with superheat and reheat attemperation which limited the amount of gas recirculation which could be used. Therefore, no noticeable advantage was gained through the use of gas recirculation.

Calcium hydroxide was injected into the Unit 5 furnace through the same nozzles and injection system as was used for the limestone injection. Tests were conducted using 6, 4 and 3 nozzles at the 360' elevation. Due to the higher calcium content of calcium hydroxide as compared to limestone, the mass of sorbent injection to achieve the same calcium to sulfur ratio is lower. As a result, it was believed that the sorbent did not penetrate the flue gas stream as effectively. Therefore, most of the tests were performed with four or three nozzles in order to direct all the mass through the selected nozzles and achieve better penetration.

Test results for calcium hydroxide injection are summarized in Figure 4-22, where the data indicate SO_2 capture of 50 percent at Ca/S = 3 when burning a nominal 1.7 percent sulfur coal. As with limestone, the highest SO_2 captures were achieved when the coal sulfur content was higher. On the calcium hydroxide injection test however, there was not the same variance in sulfur content of the coal as was experienced during the limestone injection. The SO_2 capture with calcium hydroxide is somewhat lower than expected based upon previous experience, and this was attributed to inadequate mixing of sorbent and flue gas in this case. Isothermal modeling studies had suggested a reduction of some 5 percentage points in SO_2 capture due to inadequate mixing.

Edgewater

On the Edgewater boiler testing was conducted with a commercial calcium hydroxide and with a modified $Ca(OH)_2$ where calcium - lignosulfonate had been added to the water of hydration. The modified sorbent had shown improved capture and less sensitivity to higher injection temperatures in selected small scale feasibility tests.

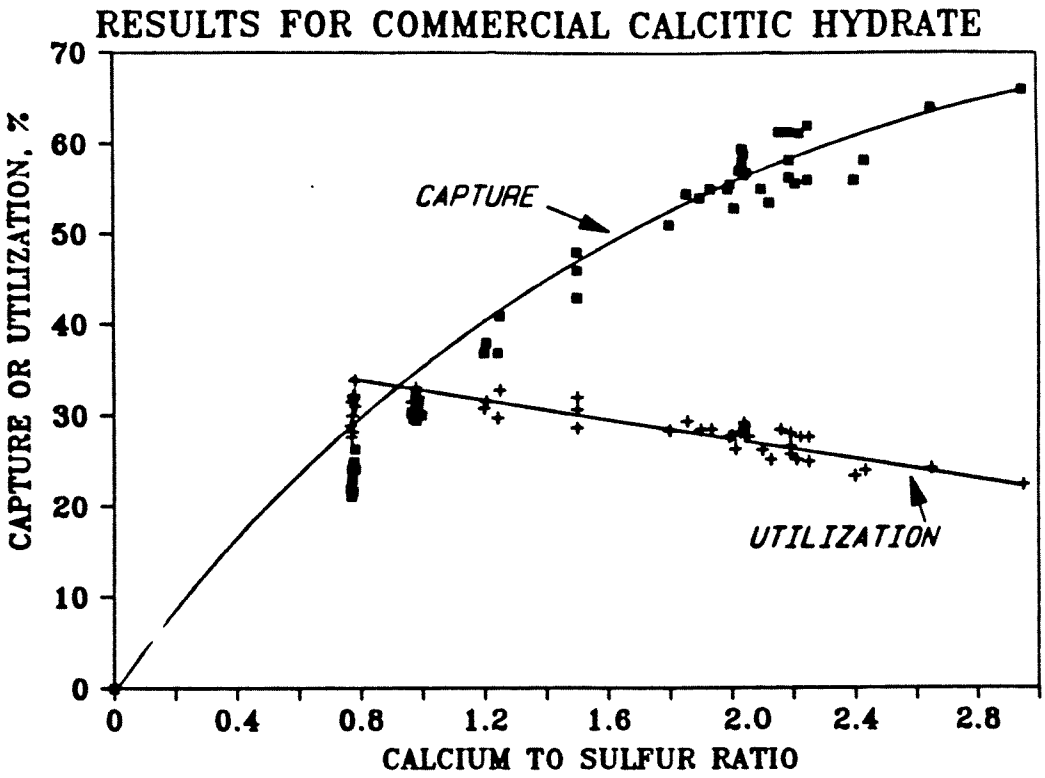
The results available from the Edgewater project represent test series conducted in September 1987 and are summarized in Figure 4-24. Injection was carried out from nozzles located at the 181 ft. (55 m) elevation on the boiler, with zero nozzle tilt for all except one test series with the modified sorbent which was conducted with -15° tilt. Figure 4-24 shows both SO_2 capture data and calcium utilization for the commercial and modified sorbents, and indicates a removal efficiency of approximately 55 percent for an injected Ca/S mole ratio of 2.0. Statistical analysis of the data suggests a slight improvement in SO_2 removal efficiency to approximately 59 percent for the modified sorbent at calcium to sulfur ratios above approximately 1.5.

4.2.4 Operational Impacts of Sorbent Injection

The injection of sorbent materials into the furnace cavity is expected to impact boiler operation, due primarily to the substantially increased fly ash mass loading, and to changes in ash physical and electrical properties. The increase in ash loading can be significant depending upon factors such as the sorbent addition rate, the coal sulfur content and the extent of sorbent utilization. For a low sulfur coal (e.g. Polish coal with 0.6 percent S, and 9.2 percent ash) the injection of limestone at Ca/S = 2 would be expected to result in a 33 percent increase in ash loading relative to normal baseline levels. At the other extreme, for a high sulfur coal (e.g. Edgewater, 2.5 percent S and 10 percent ash), sorbent injection at Ca/S = 2 would be expected to increase ash loadings by a factor of 2.5. Previous experience has also indicated significant increases in fly ash resistivity and reductions in ash mean particle size due to the nature of the sorbent materials employed. Because of these differences sorbent injection is expected to impact boiler operation in the following main areas:

- Increased fouling of heat transfer surfaces, leading to increased pressure drop and requiring modified sootblowing practices.

- Reduced heat transfer, leading to changes in steam temperature and a potential loss of boiler efficiency.



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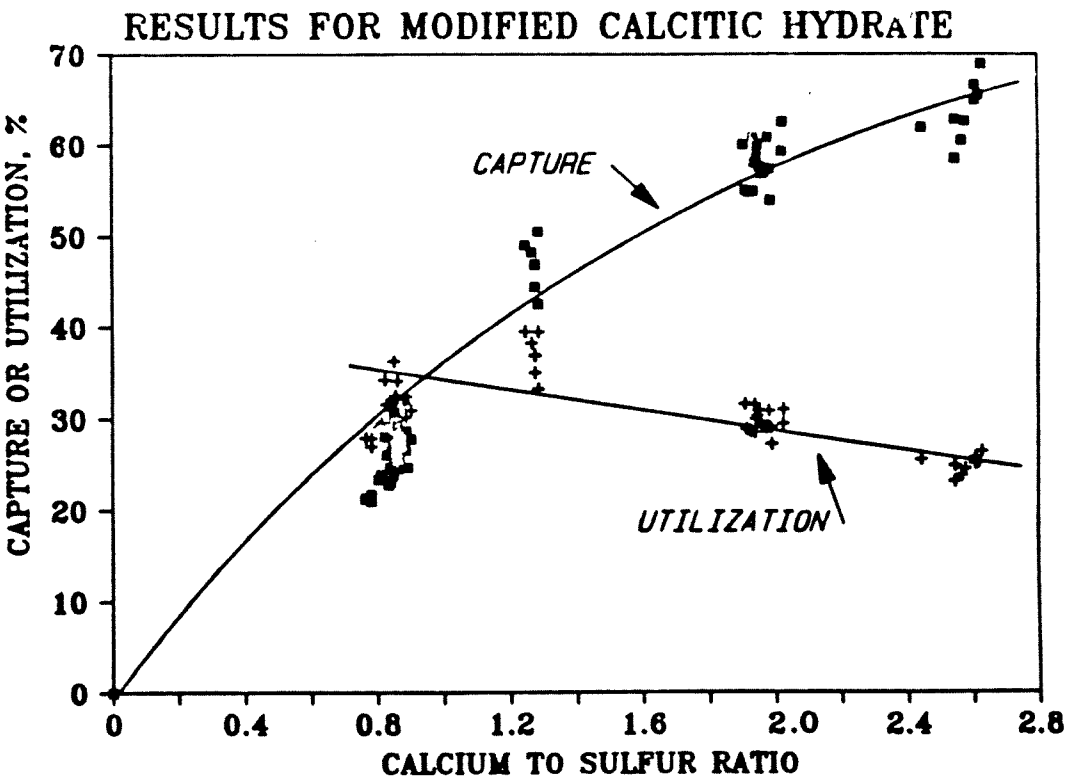

b)

Figure 4-24. Summary of Edgewater SO_2 removal data.

