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by

H. Whaley*, P.J. Read** and K.V. Thambimuthu*

Canada's interest in coal-liquid fuels began in the early 1970's, prior to the first energy crisis, because of the possibility of using a pipelineable coal-fuel oil mixture directly in a utility boiler. This possibility led to an R and D study on the combustion and heat transfer characteristics of a number of coal-oil mixtures in a pilot-scale tunnel furnace at the Canadian Combustion Research Laboratory in 1971. The results of this work were presented at a joint industry-government seminar in 1972 and subsequently reported in the literature. This early research into coal-oil mixture combustion was discontinued at that time due to the availability of cheap fuel oil. The rapid escalation of oil prices in the mid 1970's led to a renewed interest in coal-oil mixtures by Energy, Mines and Resources Canada (EMR) as a means by which the eastern part of Canada might reduce its dependence on imported oil. The department stimulated industrial interest in coal-oil mixture technology through initiatives and funding support in demonstrations and R and D.

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The first demonstration project to utilize coal-oil mixtures was undertaken from 1977 to 1980 in a small utility boiler at the Chatham generating station in New Brunswick. This 10 MWe unit was selected because of its small size and stand by status. This latter as- pect made it ideal for the coal-oil mixture study.

After more than 1500 h of operation on coal-oil mixtures, it was concluded that erosion of burner tips constituted the major obstacle to successful boiler operation. This could be attributed to rapidly deteriorating combustion performance and occurred despite significant ash removal through beneficiation during fuel preparation. Similar observations regarding wear were made during diesel engine trials.

The goal of this early work was to replace oil directly through partial substitution by coal in unmodified oil-burning equipment using fuel mixtures containing up to 40% by weight of finely pulverized coal, the maximum amount of solids attainable within acceptable limits of fuel viscosity. This constraint limited coal's ability to replace oil to about 25% of its heat value, and as oil prices continued to rise, the need for substitution of a higher proportion of oil brought about different approaches. The response to these challenges led to the construction of a very small pilot plant to produce coal-oil-water fuels which contained approximately 60% coal, 20% oil and 20% water, and later a larger pilot plant, based on the Carbogel technology, to produce coal-water fuel containing approximately 70% coal and 30% water.

The next phase of the demonstration program had two objectives: to create a coal-water fuel supply system and to select and use burners for the 10 MWe front-wall fired and 22 MWe tangentially-fired units at Chatham. Approximately 5000 tonnes of coal-water fuel were used at Chatham and although substantial improvements were made, the burner wear problem was not completely overcome. Difficulties were encountered initially in maintaining fuel consistency due to inexperience in manufacturing, to unexpected microbiological attack, and the wide variation in ambient temperatures. New burner designs, while less susceptible to wear, did not achieve acceptable levels of carbon combustion and poor carbon conversion performance emerged as the most serious problem for coal-water fuel in boilers. Consequently the program concentrated on burner development, fuel handling problems, and the development of fuel specifications designed not only to allow users to verify the the fuel they received would behave properly, but also to provide parameters for control of the manufacturing process.

A subsequent program at Chatham in the smaller unit led to the development of a wear-resistant ceramic atomizer in an optimized combustion air register in which excellent combustion performance and negligible wear were observed during short performance tests.

The utility boiler coal-water fuel demonstration program at Chatham also led to two industrial demonstrations, one in an iron ore induration furnace and another in a wet process cement kiln. The latter has subsequently been operated on a long term commercial basis by the cement company.

Implementation of coal-water fuel technology is impeded, except in a few special circumstances, while international oil prices stay below $20 (U.S.) per barrel.

However, there could be advantages in the future to using coal-water fuels as an alternative to pulverized firing of coal as well as to oil. Many experts have theorized, based on extrapolation of their experience with pulverized firing, that oil-designed boilers would be derated if fired by coal-water fuel. Factors hypothesized to cause derating include lack of a hopper to remove bottom ash, inadequate furnace volume, proximity of furnace walls to flames causing slagging, close tube spacing causing pluggage due to fouling, and high gas velocities causing erosion. All these factors arise from the fact that oil-fired boilers are based on a more compact and hence cheaper design which could offer a cheaper way of burning coal if derating is minimal. The Canadian coal-liquid fuel program is currently testing the validity of supposed derating constraints by firing coal-water fuel in a compact, front-wall fired, flat-bottom, oil-designed utility boiler at Charlottetown, Prince Edward Island. Preliminary observations indicate that ash behaviour is more benign than calculations would infer and therefore that calculated derating factors may be exaggerated. These observations have been corroborated by studies of the deposition of coal-water-fuel ash in a test rig. It may therefore prove possible to run oil-designed boilers very close to their maximum continuous ratings on coal if the fuel and the burners are properly designed.

R and D studies on the combustion, heat transfer and atomization of coal-water fuel are also on going in support of the demonstration program. The following is a selection of papers from 1982 to the present which provide a historical perspective on the motives for and background to the Canadian program of coal-liquid fuel development.

ÉTAT D'AVANCEMENT DU PROGRAMME CANADIEN DE RECHERCHE SUR LES SUSPENSIONS DE CHARBON: DE 1971 À 1987

by

H. Whaley*, P.J. Read** et K.V. Thambimuthu*

Le Canada a commencé à s'intéresser aux suspensions de charbon au début des années 70, avant la première crise de l'énergie, en raison de la possibilité d'utiliser directement, dans les chaudières des services publics, des mélanges charbon-mazout transportables par pipeline. En 1971, au Laboratoire canadien de recherche sur la combustion, cette possibilité a mené à des travaux de R-D sur les caractéristiques de combustion et de transfert thermique de certains mélanges charbon-mazout, dans un four-tunnel expérimental. Les résultats de ces travaux ont été présentés en 1972 lors d'un colloque mené conjointement par le secteur privé et le gouvernement, et publiés par la suite. Ces premières recherches sur la combustion des mélanges charbon-mazout ont été interrompues, le mazout étant alors bon marché. Au cours des années 70, en raison de l'escalade des prix du pétrole, les mélanges charbon-mazout ont de nouveau suscité l'intérêt d'Énergie, Mines et ressources Canada (EMRC), qui les percevait comme un moyen de réduire la dépendance de l'Est du Canada à l'Égard du pétrole importé. EMRC a alors stimulé l'intérêt de l'industrie pour les mélanges charbon-mazout par le biais d'initiatives et du financement de projets de R-D et de démonstration.

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Le premier projet de démonstration concernant les mélanges charbon-mazout a été mené de 1977 à 1980, à la centrale électrique de Chatham, au Nouveau-Brunswick. Une chaudière de 10 MWe avait été choisie pour sa petite taille et parce qu'elle ne servait qu'en cas de besoin comme source auxiliaire. Ce dernier aspect la rendait idéale pour l'étude des mélanges charbon-mazout.

Après plus de 1 500 heures d'essais avec des mélanges charbon-mazout, on a conclu que l'érosion des atomiseur du combustible constituait l'obstacle principal. Cette érosion s'expliquait par une détérioration rapide de la qualité de la combustion et se produisait malgré l'élimination des cendres, dans une large mesure, à l'étape de la préparation du charbon. On a observé le même phénomène lors d'essais dans des moteurs diesel.

L'objet de ces premiers travaux était de remplacer partiellement le mazout dans des chaudières ou d'autres appareils au mazout non modifiés en y substituant des mélanges contenant jusqu'à 40 % en poids de charbon finement pulvérisé, ce qui constitue la quantité maximale de solides pouvant être introduite dans un combustible sans trop en accroître la viscosité. Cette restriction faisait en sorte qu'on ne pouvait récupérer, au moyen du charbon, qu'environ 25 % du pouvoir calorifique du mazout. Ainsi, au fur et à mesure de la montée des prix du pétrole, le besoin de remplacer une plus grande proportion du mazout s'est fait sentir. On a alors construit une très petite usine-pilote pour produire des mélanges charbon-mazout-eau contenant environ 60 % de charbon, 20 % de mazout et 20 % d'eau. Par la suite, on a construit une usine-pilote plus importante qui, selon la technique de Carbogel, permettait de produire un mélange de charbon-eau contenant 70 % de charbon et 30 % d'eau.

L'étape suivante du programme de démonstration avait deux objectifs: mettre au point un système d'approvisionnement en mélange charbon-eau, et choisir et mettre à l'essai des brûleurs pour les chaudières à chauffe frontale de 10 MWe et à chauffe tangentielle de 22 MWe, à Chatham. Environ 5 000 tonnes de mélange charbon-eau ont été utilisées à Chatham et, même si l'on a pu noter d'importantes améliorations, on n'a pas réussi à régler complètement le problème de l'usure des brûleurs. Au début, il a été difficile de maintenir la consistance homogène du combustible à cause du manque d'expérience au stade de la production, d'une attaque microbiologique inattendue et d'importantes fluctuations de la température ambiante. Si les nouveaux modèles de brûleurs résistaient mieux à l'usure, le niveau de combustion du carbone était inacceptable; ce faible rendement de conversion du carbone représente le principal obstacle à l'utilisation des mélanges charbon-eau dans les chaudières. Par conséquent, le programme a mis l'accent sur l'amélioration des brûleurs, les problèmes liés au système d'alimentation en combustible et l'élaboration de normes relatives au combustible non seulement pour permettre aux usagers de vérifier si le combustible qu'ils ont reçu se comportera convenablement, mais aussi pour établir des paramètres en vue de contrôler le processus de fabrication.

Lors d'un projet subséquent également mené à Chatham dans la plus petite unité, on a mis au point un atomiseur en céramique résistant à l'usure, dont la grille de passage d'air permettait une combustion optimale. Au cours de brefs essais de fonctionnement, cet atomiseur s'est révélé entièrement satisfaisant et l'on a observé très peu d'usure.

Le programme de démonstration de la combustion d'un mélange charbon-eau dans une chaudière, à Chatham, a mené à deux projets de démonstration industrielle, l'un utilisant un four de durcissement du minerai de fer et l'autre, un four à ciment à procédé en voie humide. Ayant fait l'objet de projets de démonstration, la technique s'est maintenant passée au stade de l'exploitation sur une base commerciale chez un fabricant de ciment.

L'application du système d'approvisionnement en mélange charbon-eau-mazout est entravée, sauf dans des cas particuliers, tant que le cours international du pétrole demeurera sous le seuil de 20 $ US le baril. Toutefois, il pourrait être avantageux à l'avenir d'utiliser des mélanges charbon-eau pour remplacer le charbon pulvérisé ou le mazout. Par suite d'expériences sur le chauffage au charbon pulvérisé, bon nombre d'experts ont émis la théorie selon laquelle le rendement des chaudières au mazout serait réduit si ces dernières étaient alimentées par un mélange charbon-eau. Cette baisse de rendement serait attribuable à l'absence d'une trémie pour éliminer les dépôts de cendres, à la grosseur inadéquate des chaudières, à la scorification des parois due à la proximité des flammes, à une obstruction causée par l'encrassement de tubes trop rapprochés et à l'érosion provoquée par l'arrivée des gaz à trop hautes vitesses. Tous ces facteurs résultent du fait que les chaudières au mazout sont d'un modèle plus compact, donc moins coûteux, ce qui pourrait permettre de brûler du charbon d'une façon plus économique si la baisse de rendement est minimale. Dans le contexte du Programme canadien de recherche sur les suspensions de charbon, on étudie actuellement la validité des présumées restriction imposées par les baisses de rendement en chauffant le mélange charbon-eau dans une chaudière au mazout à fond plat et à chauffe frontale de modèle compact, à Charlottetown (Ile-du-Prince-Edouard). Les premières observations révèlent que le comportement des cendres est plus inoffensif que les calculs ne le laissent croire et, par conséquent, que les coefficients de baisse du rendement sont peut-être exagérés. Ces observations ont été corroborées par l'étude des dépôts de cendres d'un mélange charbon-eau dans un appareillage d'essai. Il pourrait donc s'avérer possible de faire fonctionner au charbon, avec un rendement proche de la capacité maximale, des chaudières au mazout, à condition que le combustible et les brûleurs soient bien conçus.