- Reduced ESP performance

- A requirement for modified fly ash handling procedures due to the high CaO content of the ash.

Each of the demonstration boilers experienced some effects of sorbent injection in the above areas. Experiences were however varied and are summarized briefly below.

Fouling

Each of the boilers reported increased fouling of convective passes during periods of sorbent injection. However, the deposits were always friable and apparently easily removed by normal sootblower operation. Only at the Lakeview plant were significant increases in pressure drop reported. Here, the pressure drop between the economizer inlet and precipitator outlet increased from 50 mm WG to 84 mm WG. Although this was not sufficient to impact ID fan performance because of the reduced boiler load, it was expected to be marginal for full load operation.

The typical method of dealing with increased convective pass deposits was by increasing the frequency of sootblowing according to changes in steam temperature. At the Hasselby power plant for example it was necessary to apply the sootblowers every 4-6 hours for full load operation and sorbent injection at Ca/S = 2-3, compared to a sootblowing interval of 6-8 hours under nominal baseline conditions. At the Stigsnaes plant, on the other hand, ash deposition in the convective pass was found to be beneficial in that it eased boiler operation by reducing the need for superheat attemperation during progressive lower furnace fouling between sootblowing events. High sorbent feed rates (greater than Ca/S = 3) were however found to reduce attemperation requirements and could, without superheater/reheater sootblowing, result in reduced steam temperatures.

Only on the Hasselby boiler was there any reported incidence where fouling limited sorbent injection testing. Here more severe problems were

reported when injecting the 0-10 micron dolomite, when boiler exit temperatures became excessive after only 1-2 hours of operation. On this boiler the injection of dolomite at Ca/S = 2 results in a fly ash mass loading which is approximately 160 percent of the nominal baseline value. However, the fine particle size and increased utilization may have exacerbated ash deposition in the convective pass since similar problems were not experienced with the coarser dolomitic sorbent.

Boiler Performance

No major impacts on boiler performance were noted in any of the demonstration projects. With adequate sootblowing, and modified sootblowing cycles, it was always possible to maintain steam temperatures and steam flows during sorbent injection at nominal levels. Inspection of plant data shows however that a slight increase in boiler exit gas temperatures usually occurred with sorbent injection. When coupled with an increase in flue gas mass flow due to incremental sorbent transport air (typically 2-4 percent of the combustion air), this represents a slight reduction in boiler efficiency. During the sorbent injection tests at Stigsnaes the combined impact of increased stack temperature and mass flow corresponded to a decrease in boiler efficiency of -0.6 percent. Additionally at Stigsnaes, station consumption was increased by approximately 1.2 percent (100 kw), due mainly to the power requirements of auxiliary equipment such as air compressors and booster fans. These values are considered to be fairly typical, and in cost analyses conducted as a part of various feasibility studies, it has been customary to assume on the order of a 1 percent loss in boiler efficiency and a 1 percent increase in auxiliary power as penalties resulting from the application of sorbent injection.

As an additional point, flue gas measurements have also shown that the concentration of SO_3 is reduced virtually to zero when sorbent is being injected, and the dew point of the flue gases approaches the water dew point. This is expected to reduce problems of cold-end corrosion, and also raises the possibility to reduce boiler exit temperatures and thereby improve overall efficiency.

ESP Performance

Previous experience with sorbent injection has shown that a major impact can be felt in terms of ESP performance. This results from the significant increase in fly ash mass loading, increased resistivity and reduced particle size, which are usually a consequence of sorbent injection. This can be particularly critical in older units where the precipitator has been installed as a retrofit, and where space restrictions have dictated a minimal collection area, consistent with prior use of high sulfur fuels.

In this study four of the units (Hasselby, Stigsnaes, Lakeview and Edgewater) were equipped with electrostatic precipitators. Two of these units (Hasselby and Stigsnaes) performed satisfactorily with sorbent injection, while two (Lakeview and Edgewater) experienced severe problems. Increases in fly ash mass loading at the ESP inlet ranged from 30 percent (Hasselby, limestone injection at Ca/S = 2), through 60 percent (Stigsnaes, U.S coal and limestone at Ca/S = 2; Hasselby, dolomite at Ca/S = 2), up to a factor of 2.5 increase (Lakeview at Ca/S = 3, and Edgewater at Ca/S = 2). Measurements of particle size distribution also showed that this decreased from a mean size of typically 20-30 microns down to 15-20 microns. At the outlet of the precipitator, mean particle size was found to remain in the neighborhood of 2 microns, but with significant increases in the submicron fraction when sorbent was injected. Measured impacts on fly ash resistivity are summarized in Table 4-4.

TABLE 4-4. IMPACT OF SORBENT INJECTION ON MEASURED FLY ASH RESISTIVITY

SORBENT	Resistivity (Ohm-cm)			
	Hasselby(1)	Stigsnaes(1)	Lakeview(2)	Edgewater(1)
Baseline	7×10^9	3×10^{11}	1×10^{10}	3×10^{10}
Limestone	6×10^{10}	6×10^{11}	1×10^{12}	--
Hydrate	2×10^{10}	--	1×10^{13}	3×10^{12}
Dolomite	1×10^{10}	--	--	--

(1) Ca/S = 2.0
(2) Ca/S = 3.0

As indicated earlier, both the Hasselby and Stigsnaes precipitators experienced few problems with sorbent injection, even at comparatively high injection rates (Ca/S > 3). At Hasselby, stack particulate mass emissions did increase but remained well within regulatory mass and opacity limits. At Stigsnaes however, measurements indicated that the mass loading at the exit of the ESP actually decreased for all coal types when sorbent was injected. This was attributed to a tendency of the ash to agglomerate, which had the effect of reducing rapping losses. The experiences at Lakeview and Edgewater were however quite different. At both units, shortly after the initiation of sorbent injection, the first ESP fields began to lose power, with indications that the high resistivity of the ash was producing back corona. With time, this effect was observed to progress through the subsequent ESP fields, leading to excessive stack opacity after only a few hours of operation.

The above differences in experience are quite significant, and may be attributable as much to ESP design as to factors such as unit size, ash loading and coal sulfur content. Both the largest (Edgewater, SCA 118 $m^2/m^3/s$) and smallest (Lakeview, SCA $61 m^2/m^3/s$ at 235 MW) precipitators experienced

similar problems, while the two intermediate sized units (Hasselby and Stigsnaes) were relatively unaffected. These latter two units were designed specifically to accomodate high resistivity ashes, and since both were operated on low sulfur coals the incremental change in ash loading with sorbent injection was much less than on the other units. The Stigsnaes ESP was additionally equipped with pulse-energization which can also suppress effects due to increased resistivity. For all of the above precipitator results, it should however be noted that data were obtained only after relatively short periods (up to 2 days) of continuous operation with sorbent injection. Periods as long as 2 to 4 weeks are believed to be necessary to fully condition an ESP to a new situation, and test periods of this order would be required to provide a conclusive evaluation.

Various techniques have been proposed to restore precipitator performance with sorbent injection, without resorting to costly plate area extensions or internal modifications. Flue gas conditioning using SO_3 injection or humidification are two techniques which have proven effective. The use of SO_3 injection was evaluated during the testing at Lakeview, and for moderate conditioning levels (50 ppm) proved effective in restoring opacity levels when limestone was used as the sorbent. The use of SO_3 conditioning also helped precipitator performance while injecting calcium hydroxide. However at the maximum conditioning levels available (70 ppm) there continued to be a slow deterioration in precipitator performance with time, suggesting that the effectiveness of the technique may be sorbent type dependent. Humidification as a fly ash conditioning technique was evaluated at the Edgewater demonstration site by injecting water upstream of the precipitator. Here a special humidification chamber was installed to permit humidification to a close approach to saturation temperature, though in principle, and for moderate levels of humidification, water injection could be carried out in existing duct work. At Edgewater, humidifier outlet temperatures of roughly 120°C were found to be sufficient to enable continuous operation of the ESP without other detrimental impacts. It is also note worthy that, at Edgewater, when the humidifer was operated at a close approach to saturation (+10°C) significant incremental SO_2 capture was observed, yielding greater than 70 percent overall removal rate at Ca/S= 2.[8]

Ash Handling

Specific studies related to the handling and subsequent disposal of the sorbent modified fly ash were not conducted as an integral part of this study. However some experience on these issues was gained in the normal course of conducting the demonstration testing. In general few problems were experienced in handling the ash in existing dry ash handling equipment. Greater care was however required due to the high CaO content of the modified ash. Wetting of the ash results in considerable heat generation and requires a higher water to solids ratio than conventional fly ash in dustless unloaders, and is one area of the handling process which requires some attention . Ash from the demonstration projects was mostly disposed of in controlled landfills, although at Stigsnaes the ash was collected and blended with normal fly ash for use as a construction material. Further studies on possible end-uses for the fly ash; its possible re-use as a sorbent material under recycle conditions; and ash physical and chemical properties and the long term implications for disposal, are all areas of continuing investigation.

4.3 Discussion of SO_2 Capture Results

From the presentation of SO_2 capture data in the preceding sections it can be seen that a direct comparison of the results obtained on the different boilers is difficult, because to some extent each situation is unique. Reported SO_2 capture values under nominal full load operating conditions have ranged from approximately 15 percent up to 55 percent at an injected calcium to sulfur molar ratio of 2.0. Sulfur capture by sorbents injected into the furnace cavity has been shown to be affected by:

- Sorbent type and reactivity
- Peak temperature experienced by the sorbent
- Coal sulfur content

- Boiler specific temperature vs. time characteristics after the sorbent injection point

In an attempt to rationalize the impacts of these different parameters, predictions for SO_2 removal performance were made for each of the boiler situations, according to the methodology described in Section 4.2.2 (Figure 4-15). Such predictions represent an ideal means of evaluating and comparing the test data since they include all the site specific factors which are expected to affect SO_2 removal. Comparison of actual measured removal rates with those expected should therefore indicate whether the anticipated performance has been achieved, or whether there are additional factors which could be affecting SO_2 removal performance. Selected measurement data, interpolated to an injected Ca/S ratio of 2.0, are compared to predictions in Figure 4-25, 4-26, and 4-27, for each of the major classes of sorbents (limestone, hydrate and dolomite). Here representative temperature levels at the plane of sorbent injection have been estimated from heat transfer modeling data, or from measurement data where these were available. It should also be noted that, as indicated in Section 4.2.2, the prediction approach employed is essentially a one-dimensional treatment of the sorbent injection process, and the capture of SO_2 by sorbent particles in flight. Consequently, the overall prediction approach does not account for three-dimensional flow and mixing effects, or for incremental SO_2 capture which might occur on material deposited on tube and wall surfaces.

From the results presented in Figures 4-25 to 4-27 it can be seen that in general there is a good agreement between the measured SO_2 removal data and the levels expected when the various controlling parameters are taken into account. This suggests that the measured values are generally consistent with the combination of sorbent properties, baseline SO_2 concentration, and temperature profile unique to each boiler application.

There are, however, some exceptions to the generally good agreement which may be worthy of further consideration. On the Gagetown boiler for example, the SO_2 removal rate with limestone injection was underpredicted for the high sulfur coal and significantly over predicted for the low sulfur

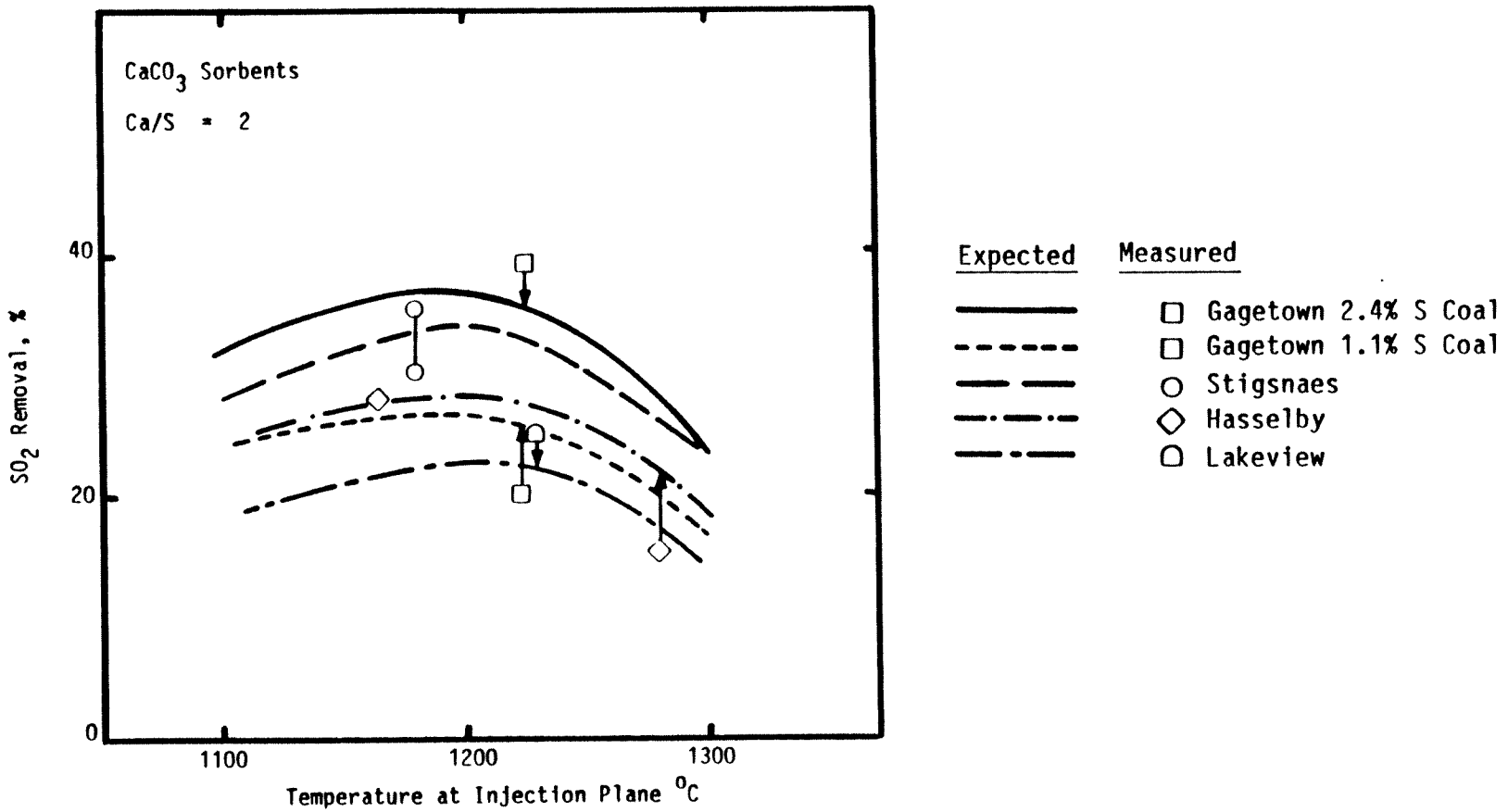

Figure 4-25. SO_2 removal - comparison of expected and measured performance - limestone sorbent.