On mène également, à l'heure actuelle, des études de R-D sur la combustion, le transfert thermique et la pulvérisation d'un mélange charbon-eau pour appuyer le programme de démonstration. Vous trouverez ci-après des textes remontant jusqu'en 1982 et présentant, dans une perspective historique, les antécédents et la raison d'être du Programme canadien de recherche sur les suspensions de charbon.

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EVOLUTION OF CANADA'S COAL-LIQUID MIXTURE PROGRAM

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ABSTRACT

Interest in coal-liquid mixtures as potential oil replacement fuels has been continuing in Canada since the early seventies. The motives for this interest have been the rapidly rising cost of oil coupled with an insecurity of supply. These factors have caused the western industrialized nations to seek feasible alternatives to petroleum-based fuels.

A description is given of the three phases of an early program undertaken at Chatham, New Brunswick in which coal-oil mixtures were used in a small utility boiler. Phase I of this program showed that burner and equipment wear was a significant impediment to coal-oil mixture utilization. This led to the inclusion of an oil agglomeration coal beneficiation process being incorporated into the fuel preparation process as a means of reducing the sulphur and abrasive ash content of the coal.

The evolution of this early program into the present program of coal-water slurry technology development for utility applications is described in detail, together with other support programs which may enable coal-liquid mixtures to penetrate the industrial and transportation sectors.

1. Introduction

Coal-liquid mixtures could replace oil in many stationary combustors and in some mobile uses provided that they can be burned reliably, cleanly, safely and economically. This paper deals with Canada's approach to development of coal-liquid-mixture technology to meet these requirements. Canada is a net importer of some ten percent of its oil consumption and will become more dependent on foreign oil unless new ways are found to substitute for the depletion of its limited conventional oil supplies. The chosen approach to reducing reliance on imported oil is a multifaceted one which includes conservation, upgrading of bitumens, heavy oils and residuums and replacement by other domestic fuels, particularly natural gas and coal. Coal-liquid mixtures offer a means of replacing oil by coal where direct substitution of a solid fuel is impossible or uneconomic.

In central and western Canada, natural gas and coal are readily available and can be chosen as replacements for oil depending on price and convenience. However, in eastern Canada, the only part of the country where electricity is generated from oil, natural gas has not been generally available and local coal tends to be both expensive and high in sulphur. The need for oil replacement is thus most urgent where it is most difficult to find an economic substitute. Coal-liquid mixtures may ultimately find use in the West or for export but the decision was taken to investigate their potential in eastern Canada because of the most urgent need, because of the possibility of environmental benefits, and because there are more smaller units of a suitable size for demonstration in the East.

Economics dictate that coal-liquid mixtures, because they inherently cost more per unit of energy than coal, must be tailored for a fuel market in which they can command a higher price than coal. To command this higher price, the coal-liquid-mixture fuel must have desirable qualities that its coal feedstock lacks. The primary qualities required, besides combustibility, are behaviour as a liquid with appropriate viscosity for pumping, transportation and storage, minimization of ash-handling and collection requirements, and, a vital selling point in some cases, a decrease in sulphur content.

Utilities and other industries which might use coal-liquid mixtures are generally not in a position to switch to such a fuel or even to assess the economics of switching while there is no proof that it can be burned reliably and safely. The program will therefore demonstrate the combustion of coal-liquid mixtures at small commercial scale, make available trial quantities of coal-liquid mixtures manufactured from Canadian coal, and ensure that all ancillary equipment is available for conversion of larger units. Once these goals have been achieved it is expected that normal commercial practice will take advantage of the technology wherever it is economic to do so.

2. Background

In 1972 the Canadian Combustion Research Laboratory, CCRL, conducted an in-house program to study the combustion and heat transfer characteristics of several coal-oil mixtures in a pilot-scale research tunnel furnace. The results of this work were presented at a joint industry/government seminar in 1972 (1) in order to stimulate interest in coal-oil mixture technology. Subsequent evaluations of the data were presented at the International Flame Research Foundation, IFRF, 4th Members Conference (2) and the ASME winter annual meeting (3) both in 1976. This early research into coal-oil mixture combustion was discontinued because the availability of cheap fuel oil did not make coal-oil mixtures attractive to industry. However, following the rapid escalation of oil prices in the late seventies there was renewed interest in coal-oil mixture technology and Energy, Mines and Resources, Canada, as part of its program to reduce reliance on foreign oil supplies, encouraged this interest by financial and technological support through demonstration projects and R and D.

The first demonstration project was undertaken in three phases from 1977 to 1980 to study the potential for utilization of coal-oil mixtures in a small utility boiler at Chatham N.B.

The Chatham Thermal Generating Station, Unit No. 1 of 10 MW(e) generating capacity was selected for this project, due to its small size, coal design and the fact that it is rarely required to supply electricity to the grid. Thus the unit had the operational flexibility required for the coal-oil mixture study. The boiler, manufactured by Foster Wheeler, is rated at 17.6 kg/s steam flow and is a dual-fired boiler, having the capability for independently firing coal or oil and of simultaneously burning coal and oil using separate burners.

The Phase I coal-oil mixture program at Chatham was begun in 1977/78 and employed simple mechanical mixing of coal, pulverized and collected in a cyclone and baghouse, with No. 6 fuel oil in a blender. The coal-oil mixture was then pumped to the four existing steam-atomized oil burners using a screw type oil pump. Neither the pumps nor the burners were specifically chosen for the coal-oil mixture application and as a consequence significant wear problems which could be attributed to the abrasive coal ash, were encountered. The results of Phase I operation in which a 10 wt % coal-No. 6 fuel oil mixture was burned, have previously been reported in detail(4).

Modifications were made to the coal-oil mixture preparation system during the 1978/79 Phase II program to accommodate the NRC oil agglomeration system. The purpose of the agglomeration process is to beneficiate the coal by partial ash and sulphur removal with a corresponding reduction in materials erosion and stack fly ash and SO_2 emissions. A wet scrubbing system was used to replace the former cyclone-baghouse combination to facilitate collecting the pulverized coal in water for secondary grinding using a wet mill.

The oil agglomeration process(5) has become a key part of the Canadian coal-liquid mixture program where Eastern coals of high ash content are to be used.

The principle of the method is that fine particles in suspension can readily be agglomerated by the addition under agitation of a bridging liquid which preferentially wets the solid particles and is immiscible with the suspending liquid. In the cleaning of coals by grinding in water to release impurities, the carbonaceous constituents can be agglomerated and recovered with many different oils as a collector liquid, while the inorganic constituents remain in the aqueous suspension and are rejected. Conventional gravity methods for the cleaning of coals are not practical for particles finer than about 150 micrometres and methods such as froth flotation which depend upon differences in surface chemistry of coal and mineral matter are used for the finer sizes. Flotation, however, becomes less effective where extremely fine sizes of coal must be processed or if the clay content is high. The oil agglomeration process provides an attractive method for the cleaning and recovery of these fine coal particles in the form of compact, oil-bonded aggregates.

The ability to utilize fine coal particles is particularly useful for coals which contain finely-disseminated impurities as in the case of the New Brunswick coal used at Chatham. These coals can be ground in water to a size sufficiently fine to liberate the required amount of impurities and reconstituted as oil-bonded agglomerates free of the liberated mineral matter. Alternatively, fines contained in waste slurries from conventional cleaning operations can be recovered by oil agglomeration as a low-cost source of clean fine coal. This latter aspect is particularly important where friable coals are being mined.

Two types of burner tips were tried in Phase II, a Y-jet type and a similar burner with replaceable inserts. The burner tip erosion encountered during Phase I still remained a major problem and the performance of the agglomeration system was not as good as had been demonstrated in the laboratory(6). The Phase III program which ended in April 1980 was undertaken with two major objectives, to improve the effectiveness of the agglomeration process and to test two new burners for long-term performance on coal-oil mixture. Neither of these objectives were met primarily due to the equipment wear problems associated with the highly abrasive coal used to make the coal-oil mixture(7,8).

After three phases amounting to more than 1500 hours of operation on coal-oil mixture ranging from 10 wt % to 40 wt % coal, it was concluded that:

The abrasive wear of burner tips has been the main obstacle preventing the successful utilization of coal-oil mixture technology in a small utility boiler in Chatham N.B. The abrasive wear which results in progressive flame deterioration can be attributed to the use of a highly abrasive coal in the coal-oil mixture. The problem still persists even when incorporating an in-line coal cleaning process to reduce the ash and pyrites content of the coal.

Pumps, valves and secondary grinding equipment also suffered from significant wear-related damage which resulted in deterioration of performance. It is felt that this problem can be eliminated by appropriate materials and equipment design considerations. Pipework was relatively unaffected by wear, essentially due to the low prevailing fluid velocities.

The major problem of burner tip erosion may be solved by choice of a less abrasive coal, improved coal cleaning by ash and pyrites rejection, further reductions in coal particle size, materials selection or the use of externally atomized burners with low coal-oil mixture efflux velocities and a simple configuration.

In 1980 and 1981 a pilot plant for production of coal-oil-water mixtures was constructed in Dartmouth, Nova Scotia, with assistance from the governments of Canada and Nova Scotia through their Oil Substitution and Conservation Agreement. This pilot plant is designed to produce about 5 tonnes per hour of coal-oil-water mixture containing about 60 percent coal, 25 percent oil and 15 percent water. Special proprietary features of the preparation process include a specially designed grinding mill, ultrasonic stabilization of the mixture, and spherical agglomeration to reduce mineral matter. Production and small-scale combustion of fuel (known by the proprietary name of Scotia Liquicoal) from this plant have progressed well, apart from the severe wear on burner tips which paralleled early experience at Chatham. The relative advantages of a coal-oil-water mixture over coal-water are its better ignitability and reactivity and less susceptibility to freezing: the relative disadvantages are that it requires a substantial proportion of oil and that its viscosity varies widely with temperature.

In developing a marketing strategy for their product Scotia Liquicoal conducted field trials in small commercial installations to demonstrate the feasibility of burning their fuel . During these boiler evaluations, burner tip erosion remained the major problem which the company was then compelled to address as a matter of some urgency. Using the experience gained at Chatham and in consultation with experts at the National Research Council (NRC) and the Canada Centre for Mineral and Energy Technology (CANMET), a ceramic burner tip was selected and spray tested for 200 h on coal-oil-water mixture under a simulated operating conditions. When this nozzle was compared to a conventional Y-jet tip the abrasive wear was less than one percent compared to 40 percent for the Y-jet (measured as the percentage increase in flow due to flow channel wear under standard test conditions(9)). The ceramic nozzle has now been rigorously tested under intermittent and steady conditions without failure despite some extreme thermal shock procedures. The company now plans to test the nozzle in a 1000 h demonstration in an industrial boiler or kiln.

3. Current problems and opportunities

The price range which coal-liquid mixtures can command is determined by competing fuels. In large industries and electric utilities these fuels are usually residual oil, Bunker 'C' or coal. Smaller energy consumers use No. 2 or No. 4 fuel oil or natural gas which, in Canada, may also be used in larger industries and utilities. For most of these users, the prices per unit of energy for the competing fluid fuels are approximately two-thirds that of crude oil. In order to attract customers by pricing significantly below that of the competition, coal-liquid mixtures must therefore sell for less than 60 percent of crude oil prices on a heat value basis. The most expensive Canadian coal sells for about 40 percent of the crude oil price so where direct use of coal is possible it is the most attractive fossil fuel. However, where solid fuel cannot be used, even if the starting material for a coal-liquid mixture is one of the more expensive Canadian coals, there is about a 50 percent margin above its regular price available to cover additional preparation costs and return on investment.

Feedstock costs all but preclude the use of coal-oil mixtures since, at the upper physical limit (about 50 percent) of coal concentration, the cost of coal, oil and preparation exceed the price of competing fuels. There may be an exception to this generalization in the case of proprietary fuels containing about 25 percent oil, 15 percent water and 60 percent coal, particularly for modest scale heating plant and marine use, but overall the Canadian coal-liquid-mixture program has veered away from its early interest in coal-oil mixtures on economic grounds.

Canada has the objective of decreasing its atmospheric emissions of sulphur oxides by 50 percent between 1980 and 1990 and the substitution of low sulphur coal for residual oil can materially assist in reaching this objective. The multistage cleaning process associated with coal-liquid mixtures can reduce medium-sulphur coal to this desirable state. However, even where such mixtures might be chosen as an oil substitute preferable to coal on environmental grounds alone, such as in a furnace originally designed to burn coal but later switched to oil (to minimize particulate as well as sulphur emissions), the competitiveness of clean-burning natural gas sets an upper limit to the price.

In utilizing coal-oil mixtures in utility boilers, particularly those designed for oil-firing, many problems arise which must be overcome. Usually an oil-designed boiler is smaller, the steam-raising tube banks are configured differently and the gas velocities in the banks much higher than for an equivalent capacity coal-fired unit. In addition to this, coal slurry fuels contain ash which poses problems of tube erosion and slagging and/or fouling. The ignition, flame and heat transfer characteristics of coal-oil mixtures may be quite different from those of heavy fuel oil and therefore the heat release pattern from the flame may not be suitable for the oil-designed unit. The combination of all these factors usually means that the oil-designed unit will be derated; that is it will not be able to attain the maximum generating capacity for which it was designed when firing oil. The extent of this loss of electrical output will depend on the coal, its rank and reactivity, (volatile matter, inert macerals content, degree of oxidation) as well as the ash content and composition and the slagging/fouling propensity of the ash.

A coal-liquid mixture which burns well is not necessarily ideal for transportation or storage. The mixture should ideally have a low viscosity which does not vary with temperature and should be readily pumpable after long periods of storage. It should not freeze in anticipated weather conditions. It should contain a minimum of inert components to minimize transportation and storage costs. At the present stage of the program, transportation of coal-liquid mixtures will be by road, rail or barge, therefore the ultimate requirement for very low viscosity, which is needed for pipeline transportation, can be waived but the need for maximum concentration of combustibles remains.

Removal of mineral matter from coal is important for boiler performance, for economy of distribution, for ash disposal, and for environmental protection. Conventional coal beneficiation removes much of the adventitious mineral matter but cannot extract minerals that are very finely interspersed or are part of the molecular structure of the coal. In the case of sulphur, the occurrence may be in pyritic, sulphatic or organic form. Very finely divided pyritic sulphur is often reported as organic because it is so difficult to remove by physical means. In Canada most beneficiation is currently applied to coarser coking coals, however, where coals will be burned as a slurry and fine grinding is essential, advantage can be taken of this grinding to liberate sulphur compounds and other minerals. Therefore in the preparation of coal-liquid mixtures, conventional washing is followed by milling and separation on the basis of surface characteristics: froth flotation for coal-water mixtures and oil agglomeration for coal-oil-water mixtures. Coal from the Sydney coalfield in Nova Scotia is particularly amenable to this combination of processes and shows promise of good yields with mineral matter in the 1.5 to 3 percent range and with about two-thirds of the original sulphur removed.

Several estimates have indicated that deposition of slag on the tubes of boilers tightly designed for oil firing would contribute very substantially to boiler derating which could be as much as 50 percent when coal is used as fuel. The site chosen for preliminary tests was again the generating station at Chatham, New Brunswick since it has two boilers originally designed to burn coal but recently adapted to burn oil, one front-wall fired and one tangentially fired, and of 12 and 23 MW(e) capacity respectively. The results obtained at Chatham, where coal-liquid-mixture burners will replace oil nozzles, will yield, at a small utility scale, virtually all the data required to assess burners and fuel without risk of damaging a bigger furnace or of seriously interrupting electricity supply.

4. Objectives of Present Program

The ultimate objective of the coal-liquid-mixture program is to derive enough data concerning the fuels and how to burn them that potential users will be able to make decisions to replace oil, based on economics and without technical risk. An essential sub-objective is the establishment of a quality-cost-price relationship. Obviously it costs more to prepare a high quality (i.e. low sulphur, low ash) mixture than a low quality one. Research into the application of oil agglomeration to coal-oil-water mixtures has indicated the costs in terms of light oil addition for various levels of rejection of mineral matter including sulphur. Depending on the fineness of grind and mineral content needed, light oil requirements may vary from 1 to 5 percent of coal weight. For coal-water mixtures, conventional cleaning applied to the highest quality coal can reduce mineral matter to 3 percent and sulphur to 1.2 percent: grinding and multistage flotation can reduce these levels to 1.5 percent and 0.8 percent respectively: if lower quality (less expensive) coals are used, the same process is expected to attain about 3 percent minerals and 1.5 percent sulphur, the cost difference being in the starting feedstock rather than in the process.

The program will include preparation and combustion of the cleanest coal-water mixtures that can be manufactured as well as fuels containing more ash and sulphur. This range of fuels will enable an economic assessment to relate cost of production to saleability and price which is one of the major objectives.

Use of coal-liquid mixtures by utilities requires a delivery and storage system, including stirring vessels where necessary, and pumps which can deal with fluctuations in diurnal and seasonal demand. The program will demonstrate methods of transportation which would be applicable to industrial users and at least one of the combustion tests will be scheduled in freezing weather so that any problems due to low temperature operations can appear and be solved. Addition of antifreeze may be necessary, this will add to the cost but may improve combustion characteristics or cause corrosion problems.

The performance of utility boilers designed for oil will be significantly different when using coal-water mixtures. The problem of unit derating has already been mentioned and each unit to be converted will need a detailed individual assessment to ascertain its loss in electrical generating capacity when firing a typical coal-water mixture. Again, the derating will depend strongly on the fuel and the boiler design. One of the objectives of the current program is to provide data for the determination of the inter relationship between quality and quantity of mineral matter in the coal-water fuel, the flame and unit derating. The utility company will then determine the net loss in its system generating capacity if several units are to be converted to coal-water fuel. It must be noted that a significant requirement of the coal-water mixture program is that the slurry burners be also able to utilize fuel oil, thereby retaining the capability to attain full generating capacity during peak demand periods.

Assuming successful demonstrations at Chatham, the next step will be to design systems for burning coal-water fuel in larger utility units. In eastern Canada there is a 100 MW(e) front-wall fired unit which originally used coal but was converted to oil in 1969 to minimize particulate emissions; there is also a 50 MW(e) tangentially fired unit designed for oil-burning. The current program embraces the design of coal-water systems for these two units.

5. Details of Present Program

The present program comprises several elements which will combine to achieve the objectives set out above. These are construction of a 5 tonne per hour pilot plant at Sydney, Nova Scotia, for preparation of a coal-water mixture containing about 70 percent coal, the design of burners suitable for reliable combustion of this fuel, the demonstration of the use of fuel and burners at Chatham and the design of coal-water burner systems for larger units. The fuel preparation pilot plant will treat clean coal (- 3 mm) from an adjacent conventional dense medium coal preparation plant which reduces the mineral matter content from about 8 percent to 3 percent. The pilot plant will comprise two stages of grinding, particle size control, two stages of froth flotation (further reducing the mineral matter to about 1.5 percent) and the mixing to add a stabilizer. The process is based on the proprietary CARBOGEL process. The target solids content is 75 percent with viscosity in the 800-1000 centipoise range. Attempts will be made to use different coals with higher mineral matter and sulphur contents, and with poorer washability characteristics: use of high (coking) quality coal is planned for the first trials to minimize problems with ash handling but coal from a seam with lower quality could save $20 per tonne (of coal). The prepared fuel will be held in day-storage tanks for regular delivery by tank truck (three trucks per day for some 750 km) to Chatham: storage tanks of 500 m^3 capacity already in existence at Chatham will form the buffer to match demand with production capacity. Fuel production costs will be recovered by the producer through the price charged to the electric utility. The utility will pass on the differential between this price and normal coal-fired generating costs, as well as the cost of burner development, to the federal government. The schedule, which calls for construction of the pilot plant to begin in August 1982, should be completed by March 1983 with start-up tests in April and May and regular fuel production in June 1983.

Concurrently with the construction of the coal-water pilot-plant preparation facility, a program to develop slurry burners for the 10 MW(e) front-wall fired and 22 MW(e) tangentially fired units at Chatham NB will be undertaken. The two phases of the coal-water program are as follows:

Phase I:

Design, testing and evaluation of a burner rated at approximately 30 GJ/h thermal input, of a type suitable for coal-water slurry fuel combustion in the 10 MW(e) front-wall fired Chatham Unit No. 1. A testing and evaluation program for the burner together with boiler performance assessment will be developed for the performance trials in Chatham Unit No. 1 to be undertaken during Phase III. A similar program for tangentially fired units will be undertaken leading to performance trials in Chatham Unit No. 2 of 22 MW(e) capacity.

Key elements of Phase I will be a review of the state of the art of coal-liquid mixture burner technology and recommendation of the most promising burner concepts for coal-water mixture firing for each boiler configuration. Full scale burners will then be designed and tested prior to installation in the units at Chatham NB.

Phase II:

This phase will be to assess burner and boiler performance when firing coal-water mixtures in front-wall and tangentially fired boilers, with special emphasis on reliability of equipment. It is anticipated that 6000 tonnes of fuel will be prepared for the performance trials, 2000 tonnes for Unit No. 1 and 4000 tonnes for Unit No. 2. The fuel will contain less than 2 percent ash and be similar to that used in Phase I for burner development. The Phase II performance trials are currently scheduled for the Spring of 1983. It is expected that these two phases should lead to the scale-up and testing of burners for demonstrations of coal-water mixture technology in oil-designed utility boilers in the 50 to 150 MW(e) capacity range and of both basic configurations typical of eastern Canada.

During the last five decades, coal has been considered as a possible fuel for diesel engines. This interest has usually been moderated by the fact that until fairly recently, the availability of relatively cheap diesel fuel together with its ease of use has made other fuels, unattractive. For the same reasons that coal-liquid mixtures are now receiving attention as industrial and utility fuels, a coal-based diesel fuel becomes more attractive. Chemically processed coal-derived fuels are very costly and some attention is now being given in Canada to mixtures of very clean coal and diesel fuel as a means of reducing the consumption of expensive refined petroleum products in diesel engines. Obviously high speed diesel engines are unsuitable for coal-liquid mixtures, but the low and medium speed diesels with longer combustion chamber residence times may be suitable for less reactive fuels such as coal-liquid mixtures. The major problem with the use of coal-liquid mixtures in diesel engines is likely to be the injector and the possibility of abrasive wear and premature failure. In order to address this problem CANMET and the NRC have been studying injector performance using a clean coal-diesel fuel mixture. The feed coal supplied was 3.3 percent ash Nova Scotia coal which was then cleaned by the oil agglomeration process to less than one percent ash. In the final mixture, the clean coal was mixed to 28 wt percent with diesel fuel and was 90 percent less than 10 micron. Some problems with stability were observed but it was concluded that with some modification and materials hardening the injector would withstand prolonged use. It is now planned to conduct stationary combustion tests in a medium-speed diesel locomotive engine.