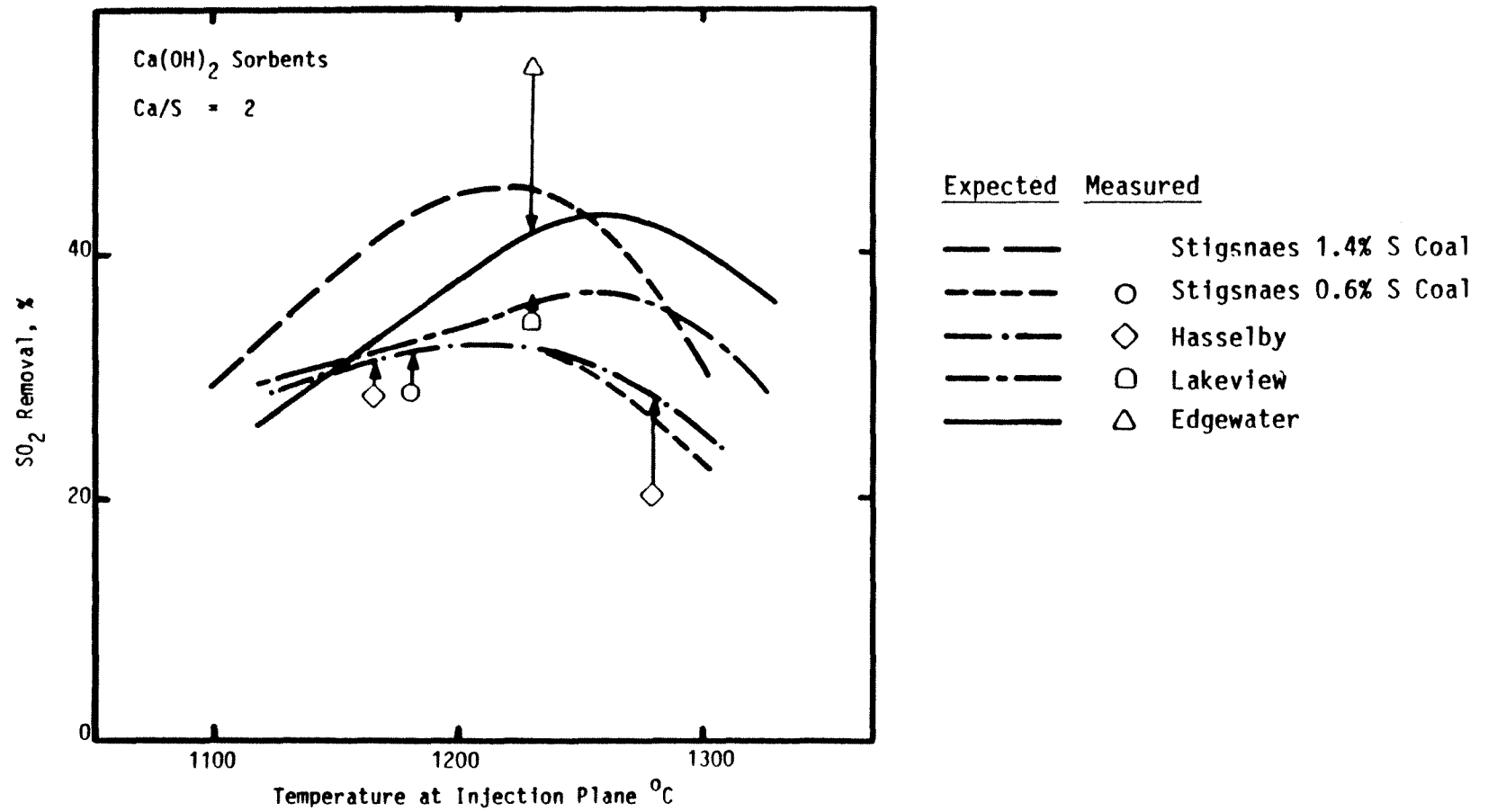

Figure 4-26. SO_2 removal - comparison of measured and expected performance - $Ca(OH)_2$ sorbents.

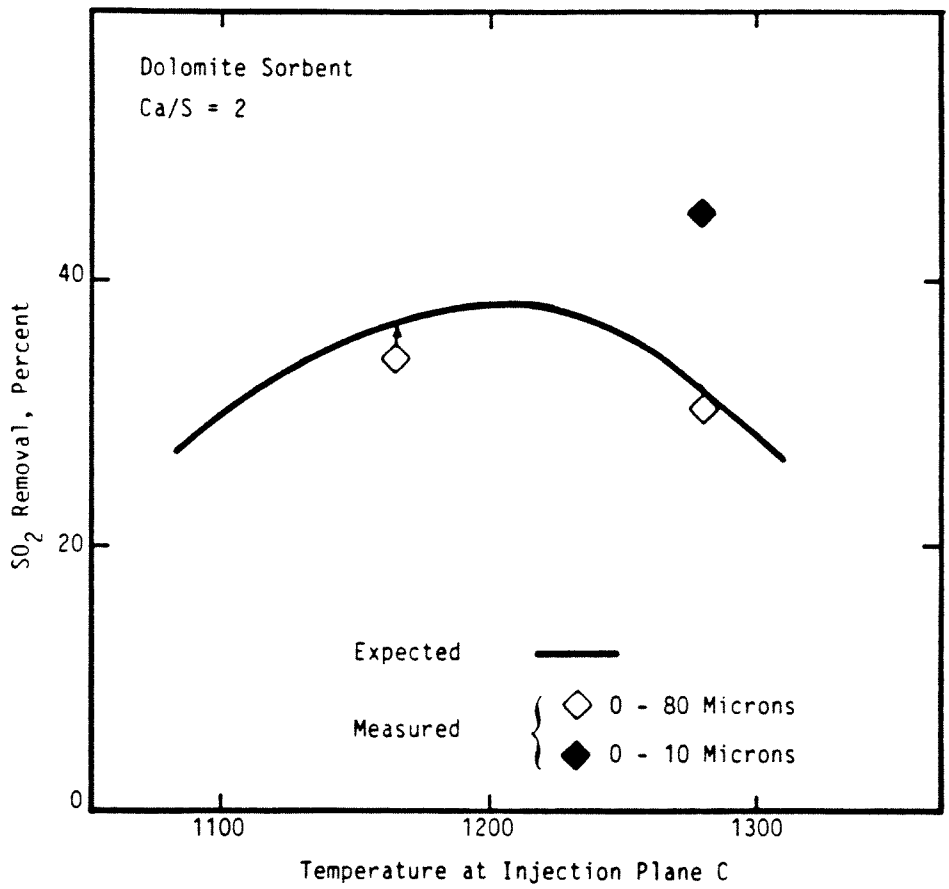

Figure 4-27. SO_2 removal - comparison of measured and expected performance - Dolomite.

coal. The reasons for this are not clear, but may be related to the flow field and to the mode of sorbent injection, which are unique to this boiler. Here the sorbent was injected close to the burners in such a way that some of the material may have become entrained into the large recirculation zones which are characteristic of the flow field in this unit. In this way the sorbent may have experienced temperature profiles different from the mean profile established for the flue gases, representing an extremely complex situation which is difficult to evaluate. Predictions carried out for this unit assumed that a fraction of the sorbent material was entrained into the recirculation pattern, and consequently experienced residence times longer than the mean. The predicted SO_2 capture was found to be quite sensitive to both entrainment and residence time assumptions. Moreover, the impact of recycling sorbent material through high and low temperature zones is poorly understood, although it is expected that this may improve utilization to levels not normally expected.

On the Hasselby boiler the high-load SO_2 capture data were generally poorer than expected. This has been attributed to an underestimation of the actual temperature levels experienced by the injected sorbents. Heat transfer modeling of the boiler, coupled with earlier temperature measurements, had suggested a mean temperature at the sorbent injection plane of approximately 1200°C. However, some of the measurements made during the test program had indicated temperatures significantly higher, with local values exceeding 1300°C. Certainly, much of the parametric data obtained during testing (e.g., the effects of injector tilt and boiler load) are consistent with high injection temperatures, and an injection elevation which is situated too low in the boiler. There is therefore some uncertainty associated with injection temperature levels, and actual values may well be somewhat higher than those indicated in the figures. The Hasselby low load data are generally in better agreement with expected values, mainly because at reduced thermal input temperature at the injection elevation are reduced and fall into a regime where SO_2 capture is expected to be less sensitive to this parameter. For the dolomitc sorbent the experimental data indicate a reduced sensitivity to high temperatures, which is presumed to occur because the relatively inactive magnesium components helps to maintain access to the

sorbent internal structure in spite of sintering. This is illustrated in Figure 4-27.