In its role of technology support to the various coal-liquid mixture projects that are being undertaken, CANMET is involved in contract and in-house research to address the following key problem areas:

1) Burner development for coal-liquid mixtures including the study of abrasive wear of atomizer components.

2) Assessment of the potential loss of capacity (derating) when converting oil-designed boilers to coal-water mixtures.

3) Slagging and fouling assessments of coal-liquid mixtures in utility and industrial boilers and combustors.

4) Parameters for upgrading existing and designing new environmental control equipment for oil-fired boilers when converting to coal-liquid mixtures.

5) Combustion and heat transfer properties of coal-liquid mixtures in various combustion system configurations.

6) Upgrading coal quality by advanced cleaning techniques in order to minimize abrasive wear and to reduce environmental emissions of sulphur dioxide and flyash.

6. Current Progress

At the time of writing, formal contracts have been signed among the Cape Breton Development Corporation, the New Brunswick Electric Power Commission and the federal government to conduct the program, Cape Breton Development Corporation has entered a licensing agreement with Boliden - Scaniainventor to use their CARBOGEL process, the detailed design of the pilot plant has been finalized, requests for proposals have been issued and five bids have been received for design and development of burners for front-wall and tangentially fired boilers. Foundation work for the pilot plant has begun and two batches of coal-water mixture of 30 tonnes and 150 tonnes have been produced in Sweden using Nova Scotian coal. These batches have met the design objectives of less than two percent ash and more than 70 percent coal with a viscosity less than 1000 centipoises; the sulphur content was reduced from about 2.5 percent in the raw coal to below one percent; the weight yield of coal to fuel was over 80 percent and the heating value yield over 90 percent.

7. Future Program

The major emphasis of the current program is to assess whether coal-water mixtures are feasible for use in utility boilers. There will obviously be many side benefits of the program in the industrial sector, particularly in the area of burner development for coal-water mixtures. Because of the much wider variety of types of industrial boilers and process combustors it is clear that the non-utility development of coal-liquid mixture technology will be much more difficult. A start has been made in this direction with the development of the ceramic atomizer by Scotia Liquicoal, and it is anticipated that this burner will require industrial demonstration in boilers, kilns, both of which are drastically different in their burner, flame shape and heat transfer requirements. However, whilst much scale-up information will be generated as larger utility demonstrations proceed, the small Chatham units are typical of many industrial boilers which may directly utilize the operating experience gained there. Consequently, at the conclusion of the coal-water mixture program in eastern Canada, some of the industrial sector, particularly large kilns and boilers, may convert to coal-water mixtures as fuels. However, smaller units, which may not be large enough to accommodate this slower burning unreactive fuel, may be compelled to use coal-oil or coal-oil-water mixtures. There will be need for significantly more R and D support for the penetration of coal-liquid mixtures into the industrial, marine and diesel markets.

Following the Chatham demonstrations, scale-up is the next obvious step. Design of burners for front-wall or tangentially fired boilers in the 50 to 150 MW(e) range is planned as a third phase of the coal-water mixture program. A start has been made on a generalized derating study which uses modelling techniques to predict boiler performance when boilers designed for oil are fired with coal-water mixtures. A priori reasoning cannot predict specific derating effects because there is insufficient experience connecting the formation of ash from coal-water flames burning finely ground coal in an atomized spray to slagging or erosive effects on boiler tube surfaces. When more information concerning ash properties and ash formation is available from the current work, the program will go on to include specific application studies to 100 and 150 MW(e) oil-fired boilers in Nova Scotia which will predict the minimum overall cost, by balancing the costs of boiler derating against those of fuel beneficiation.

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Feb. 15, 1985

COAL WATER FUEL

Pilot Production Plant
Sydney, Nova Scotia

Burner Demonstration
Chatham, New Brunswick

EXECUTIVE SUMMARY

A Joint Project By:

The New Brunswick Electric Power Commission

Cape Breton Development Corporation

Energy Mines and Resources Canada

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EXECUTIVE SUMMARY

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COAL WATER FUEL
PILOT PRODUCTION PLANT, SYDNEY, NOVA SCOTIA
BURNER DEMONSTRATION, CHATHAM, NEW BRUNSWICK

EXECUTIVE SUMMARY

Project Background

The importance of coal-liquid fuel technology arises from its potential for direct heavy fuel oil replacement in industrial and utility boilers.

The price and supply advantage of domestic or foreign coal provides significant economic incentive for oil substitution, particularly where minimum capital investment is required for conversion of existing oil fired equipment.

Furnaces and fuel handling facilities originally designed for oil firing require wholesale modification and replacement to accommodate conventional pulverized coal firing. A coal-based liquid fuel possessing heavy oil-like handling and burning characteristics therefore offers significant attraction for substantial and early oil displacement.

Interest in coal-liquid fuels has continued in Canada since the early 1970's when the Canadian Combustion Research Laboratory of Energy Mines and Resources Canada undertook an in-house program to study the combustion characteristics of coal-oil mixtures in a research furnace.

This early work, as well as rising world oil prices, led to a three phase coal-oil mixture demonstration project at NB Power's Chatham Generating Station between 1977 and 1980.

The Chatham Station, which is normally on 72 hour standby for power generation on the New Brunswick system, has the facilities, support staff and operational flexibility to conduct full scale burner and fuel evaluation tests.

The Chatham station comprises two units, 12.5 Megawatt (MWe) Foster Wheeler front wall fired boiler and the 22 Megawatt (MWe) Combustion Engineering corner-fired boiler, both originally designed for pulverized coal burning and later converted to oil firing. The Chatham station offers the dual advantages of alternative boiler designs and the larger furnace volumes typical of coal firing equipment. These units, constructed in 1948 and 1956 respectively, have been well maintained and are still occasionally called upon for electrical generation.

In April of 1982, Energy, Mines and Resources Canada (EMR) the Cape Breton Development Corporation (CBDC) and the New Brunswick Electric Power Commission (NBEPC) entered into an agreement to demonstrate and evaluate continuous preparation of a coal-water fuel and its subsequent burning in a utility boiler. The agreement provided $5.5 million to carry out this work, and was amended to include evaluation of winter operation.

To this end, C.B.D.C. entered into a secondary agreement with A.B. Carbogel of Sweden to manufacture a coal-water fuel (CWF) under license, utilizing the proprietary "Carbogel" technology.

The primary agreement provided for the construction of a 4 tonne per hour continuous process CWF pilot scale preparation plant near Sydney, Nova Scotia and the operation of this plant to prepare 6000 tonnes of "Carbogel" CWF. The product was transported to New Brunswick for fuel and burner testing and evaluation at N.B.E.P.C.'s Chatham Generating Station. The selection and development of suitable burners for CWF was to be undertaken by N.B.E.P.C. through contracts with major combustion equipment manufacturers.

The project was administered by a Steering Committee comprising representatives of EMR, C.B.D.C., AB Carbogel, the Nova Scotia Power Corporation and N.B.E.P.C. N.B.E.P.C. assumed overall responsibility for the project and provided the Project Manager. Technical advice was provided through a Technical Committee comprising representatives of the organizations on the Steering Committee as well as the National Research Council, New Brunswick Research and Productivity Council, Ontario Hydro, Electric Power Research Institute and the Atlantic Coal Liquid Mixtures Working Group.

Project Summary

This project demonstrated the start-up and operation of a continuous pilot scale production plant for CWF and its transportation, handling and combustion in two small utility boilers. Operational and fuel handling constraints were identified and evaluated under conditions comparable to a year round full scale commercial operation.

The construction, start-up and operation of the pilot fuel preparation plant provided valuable information and experience relative to the practical feasibility of CWF production in general and the Carbogel process in particular. Controlling production variables were identified and studied and the performance of specific equipment used in the manufacture of CWF was evaluated.

The manufactured fuel was transported under typical year round eastern Canadian weather conditions using both insulated and uninsulated rail tank cars en route for varying periods of time. Specifically designed and developed fuel handling equipment and procedures were assessed for the loading and unloading of railcars, the transfer, storage and delivery of CWF. Special precautions, including recirculation and reprocessing, were taken as required to maintain the fuel in a workable state of fluidity for burner demonstrations.

Prototype coal-water burners were selected and developed for both the front fired and corner fired Chatham boilers and these burners were operated on CWF using both air and steam atomization. The capability of the burners to effect on-line fuel switching between heavy oil and CWF was tested and evaluated. Boiler operation on CWF was monitored and evaluated using heavy fuel oil operation as the basis of reference.

Comparison of performance was made where possible between types of fuel handling equipment used, piping layouts, storage configurations and materials of construction. The design of such key components as burner atomizer nozzles and valves was evaluated.

The project simulated and evaluated the operating conditions to be expected with commercial scale CWF preparation, delivery and utilization by a utility or industrial user.

General Conclusions

This new fuel was manufactured, transported, stored, pumped and burned with a remarkably high degree of success, despite difficulties such as consistency of C.W.F. manufacture, degradation in shipment, transportation in difficult weather conditions, separation in storage, and the need to modify burners.

It is important to note also that many aspects of the experience gained on this project apply to all coal-water fuels while some may be specific to the CBDC "Carbogel" fuel only.

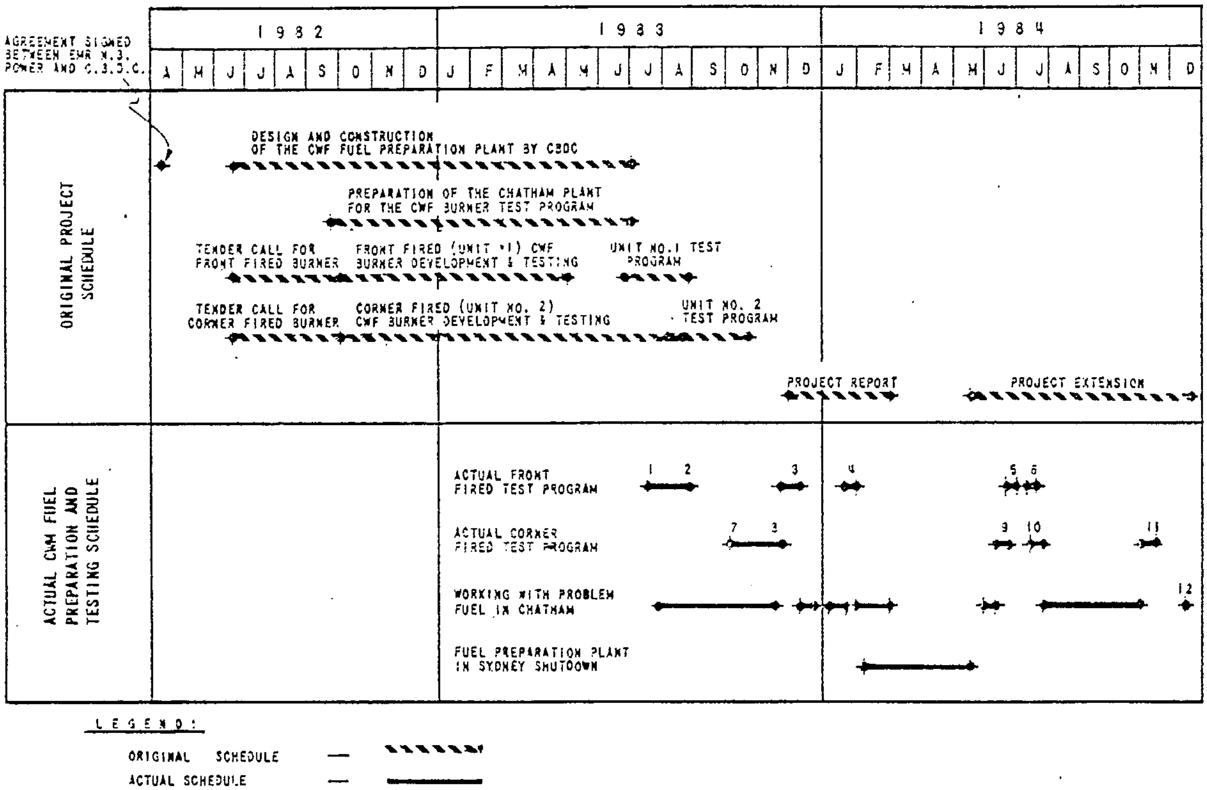
Future of Coal-Water Fuel

While development work remains to be done in the areas of fuel quality assurance, transportation, burner front fuel control and burner design, these constraints appear to be no more insurmountable than should be expected for any developing technology.

In fact, coal water fuels can reasonably be expected to provide a viable and competitive alternative to heavy fuel oils with only marginally different handling and combustion characteristics.

FIGURE 1.1

PROJECT SCHEDULE
FOR THE CHATHAM COAL WATER FUEL BURNER
DEVELOPMENT PROJECT



TEST PROGRAM MILESTONES (ACTUAL)			DATES FROM	TO
UNIT NO. 1 - ACTUAL TEST PROGRAM	1	BASE-LINE OIL TEST	JULY 19	JULY 20/83
	2	100 HOUR WEAR TEST ON ALL ATOMIZER TIP MATERIALS	JULY 23	AUG. 19/83
	3	FULL LOAD TEST WITH C.W.F. ON UNIT NO. 1	JULY 27 AND	DEC. 6/83
	4	BURNER AND BOILER EFFICIENCY TESTS WITH C.W.F. ON UNIT NO. 1	1st - JAN. 19	JAN. 20/84
	5		2nd - JUNE 27	JUNE 28/84
	6		3rd - JULY 16	JULY 17/84
UNIT NO. 2 - ACTUAL TEST PROGRAM	7	BASE-LINE OIL TEST	OCT. 26	OCT. 27/83
	8	UNSUCCESSFUL BURNER TESTS	OCT. 3	NOV. 23/84
	9	MODIFIED UNIT NO. 2 BURNER SUCCESSFULLY TESTED WITH C.W.F.	-	JUNE 14/84
	10	FULL LOAD WITH C.W.F. ON UNIT NO. 2	-	JULY 24/84
	11	BURNER & BOILER EFFICIENCY TEST WITH C.W.F. ON UNIT NO. 2	NOV. 7	NOV. 9/84
BURNING COAL WATER FUEL	12	THE LAST OF THE C.W.F. IN CHATHAM WAS BURNT		DEC. 18/84

TABLE 2.1
PROJECT MILESTONES

April 1982	Agreement signed between EMR Canada, NBEPC and CBDC.
September 1982	Front-fired burner development contract awarded to Foster Wheeler (Canada) Ltd.
September 1982	Corner-fired burner development contract awarded to CE Canada Ltd.
October 1982	Start of construction of the CWF preparation Plant at Victoria Junction near Sydney, Nova Scotia.
December 1982	Test firing of the front-fired burners in FWL/Forney test facility.
June 1983	Test firing of the corner-fired burners in CE/KDL test facility.
July 1983	Start-up of CWF production at the fuel preparation plant.
July 1983	Base-line oil test on Front Fired Unit. First firing of the CWF in the Front Fired Unit. Unit No. 1 run at full load on CWF without support ignition.
August 1983	100 hour test completed on the Front Fired Atomizers.
October 1983	First firing of the CWF in the corner-fired boiler. Base-line oil test on the Corner Fired Unit.
January 1984	Winter Transportation of CWF. 1st performance test on the Front Fired Unit.
February 1984	Modifications to the Corner Fired Burners and Boiler.
Feb. to May/84	No CWF shipped to Chatham during this period.
June 1984	Corner Fired Unit in service burning CWF, without support ignition. 2nd performance test on the Front Fired Unit.
July 1984	3rd performance test on the Front Fired Unit. Corner Fired Unit run at full load on CWF.
November 1984	Performance test on Corner Fired Unit with air and steam atomization.
December 1984	All firing of CWF under this project completed.
February 1985	Cleaning of all rail tank cars completed, and cars returned to car leasing company in Montreal.

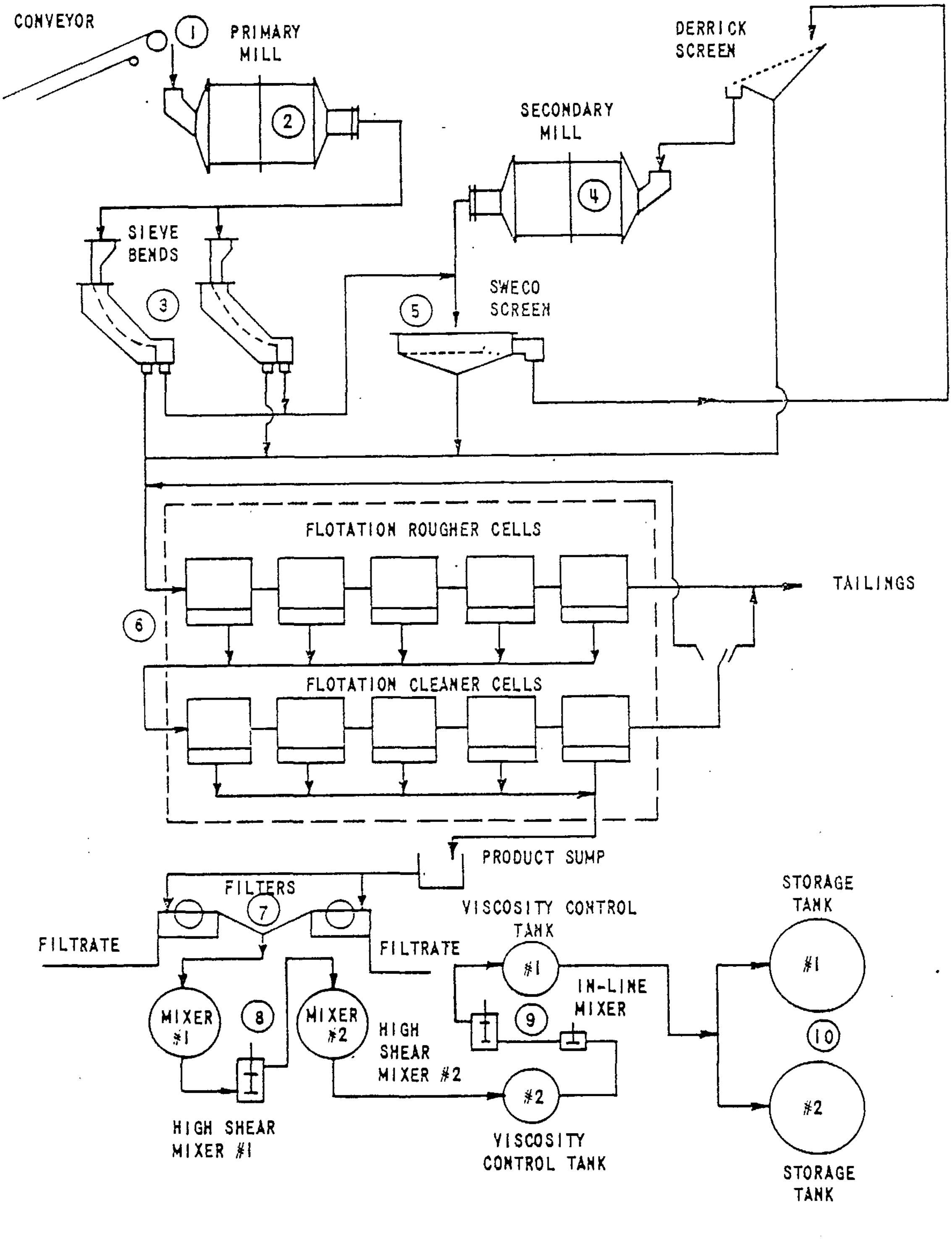


FIGURE 1.2
FLOW SHEET FOR CWF PREPARATION

FUEL PREPARATION AT VICTORIA JUNCTION
SYDNEY, NOVA SCOTIA

CWF Preparation

Cape Breton Development Corporation selected a site adjacent to its Victoria Junction coal preparation facility near Sydney, Nova Scotia for construction of the pilot scale "Carbogel" CWF production plant thereby accessing a variety of existing services. The process flowsheet, material balances, equipment requirements and specifications were developed with the assistance of AB Carbogel. Construction of the plant began in October, 1982, with first CWF production in July, 1983.

The process involves fine grinding of coal followed by size classification and two stage beneficiation resulting in a fine coal feed having a lower ash and sulphur content than the parent coal. Dewatering of the feed coal to approximately 25% is followed by chemical addition and two stage slurry mixing to produce a fluid mixture. CWF conditioning and viscosity adjustment is done in two, 70 tonne tanks equipped with mechanical mixers. The CWF product is pumped to storage in one of two 130 tonne storage tanks equipped with mechanical mixers.

The process is depicted in the following flowsheet. The steps in the process are as follows;

Fig 1.2 Flow Sheet for CWF Preparation

1. Feed is supplied via a hopper and conveyor belt.
2. Open circuit primary grinding of the raw coal by wet-milling in a 1.5m x 2.5m ball mill.
3. Size classification of the primary discharge on sieve bends.
4. Closed circuit secondary grinding of the classification oversize by wet-milling in a 1.5m x 2.5m ball mill with in-circuit screen.
5. Size classification of the secondary discharge on a Sweco screen overflow is recirculated to the secondary mill while the underflow goes to the process.
6. Two-stage froth flotation of the sieve bend underflow for cleaning of the ground coal.
7. Dewatering of the cleaned coal to about 25% moisture by rotary drum vacuum filters.
8. Chemical addition and slurry mixing in two mixing tanks operated in series.
9. Slurry conditioning with added stabilizer in two 70-tonne viscosity control tanks with mechanical stirring.
10. Fuel storage in two 130-tonne final storage tanks with mechanical stirring.

TABLE 2.2
Feed Coal and CWF Characteristics

	Washed Coal		CWF	
	As Rec'd Basis	Dry Basis	As Rec'd Basis	Dry Basis
Moisture %	8.0	-	30.0	-
Ash %	2.8	3.0	1.2	1.7
Sulphur %	1.1	1.2	0.6	0.9
Volatile Matter %	33.6	36.5	26.0	37.0
BTU/lb	13,550	14,750	10,500	15,000
MJ/kg	31.5	34.3	24.4	34.9

	No. Fuel Oil	CWF
Specific Gravity	0.95	1.18
BTU/Gallon	180,000	124,000
Viscosity Centipoise $(35 s^{-1})$	100 (At 75°F)	1,000 (at ambient temp.)
Maximum Particle Size	---	250 microns

The time frame between pilot plant construction and startup did not permit a comprehensive commissioning of plant equipment in the fuel manufacturing process. As a result, several design problems were encountered in the early stages of production, some of which required a plant outage to correct. It is important to point out that this new fuel was being produced for the first time on a continuous basis at a design rate of 4 tonne per hour. Despite early technical difficulties in the plant operation, the fuel was manufactured with a high degree of success. The experience gained on this project will undoubtedly translate into technical improvements to the manufacturing process.

TRANSPORTATION OF FUEL FROM SYDNEY, NOVA SCOTIA TO CHATHAM, NEW BRUNSWICK

CWF Transportation

Transportation of CWF for this project was not limited by facilities either at Victoria Junction or Chatham.