The most significant difference between measured SO_2 removal data and expected values was found in the case of Edgewater. As shown in Figure 4-26, approximately 55% SO_2 removal was measured, while slightly in excess of 40 percent was expected based upon sorbent properties, coal sulfur content and the specific temperature field. The reason for this large discrepancy is not immediately apparent. It has been suggested, however, that the high capture values result from the possibility of incremental SO_2 removal occurring on tube deposits in the convective pass. This may also have been a contributary factor in other data sets, notably for limestone injection at Stigsnaes, Hasselby and Lakeview, where SO_2 capture during longer term testing was higher than that measured during shorter term parametric tests. Approximate calculations suggest that for each of these cases the higher SO_2 removal rates could be explained if some 5 percent of the injected sorbent material was to achieve 100 percent utilization. Whether or not this represents a realistic scenario is not clear at the present time.

Where ash sampling has been carried out during periods of sorbent injection, analyses of fly ash and precipitator hopper samples have tended to support calcium utilization values closer to those inferred from the short term gas phase data. However, in the one instance (Stigsnaes) where convective tube deposits were analyzed these showed a high sulfur content, suggesting that very high calcium utilization can be achieved on material which has a long residence time in the flue gases. Nevertheless, since ash deposition on heat transfer surfaces is a continuous process, with periodic shedding if the deposits remain friable, it is not clear why equilibrium levels of SO_2 removal are not achieved in a matter of minutes, rather than over a period of several hours as has been observed. More fundamental considerations related to the continued diffusion of SO_2 through the sulfate product layer around individual sorbent particles also suggest that high levels of utilization are difficult to achieve once the initial rapid sulfation reactions have been shut down. This is true even in the higher temperature superheater and reheater regions where the sulfation kinetics are

favored. Attempts to calculate the tube capture system have suggested that significant swelling of the deposited particles must occur in order to create new surface area for significantly improved utilization. While there is some evidence to suggest that this can occur the situation is not well characterized. In order to resolve some of these questions, more detailed analyses of tube deposit samples are possibly required, together with more rigorous attempts to close the sulfur balance by including long term data and all ash hopper samples, where the collected solids should include the results of all sootblowing events and natural deposit shedding. In the meantime it is clear that the impact of incremental tube capture on overall SO_2 removal efficiency is not particularly well understood, and is not easily amenable to prediction.

While the preceding discussion has considered the effects of sorbent type, coal sulfur and temperature through the overall prediction methodology, the one parameter not considered in any detail thus far is that of sorbent mixing, and the impact of poor mixing on SO_2 removal performance. Here it is significant that in the various demonstration projects where injection parameters (eg. injection velocity, number of injectors in service) were varied in order to evaluate mixing effects, little significant impact on overall SO_2 removal was observed. This may be attributed to the relatively low overall SO_2 removal rates which were characteristic of this study. Under these conditions sorbent utilization is only slightly impacted by sorbent addition rates, as illustrated by the data in Figures 4-17 to 4-22 where SO_2 capture increases almost linearly with injected Ca/S ratio. From such data it can be inferred that sorbent dispersion throughout the flue gas stream may be relatively poor before any significant impact on the mean gas phase SO_2 removal is observed, since sorbent which is not fully mixed and remains in locally high concentrations will still achieve the same nominal utilization. However, when overall SO_2 removal rates are high (due to the use of reactive sorbents, high baseline SO_2, favorable temperatures, etc.), then sorbent utilization begins to fall off markedly as sorbent addition rate is increased. Under such conditions, poor mixing would be expected to have a more significant impact in limiting SO_2 removal performance. This point is further illustrated in Figure 4-28, where a sorbent mixing effectiveness

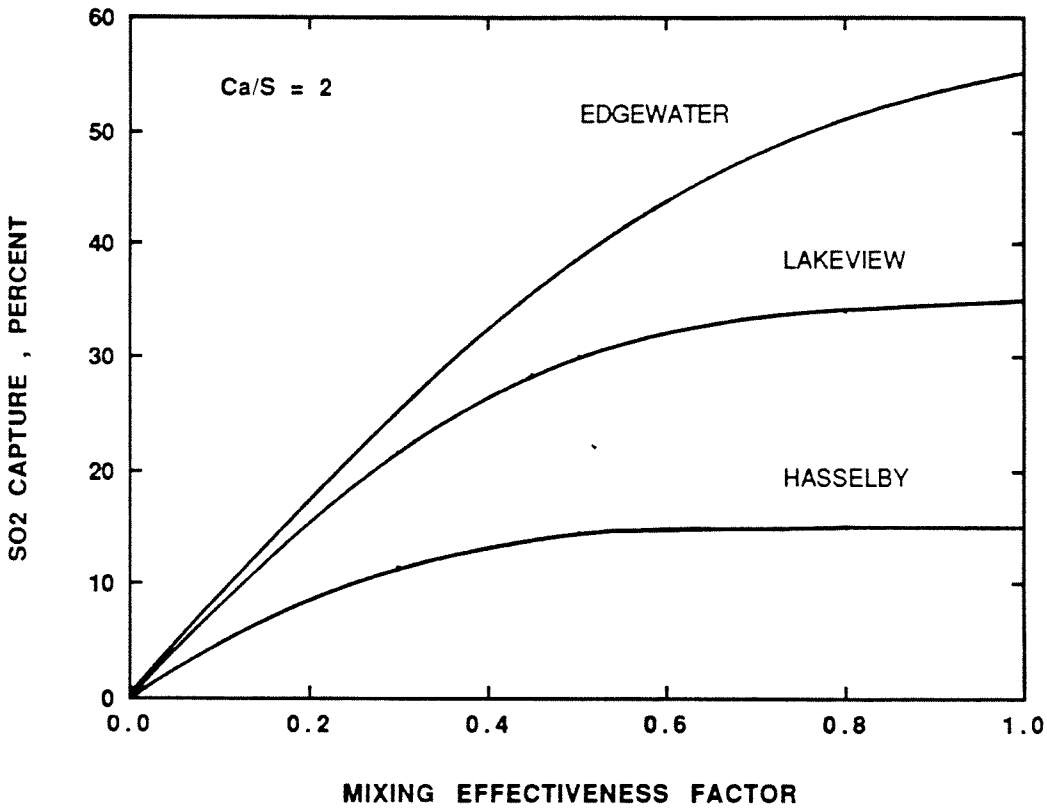

Figure 4-28. Hypothetical Impact of Sorbent Mixing on SO_2 Capture.

factor has been defined to show hypothetically how mixing would be expected to impact SO_2 capture. A mixing factor of 1.0 implies perfect mixing of the injected sorbent with the flue gases, while a factor 0.5 implies that 50 percent of the flue gas stream is not contacted by any sorbent. Characteristic SO_2 capture curves for Edgewater, Lakeview and Hasselby have been used in constructing Figure 4-28. From this it may be concluded that for most of the boiler situations covered in this study, sorbent mixing can be comparatively poor before mean SO_2 removal rate is significantly impacted, and that other parameters such as sorbent reactivity and temperature are more important.

From the test data generated in this program, and from the foregoing discussion, it is possible to identify general trends which will allow the extrapolation of data to different units, and the approximate prediction of expected SO_2 removal performance for an unknown situation. The results of this program have shown that SO_2 removal depends on three main parameters

- sorbent reactivity
- initial SO_2 concentration
- boiler temperature profiles and injection location

Of the different sorbent types tested, dolomitic sorbents have proven to be most reactive, followed by calcitic hydrates, with limestones being the least reactive. This general ranking of different sorbent materials is expected, and is in keeping with the extensive data base available from both experimental and full scale facilities. However, within each class of sorbents differing levels of reactivity may be expected, and it is believed that a clear picture of how a given sorbent will perform can be achieved only through experimental study. Data presented in Figure 4-13 has shown the relative performance of the different sorbents employed in this program, and may be used to determine reference SO_2 removal rates for a given sorbent, or as a basis for estimating a reference reactivity for an unknown sorbent material. Here a given sorbent is used together with different coal types, then the data of Figure 4-14 may be used to estimate the impact of the initial SO_2 concentration on overall SO_2 removal performance. For example, a

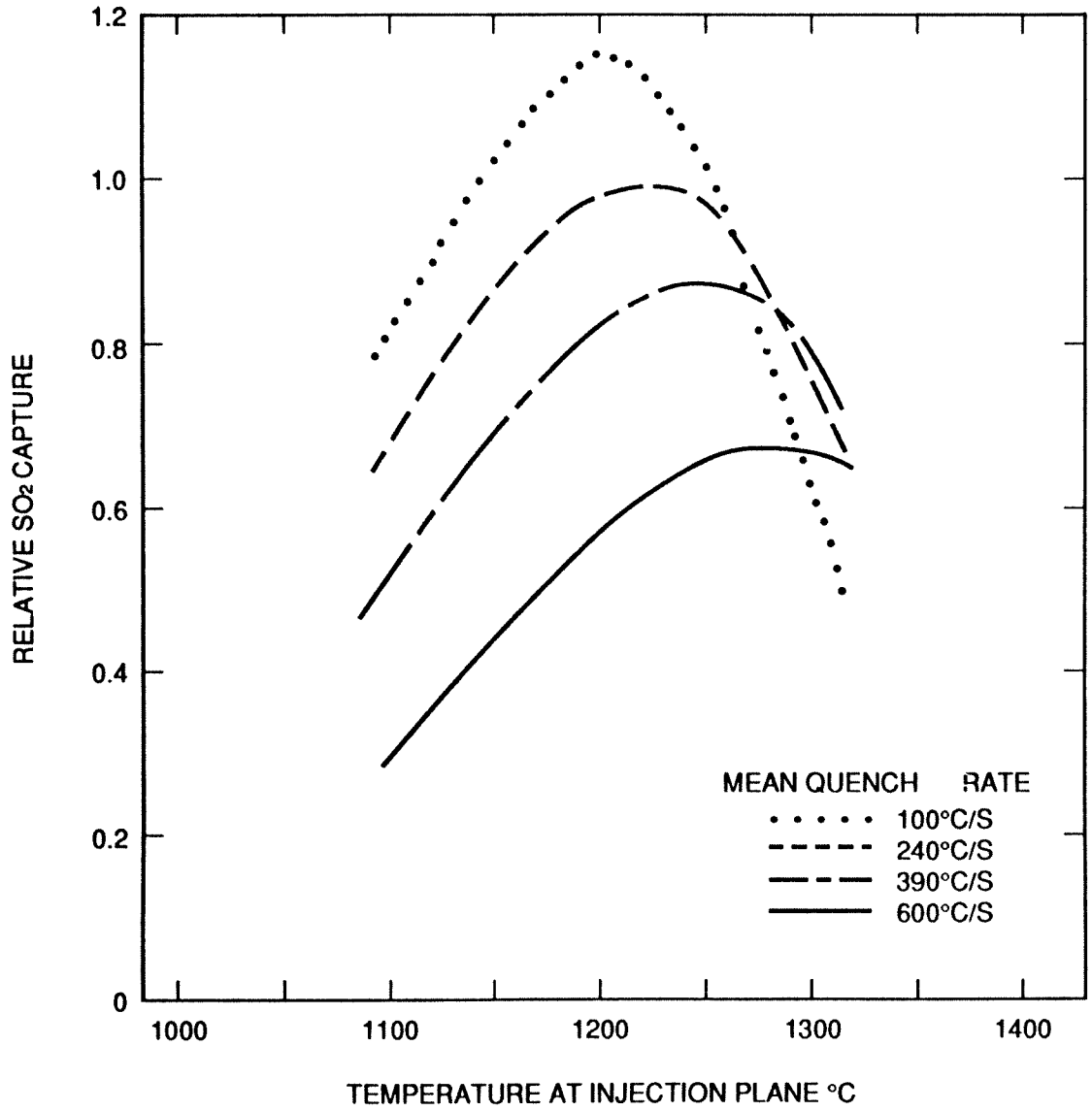

Figure 4-29. Impact of quench rate and injection temperature on relative SO2 capture.

sorbent which yielded 50 percent SO_2 removal with a high sulfur coal would be expected to yield only 50 x 0.84 = 42 percent with a lower sulfur coal for which the initial SO_2 was only 1000 ppm.

The impacts of boiler conditions and sorbent injection location on SO_2 capture is illustrated in Figure 4-29. This figure has been developed from the application of the sorbent sulfation model for a series of idealized conditions in order to illustrate SO_2 capture trends in a more generic fashion. Here the boiler thermal profile has been characterized by a mean quench rate, which represents an assumed linear temperature decay rate between nominally 1250 and 900°C. The sorbent injection elevation is represented by the mean gas temperature at a location just upstream of the injection plane, and assumes that 2-4 percent of the total combustion air is used for sorbent transport. Figure 4-29 shows clearly how SO_2 capture is impacted by thermal conditions, where capture is reduced at the higher quench rates, and the optimum location for sorbent injection shifts to progressively higher temperatures. Figure 4-29 may therefore be used together with Figures 4-14 and 4-13 as a basis for sorbent injection design, to estimate SO_2 removal performance for a wide range of boiler and injection situations, and to interpolate and extrapolate data between units of different design. Although the use of this approach can only be approximate, it is based on actual experimental data and fundamental process understanding, and may provide useful guidelines for performance evaluation in future boiler applications.

5.0 CONCLUSION

5.1 Low NO_X Burners

The results of this project have shown that low-NO_X burners can be an effective means of controlling the generation and emission of NO_X from coal fired power plant. Relative to uncontrolled baseline values, NO_X emission reductions of greater than 40 percent have been demonstrated, with the potential to achieve greater than 50 percent under some circumstances.

Low NO_X burners may not however be considered to be capable of achieving a fixed percentage reduction in emissions, or of achieving a constant minimum NO_X level for every application. This is particularly true when applied under retrofit conditions to existing boilers, where the degree of NO_X emission control achievable tends to be very site specific, and depends not only on burner design features. Other factors which impact NO_X emission reduction potential have been shown to include: the initial uncontrolled NO_X level; coal type; boiler design parameters such as burner spacing and firing depth; and any constraints which might be imposed due to the site specific retrofit situation. In principle, it should be possible to reduce NO_X emission down to approximately 300 ppm (at 0 percent O_2) in many boilers with moderate burner zone heat loadings. In practice, however actual emission levels achievable will be limited by design or operating parameters, such that optimum performance in all situations cannot be expected, and each retrofit situation must be approached on an individual basis.

Low NO_X burner systems are also of interest in new boiler development, where low-NO_X combustion techniques can be expected to yield their full potential. With the greater flexibility afforded to the designer it should be possible to select the most optimum burner design, and also to adapt furnace characteristics to the control of NO_X formation. Design features such as liberal burner zone dimensions, selection of burner locations and firing patterns to accommodate the longer flames which are characteristic of low NO_X combustion, and adequate upper furnace residence time to complete

burn out, may all be expected to contribute towards the optimization of NO_x emission control.

Low NO_x burners may therefore be considered to have a wide applicability, both as a retrofit measure for the control of NO_x emissions from existing units, and as an integral part of the design of new units for inherently low emissions. A major advantage of low NO_x burners is their cost effectiveness. Compared to post combustion techniques, burner modifications have low capital costs, little or no incremental operating costs compared to conventional burner systems, and do not generate any additional waste streams. However,low NO_x combustion techniques alone may not be capable of meeting all existing and proposed emissions legislation world wide. Nevertheless they do represent a most effective first approach to compliance. They may also be readily combined with other combustion modification (advanced overfire air, reburning) and post combustion (specfic catalytic and non-catalytic) techniques for a more cost effective overall control strategy.