Although various methods of transportation were initially considered including road, rail and sea transport, practical considerations relating to the rate of CWF production, storage capacities at both Victoria Junction and Chatham as well as the storage capacity in-transit all favored rail transportation. Road transportation while versatile and quick, was eliminated due to high cost and limited in-transit storage capacity. Sea transportation could be considered only if large shipments of fuel were to be made. Rail transportation using conventional rail tank cars proved to be most attractive on a unit cost basis and had the advantage of adequate in-transit storage capacity to compensate for normal variations in the rate of CWF production and use.

Transportation of CWF was initially planned for summer conditions, however, the program was extended requiring modification of systems for a year-round cycle with various periods of time in-transit. Equipment, facilities and operating conditions were evaluated.

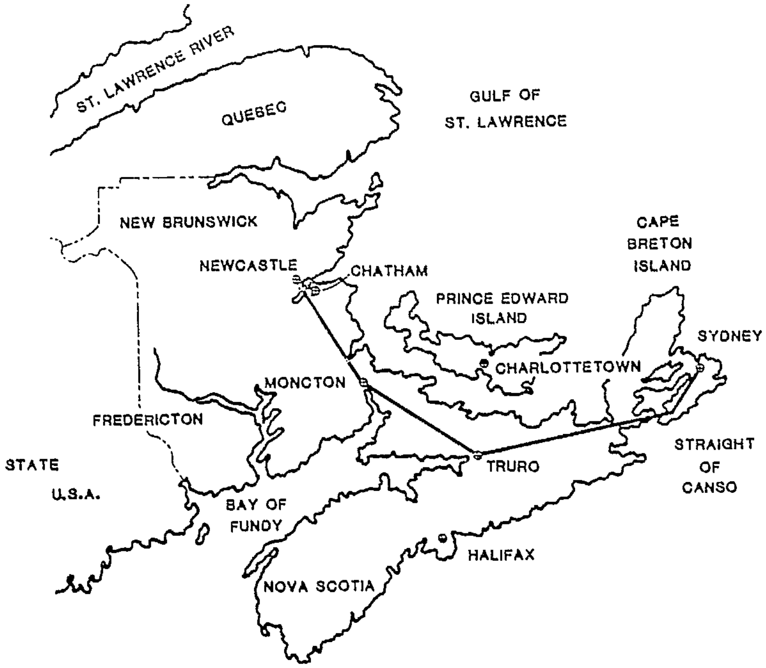


FIGURE 1.3

MAP SHOWING TRANSPORTATION ROUTE

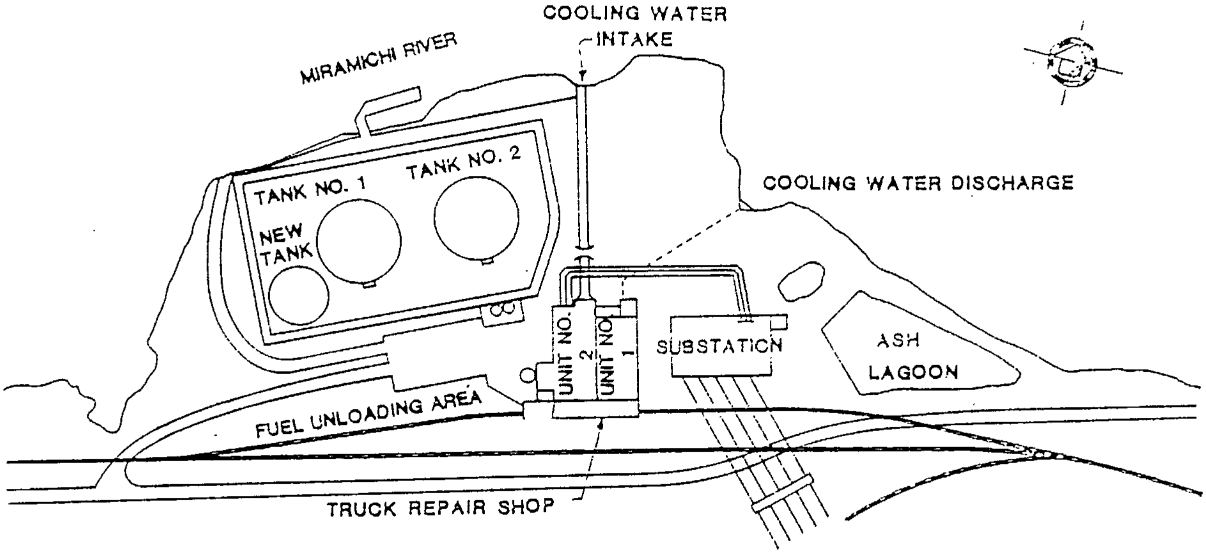


FIGURE 1.4

SITE PLAN OF THE
CHATHAM THERMAL GENERATING STATION

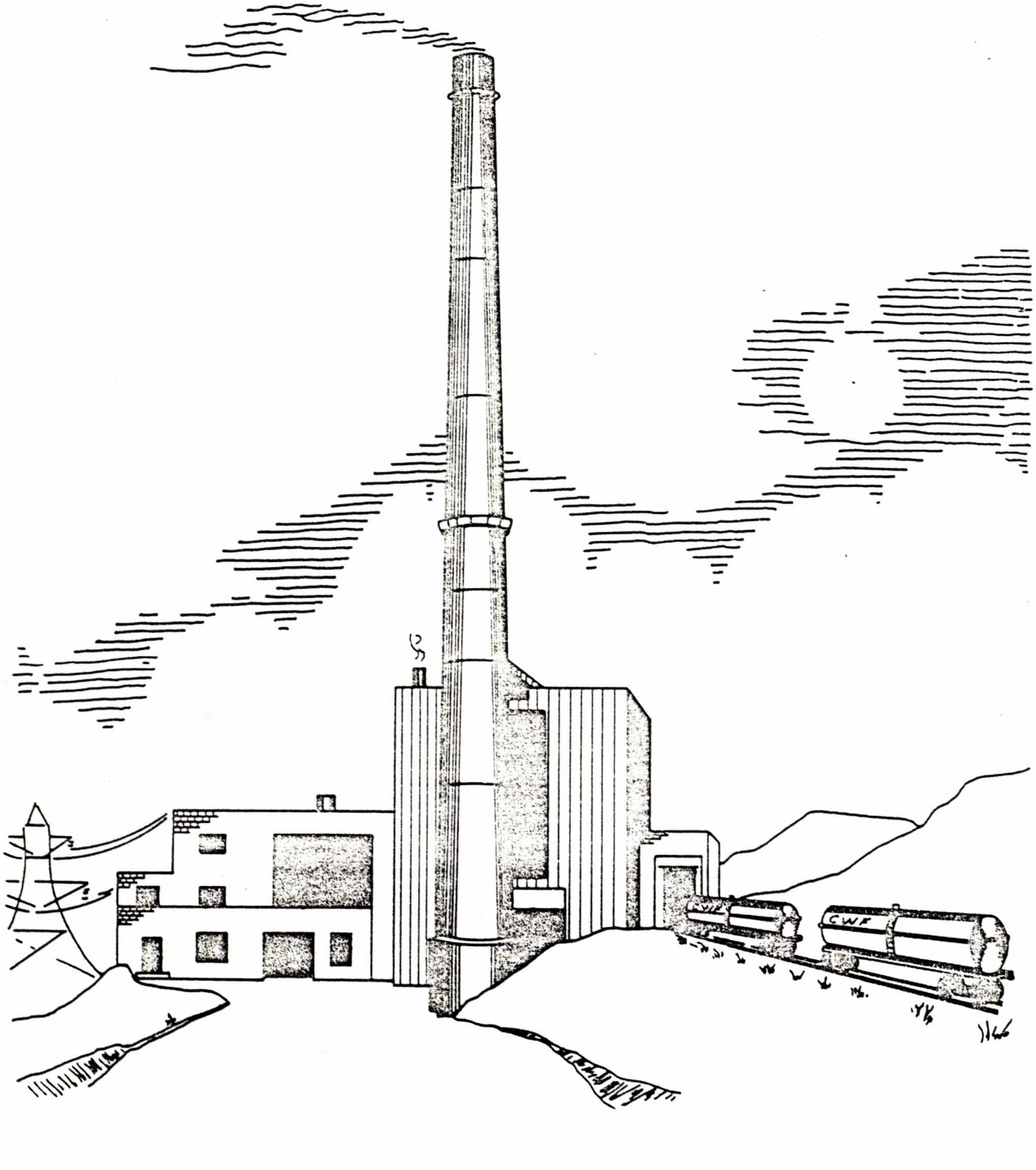


FIGURE 1.5

VIEW OF THE CHATHAM THERMAL GENERATING STATION

FUEL HANDLING

CWF Handling at Chatham

A major consideration with respect to coal fuel technology is the evaluation of its handling characteristics. The degree to which the product exhibits oil-similar pumping, recirculation, storage and other rheological characteristics will be a key determinant in its successful implementation for direct coal-for-oil substitution.

At Chatham, it was necessary to retain the existing heavy oil handling system both for purposes of availability of generating capacity and as the basis of comparison with CWF during burner demonstrations. Because oil and CWF are not readily compatible in the same piping, a new CWF handling system was designed and installed at the Chatham Plant based on best available information on the material and its characteristics. This system comprised a fuel unloading facility at the Chatham Station rail siding with a capacity to accept three railcars. Pumps were installed in the plant to transfer the fuel to a reconditioned and reinforced coal storage bunker which served as a 200 tonne storage tank for CWF. From here, the fuel flowed by gravity to the suction of a fuel delivery and recirculation pump feeding a specially designed piping circuit to either of the two Chatham furnaces. Fuel flow to the burners was controlled by a recirculation control valve station located downstream of the burners. Unused CWF was returned to the storage tank. The system could be operated in a full or partial recirculation mode for fuel mixing and to prevent settling. Progressive cavity (moyno) type pumps were used and the piping system was generously sized and as straight as possible to minimize pressure drop. Care was taken in layout of the piping system to allow for flushing with water.

Clean out and wear points were installed at all abrupt changes in flow direction.