5.2 Sorbent Injection

Compared to flue gas treatment systems for SO_2 emission control (such as scrubbers and spray dryers) the injection of calcium based sorbents directly into the furnace cavity has been shown to be capable of only moderate levels of SO_2 removal. Results from this project have shown that, under more optimum conditions and with acceptable levels of sorbent addition, 40 percent SO_2 removal was possible with limestone injection, and greater than 50 percent with $Ca(OH)_2$. However, as with low NO_x combustion, the application of sorbent injection is expected to be very site specific and to depend upon a number of design and operational parameters. Boilers with moderate firing density and access for upper furnace injection at locations where temperatures are on the order of 1100°C are likely to yield better performance than highly loaded units with high furnace exit temperatures. In new boiler designs it may be possible to provide more ideal conditions by judicious location of heat transfer surfaces and furnace cavities, such that optimum performance using this technology can be achieved.

Sorbent injection is considered to be only a partial SO_2 control technology, not capable of achieving the high levels of SO_2 removal associated with flue gas scrubbers. The applicability of the technology will therefore depend upon local emissions regulations and the levels of SO_2 control which are required. Sorbent injection may be of direct interest if low to medium sulfur coals are fired, and only moderate levels of control are required to achieve compliance. A more likely scenario however would be one in which emissions control were required on a system-wide basis, where larger base-loaded units could be fitted with scrubbers for a high degree of control, with sorbent injection applied selectively to other units for the necessary incremental control.

A major advantage of sorbent injection relative to flue gas scrubbers is that it is a low capital cost system, with only moderate ancillary equipment requirements that can more readily be accommodated in situations where available space is limited. Other advantages include the relative ease of operation and control, and low additional manpower and maintenance requirements. A major disadvantage of sorbent injection however is that the utilization of the injected sorbent is low, leading to high reagent costs relative to scrubbers.

In common with most other flue gas desulfurization technologies, sorbent injection yields a solid waste which must be disposed of. With sorbent injection the relatively low sorbent utilization rates leads to a higher volume of material, and potential handling problems due to unreacted free lime. Studies conducted in Denmark have however indicated that the modified ash may be blended with normal fly ash or sand to produce a material suitable for sale for a variety of construction applications, thus providing the potential to partially offset reagent costs.

Considerations such as those outlined above, suggest that the most favorable applications for sorbent injection will be those where low initial capital costs are more important than higher operating costs, such as:

- In older units with limited space and short remaining lifetime.

- Units with a low capacity factor

- In situations where emissions are regulated on a system-wide basis and only moderate reductions are required on selected units.

Numerous economic studies have been conducted which support this general conclusion, and imply the potential for considerable cost savings relative to scrubbers in such situations. Examples of such studies are presented in Figures 5-1 and 5-2 for a Danish 285 MW boiler with limestone injection to yield 40 percent SO_2 removal, and costs levelized over seven year and fifteen year periods respectively. It should be noted however that such economic studies are very dependent upon site specific assumptions. One major area of uncertainty lies in the impact of sorbent injection on downstream particulate removal equipment. In this project, of the four boilers which were fitted with electrostatic precipitators, two units performed satisfactorily, while two experienced significant problems which precluded long term operation without corrective measures. If major modifications to control particulate emissions are required, such as a precipitator extension or the addition of a baghouse, this would contribute significantly to the initial capital cost of specific applications. In this regard, recent advances have demonstrated the feasibility of combining sorbent injection with techniques such as flue gas humidification. Relatively small amounts of water injection upstream of the precipitator have been shown to be capable of restoring performance to acceptable levels. If provision is made to humidify to a close approach to the saturation temperature, then incremental SO_2, removal can be achieved, yielding cost effective removal rates at final overall SO_2 levels close to those associated with spray dryers.

5.3 Application Potential

The low NO_x/SO_x coal combustion technologies that have been evaluated, applied and demonstrated under this project have considerable potential for deployment in both developing and industrialized countries. Both low NO_x

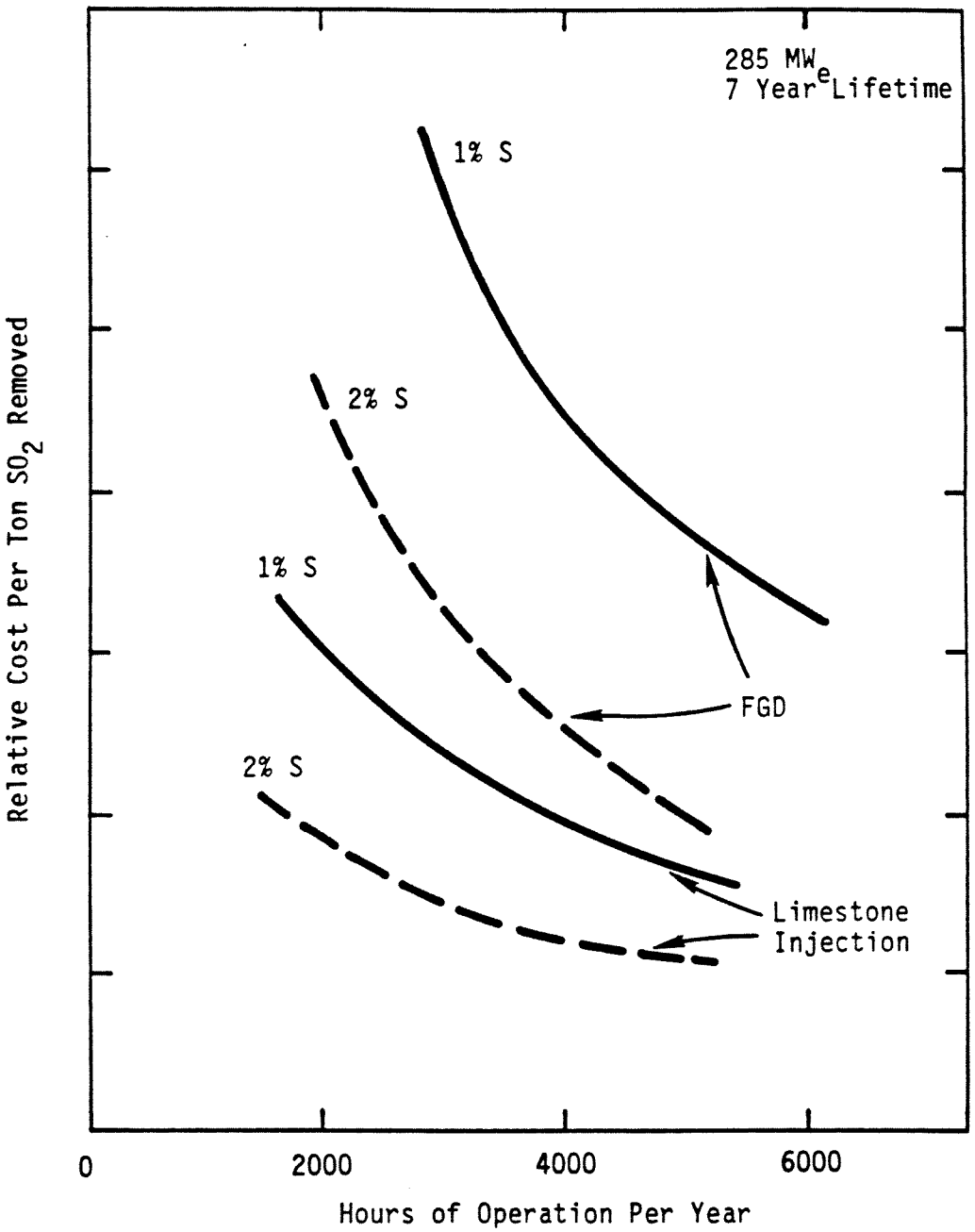

Figure 5-1. Relative costs of SO_2 removal - 7 year lifetime.