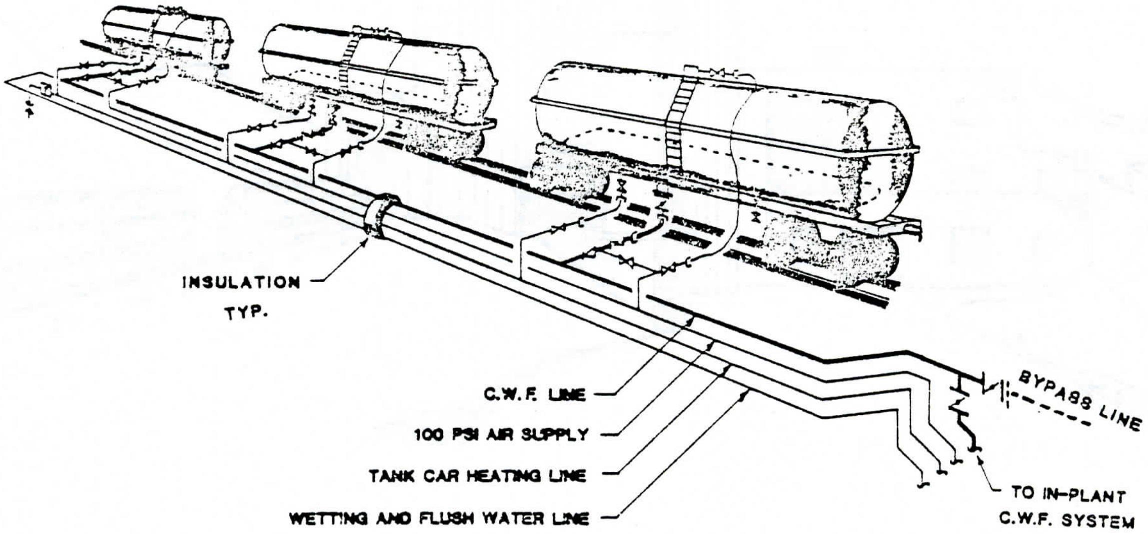


FIGURE 1.6

CHATHAM THERMAL GENERATING STATION
CWF RECEIVING STATION AT RAIL SIDING

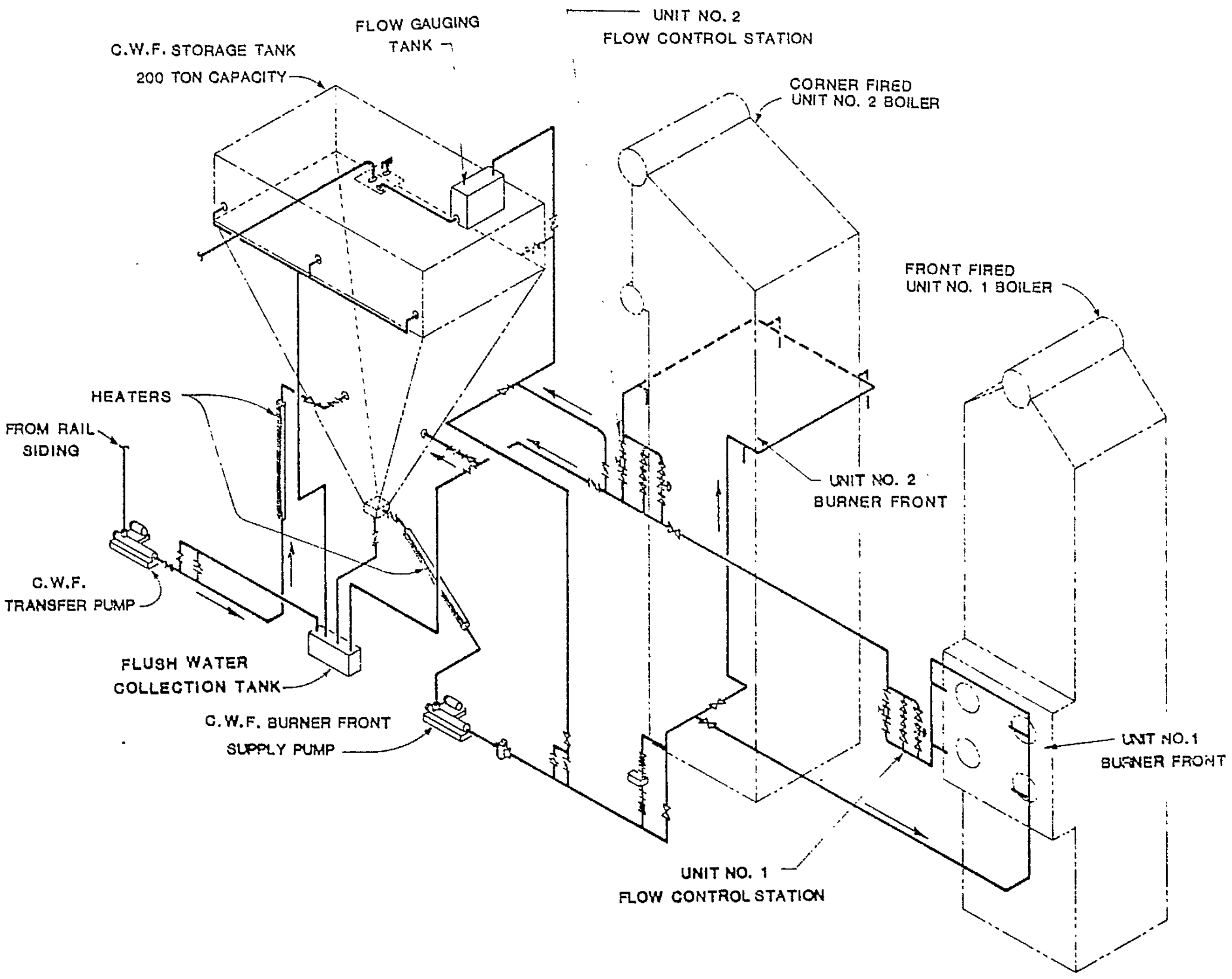
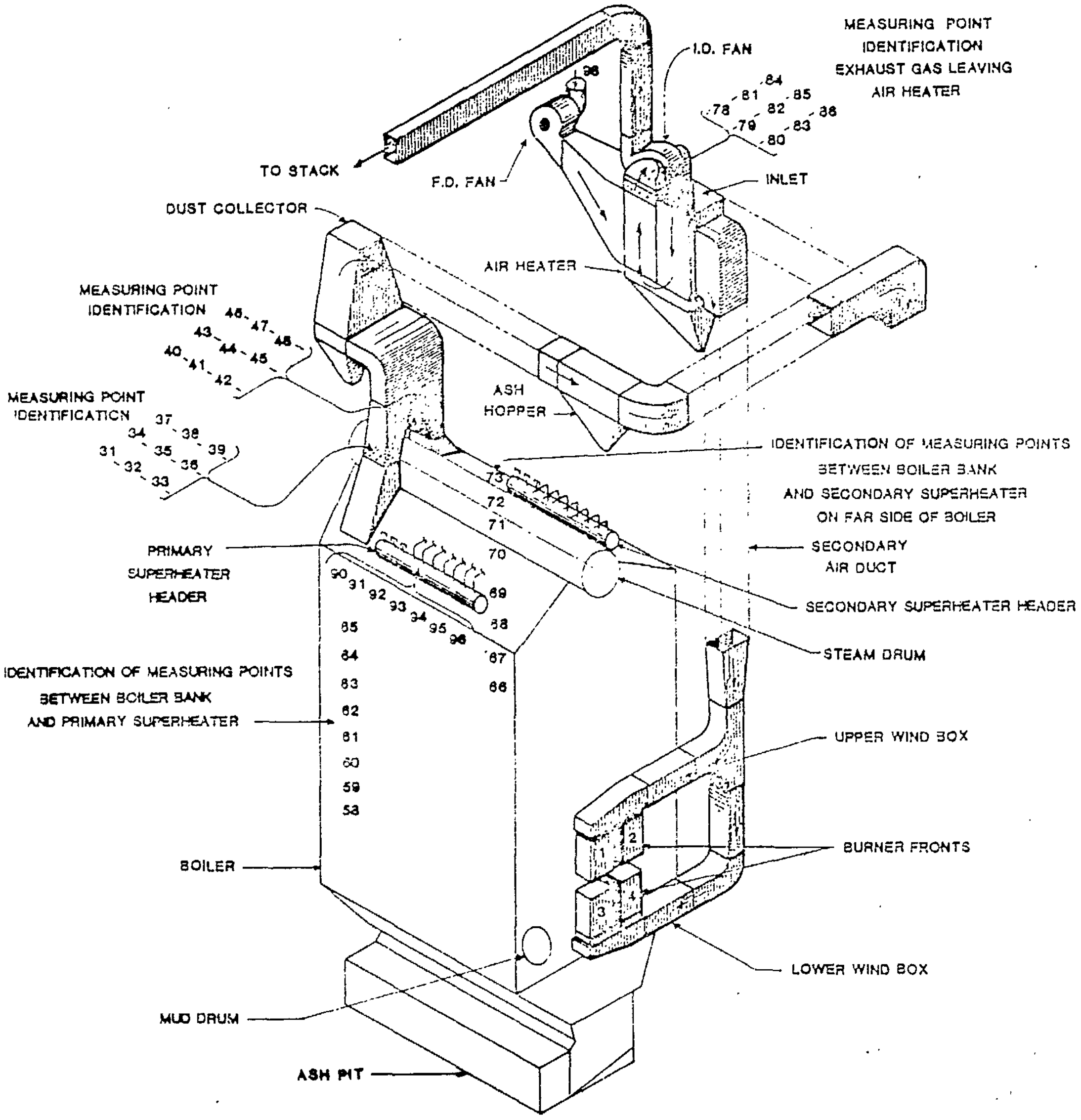


FIGURE 1.7

ISOMETRIC VIEW OF CWF PIPING
WITHIN THE CHATHAM PLANT



DUCTING HAS BEEN EXPLOADED FOR CLAIRITY

FIGURE 1.8

ISOMETRIC VIEW OF FRONT FIRED BOILER & DUCTING (UNIT NO. 1) AND LOCATION OF THE MEASURING POINTS

MODIFICATIONS TO THE CHATHAM THERMAL GENERATING STATION

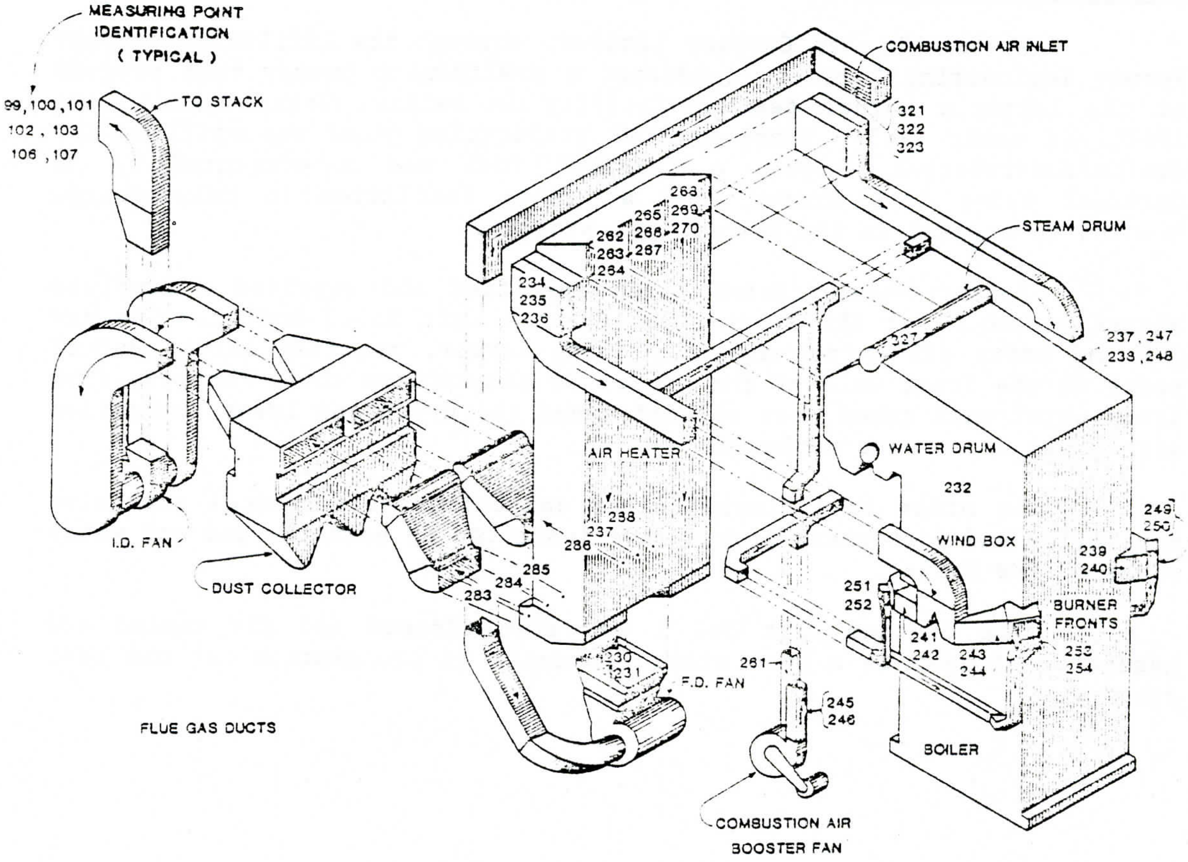
Modifications to the Front-Fired Boiler (Unit No. 1)

Foster Wheeler Company Limited, through its affiliated company Forney Engineering Limited, conducted a preliminary burner test program at the latter's burner testing facility in Dallas, Texas during late 1982, and early 1983. Since the CWF preparation plant was still in the design/construction stages, a "design" fuel was manufactured by AB Carbogel using Cape Breton coal at their facilities in Helsingborg, Sweden, to be used in the burner test program.