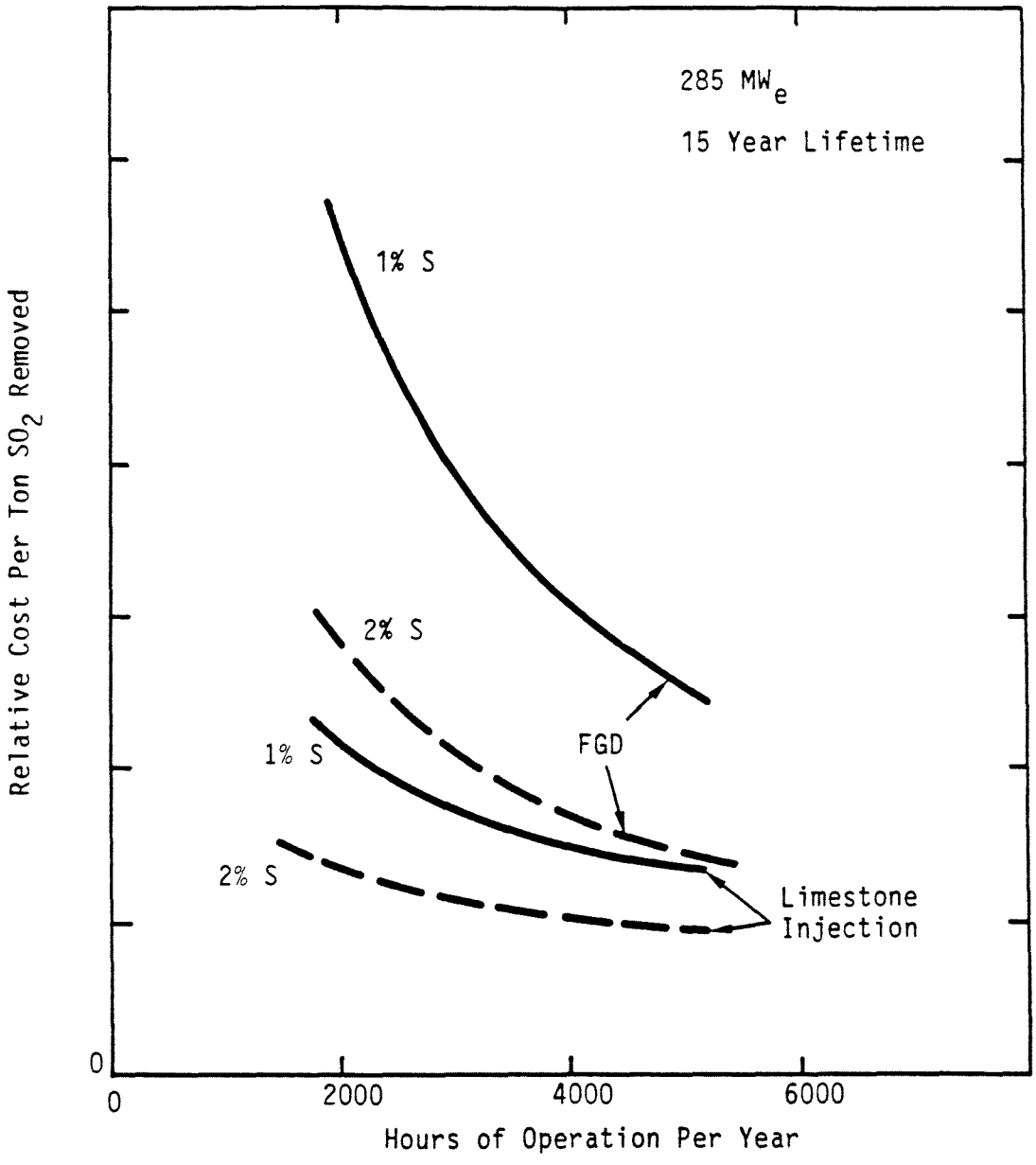

Figure 5-2. Relative costs of SO_2 removal - 15 year lifetime.

combustion and sorbent injection can, in general, be easily and economically retrofitted to existing boilers, and have the potential to reduce NO_x and SO_x emissions by up to 50 percent. The technologies may also be readily incorporated into combustion system designs for new pulverized coal fired units.

In developing countries, the consumption of indigenous coals is expected to escalate rapidly with energy demand. However, the control of NO_x and SO_x emissions, which is very desirable on a global scale, will be highly dependent upon available technologies being proven, affordable and simple to apply. By utilizing low NO_x/SO_x combustion technologies (such as those demonstrated in this project) in developing regions, significant reductions in the global forecast for acid rain fall-out could be achieved.

In the industrialized countries such low cost NO_x/SO_x control technologies may not have the potential alone to meet the stricter emission regulations which are being promulgated. They may however be readily integrated with secondary control processes with a combined potential to reduce acid rain precursors to required emission levels in a most effective manner. A number of post-furnace processes, such as humidification and recycle to enhance SO_2 capture by unreacted sorbent, and reagent injection to selectively destroy NO_x, are now commercially available.

5.4 Research and Technology Needs.

The results from the demonstration projects conducted under this IEA Stage III project have shown that low-NO_x burners and sorbent injection are viable techniques for the control of NO_x and SO_2 emissions from coal fired power plant. However, while significant reductions in emissions have been achieved, both techniques alone offer only partial control when viewed in relation to the various flue gas scrubbing techniques. Consequently there remains a need for further work in order to enhance process performance or to combine various technologies in the most optimum manner for low cost high efficiency emissions control. As a result of the work conducted in these demonstration projects and elsewhere a number of information gaps can be

identified where further definition is required or desirable in order to enhance operational performance. Selected topics are presented and discussed briefly below:

- Low NO_x burners may be readily combined with secondary de-NO_x techniques such as fuel reburning, ammonia or urea injection, and selective catalytic reduction. Further work is required to determine how these various techniques may be optimally and most cost effectively combined.

- In recent years increasing attention has been given to nitrous oxide (N_2O) as one of the stratospheric gases which participate in ozone depletion reactions. Nitrous oxide is known to be present in only small quantities in the combustion products of normally operated pulverized coal fired boilers, but may be enhanced under low-NO_x conditions. Measurements are necessary to determine the impact of staged combustion and various secondary de-NO_x techniques on N_2O emissions.

- The major disadvantage of sorbent injection for SO_2 emission control is that sorbent utilization is low, resulting in high material and operational costs. Although considerable effort has been invested in this area there is a continuing need to develop high reactivity sorbent materials to increase sulfur capture potential and to improve sorbent utilization.

- Recent laboratory studies have shown the potential to achieve higher sorbent utilization through the injection of comparatively low cost limestone/water slurries. This technique should be further evaluated along with the simultaneous use of chemical de-NO_x reagents to provide for improved overall NO_x and SO_x reductions.

- Flue gas humidification has shown significant potential for providing incremental SO_2 capture on furnace injected sorbent

materials, and as a fly ash conditioning agent to improve electrostatic precipitator performance. Further work is required to optimize the application of this process, to evaluate performance over l. g periods at full scale, and to determine impacts on particulate collection equipment.

- There is continuing need for the development of improved modeling techniques for the prediction of NO_x and SO_x removal performance, and for use as comprehensive process design and optimization tools. Key areas relate to the injection and mixing of dry or slurried sorbents, and the integration of kinetics models for NO_x and SO_x reduction directly into furnace heat transfer and combustion codes.

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7.0 ACKNOWLEDGEMENTS

The successful completion of this project has been due in a large part to the efforts and contributions of the operating staff at the various plant sites which have hosted the low-NO_x combustion and sorbent injection demonstration studies. The Executive Committee of the IEA Low NO_x Combustion Project gratefully acknowledges the significant contributions by the staff and operating personnel at the Central Heating Plant, CFB Gagetown in Canada; at the Hasselby Power Plant in Sweden; and at the Stigsnaes Power Plant in Denmark. Also gratefully acknowledged are the contributions by Ontario Hydro of Canada.

8.0 PLANT REPORTS

The results which have been presented in this report represent only a summary of large amounts of data which were obtained over many weeks of experimental testing. Comprehensive Test Reports have been prepared for each of the individual demonstration projects, and further information may be obtained from the following contact persons:

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