Foster Wheeler/Forney then specified and supplied a complete burner assembly for the front-fired Chatham Unit No. 1 boiler. The new CWF and heavy oil burner assembly being larger, required larger burner ports in the front wall of the unit. To accommodate these changes, five front water wall tubes were relocated and the upper and lower combustion air supply ducts were replaced.

In order to evaluate burner and boiler performance, extensive monitoring and instrument probes were installed on both the gas and water sides of the boiler.

The Chatham Unit No. 1 was then cleaned and air sealed and generally brought to a good state of repair in preparation for the test program.



DUCTING HAS BEEN EXPLODED FOR CLARITY

FIGURE 1.9

ISOMETRIC VIEW OF CORNER FIRED BOILER (UNIT NO. 2)
AIR HEATER, DUST COLLECTOR AND DUCTING AND
LOCATION OF THE MEASURING POINTS

Modifications to the Corner-Fired Boiler (Unit No. 2)

Combustion Engineering Superheater Limited, through its affiliate Kreisinger Development Laboratory (KDL), conducted burner development work at KDL's facilities in Windsor, Connecticut between late 1982 and mid 1983, utilizing the Carbogel manufactured "design" fuel.

On the basis of this work, Combustion Engineering specified and supplied a CWF burner for installation in the Chatham Unit No. 2 CE boiler. Unlike the Unit No. 1 burners, separate CWF and heavy oil burner guns were specified, allowing for a separate and therefore simpler CWF delivery system to the burners.

The CE burners required the addition of a booster air system to increase the pressure of primary combustion air. The extra duct work was accommodated by removing the now redundant pulverized coal supply pipework.

Instrument and monitoring probes were installed to allow evaluation of burner and boiler performance.

The Chatham Unit No. 2 was cleaned, air sealed and brought to a good state of repair in preparation for the test program.

CWF BURNER DEMONSTRATION

Front-Fired (Unit No. 1)

Baseline tests were conducted on the Chatham Unit No. 1 Boiler using heavy fuel oil. The initial fuel manufactured in the pilot plant, even though very high in viscosity, was shipped to Chatham for checking the plant's fuel handling system. This fuel was fired on July 21, 1983 with good results. The viscosity was lowered and the unit was brought to full load (10 MWe) on July 27, 1983 using all four coal-water fuel burners without support ignition.

Fuel wear tests on various burner component materials were concluded during August while modifications and adjustments were made in an effort to improve combustion and fuel handling performance.

By early 1984, some difficulties were encountered at the pilot production plant which resulted in a break in CWF deliveries. Prior to this, full and partial load tests were conducted on the Unit No. 2 corner fired unit between November 24 and December 6, 1983. Boiler and burner efficiency tests on Unit No. 2 were performed on January 19 and 20, 1984. Production at the pilot plant resumed in May 1984 and a second set of boiler and burner tests were conducted between June 25 and 27, 1984. A third set of boiler and burner tests were conducted between July 16 and 20, 1984. Tables 2.2 and 2.3 present the operating hours and boiler test data obtained.

Corner-Fired (Unit No. 2)

During October, 1983, after the first burning trials of CWF in the front-fired boiler, the focus of attention was moved to the corner-fired Chatham Unit No. 2.

After a six week program of fuel and burner adjustments during which CWF burning required continuous support ignition, the Unit No. 2 test program was temporarily delayed while the burner manufacturer made modifications to both the burners and boilers.

These modifications were carried out in the early months of 1984, and operating on the now improved CWF, the unit was recommissioned and successfully fired on June 14, 1984, without support ignition. The load was limited to 19 MWe because of a problem which developed with the combustion air booster system. Following adjustment and repairs, the corner-fired Unit No. 2 was brought to full load (22 MWe) on July 24, 1984, without support ignition.

For various reasons largely related to inconsistencies of the fuel at the burner front, the test program on Unit No. 2 could not be conducted until early November, 1984.

Fuel, which passed all tests prior to shipment, was found to be inconsistent during firing in Chatham. The testing procedures were expanded and the method for handling and storage of the fuel were modified to overcome these problems.

A test was run on November 8, 1984 in which air was used for atomization, which achieved 20 MWe. A second test brough the unit to full load (22 MWe) using steam atomization on November 9, 1984. Table 2.4 and 2.5 present the Unit No. 2 operating test data.

SUMMARY OF CONCLUSIONS

Fuel Preparation

- The Cape Breton Development Corporation - Carbogel pilot production plant successfully produced approximately 5,000 tonnes of CWF for burner demonstration trials.

- Coal cleaning performed as part of the CWF preparation process was effective in reducing ash and sulphur content in the product from 3.5 and 1.2 percent to 1.7 and 0.9 percent respectively.

- The CWF had a composition of 68 to 72 percent coal, 28 to 32 percent water and less than 1 percent chemical additives, producing a stable fluid fuel.

- Particle size distribution was achieved and maintained through control of the grinding and screening processes.

- Fuel mixing is an important step in CWF preparation for adequate dispersion of coal particles and fuel stabilization.

- A bacteriostat is required in the fuel to maintain quality control. Improved chemical additive performance should minimize the need for bacteriostat addition.

- After overcoming production difficulties at the pilot plant, Cape Breton Development Corporation were able to supply sufficient quantity of CWF of the quality necessary for this demonstration program.

Fuel Transportation

- After consideration of several transportation alternatives, rail tank cars were concluded to be most appropriately sized and cost effective method for this project.

- While uninsulated tank cars were acceptable in summer service or where short travelling times were involved, insulated cars, free of internal heating coils are recommended for year round transportation of CWF.

- Practical experience showed that CWF which was not properly stabilized settled prematurely (within a few days) during transportation or storage. Also the viscosity increases markedly as the fuel approaches freezing. Tank car mixers, possibly of a removable type, would be of an advantage when the CWF must remain in the tank car for periods over 30 days.

- Experience indicated that air pressurization of tank cars was of assistance in unloading operation. Tank cars capable of withstanding 50 psig internal pressures are recommended.

- Rail tank cars in CWF service should have good access for cleaning and inspection and discharge valves should be externally mounted for ease of maintenance and de-icing.

- CWF should be loaded into railcars at a temperature appropriate to the season. That is, maximum acceptable temperatures in cold months, minimum acceptable temperatures in hot months, consistent with the distances and geographic regions through which the fuel is to be transported.

CWF Handling

- The CWF as used in this project, was readily pumped using adequately powered progressive cavity pumps under normal conditions.

- Transfer lines required pre-wetting before handling CWF. Flushing of lines with water is recommended where they are to be left stagnant for long periods. Piping layouts must accommodate this requirement and provision to purge lines with air is recommended.

- Piping layouts should be as straight as possible without dead zones and adequately sized to minimize pressure drop.

- Normally closed block valves operated without difficulty, however, limited success was obtained with either pinch type or cam type flow control valves.

- Filters or screens are recommended in the system for removal of dry or agglomerated fuel or foreign matter.

- Three types of flowmeters were tested with limited success including one micromotion flow tube and two ultrasonic instruments. Reliable instantaneous or totalizing flows could not be achieved due to inexperience with the slurry and deposits in the piping.

- Storage tanks should be adequately sized and equipped for recirculation and/or internal mixing. Tank heating may be required where freezing weather conditions prevail. Experience with frozen fuel indicates the material can be remixed after thawing. The remixing process requires good access and mixers of adequate power.

- Flow control was found to be readily accomplished using variable speed pump drives or by adjusting recirculation flow rate using a valve station. A combination of these methods provided good control.

- At both production and utilization terminals, adequate tank storage equipped with mild agitation and recirculation facilities is recommended for blending and quality control.

Burner Demonstration Front Fired (Unit No. 1)

- CWF was successfully burned in the front-fired Chatham Unit No. 1 achieving a maximum of 100% of rated boiler capacity and a minimum of 30 to 40% of rated boiler capacity. Sustained and stable firing was obtained up to full load without support ignition.

- Boiler efficiencies were lower when burning CWF than for baseline testing of the unit on heavy fuel oil. Seven efficiency tests were conducted while the unit burned CWF at various loads. These data and the corresponding heavy fuel oil efficiencies are presented in Table 2.3.

- Ignition of CWF was effective in either a cold or hot furnace using light oil ignition burners.

- Switching of fuels from heavy oil to CWF and back again was achievable with minimal effort and was repeatable.

- All test work with the Foster Wheeler burner was conducted with air atomizing. The burners could not be operated using steam atomization due to tip fouling and plugging.

- Operations staff reported the burners to be very sensitive to adjustment of the rates of atomizing air, primary air and secondary air.

- The Foster Wheeler burners operated in a stable fashion at fuel and atomizing air pressures of less than 100 psig.

- The major factor contributing to lower boiler efficiencies when burning CWF is losses due to unburned combustibles. The quantities observed indicate poor combustion efficiency as compared to heavy oil or pulverized coal firing. All other boiler efficiency losses were as expected. It is interesting that losses due to moisture in CWF are comparable with heavy oil.

- NB Power operations staff judged the burner/fuel combination to be a limiting factor. The burners developed for this project did not have sufficient tolerance to accommodate the variations in fuel consistency. It was only toward the end of the project that the production plant was able to produce a fuel consistently within the narrow tolerance required by these burners.

- On Unit No. 1, the minimum burner requirement was two guns at 50% capacity.

- On Unit No. 1, the minimum time required from light-off to 4 burners unsupported was 1 hour.

Material Erosion Front Fired Burners (Unit No. 1)

- Three components of the Foster Wheeler burners; the distributor plug, the orifice plate, and the conical tip were examined for wear during the demonstration project.

    - Distributor plugs fabricated from hardened tool steel, boron heat treated tool steel, or tungsten carbide coated tool steel all performed equally well during 100 hour tests. Tool steel distributor plugs were used in the longer term test program. This component was not subjected to high rates of wear.

    - Orifice plates - fabricated from hardened tool steel boron heat treated tool steel and tungsten carbide coated tool steel all demonstrated significant signs of wear during 100 hour tests, one lasting as little as 15 hours. Orifice plates fabricated from cemented tungsten carbide were recommended and used in the long term test program. These plates showed good wear characteristics but suffered mechanical damage due to the brittleness of the material.

TABLE 2.3

CWF PROJECT - CHATHAM PLANT OPERATING DATA

FRONT FIRED BOILER (UNIT NO. 1)

Date		Total Hours On-Line (Hrs-Min)	Total Hours CWF Guns In Service (Hrs-Min)	CWF Guns In-Service Without Support (Hrs-Min)	Starts Hot	Starts Cold
1983	July	163:15	52:06	2:05	2	5
	Aug	319:00	288:48	10:55	2	5
	Sept	197:30	175:32	-	2	3
*	Oct	-	-	-	-	-
	Nov	62:00	38:45	5:30	1	2
	Dec	284:30	207:19	38:57	2	4
1984	Jan	88:30	55:09	11:55	-	2
	Feb	93:25	77:35	-	-	4
*	March	-	-	-	-	-
*	April	-	SHUT DOWN	-	-	-
*	May	-	-	-	-	-
	June	84:00	66:07	9:10	3	3
	July	44:20	41:43	14:22	1	3
	Aug	28:00	17:30	-	1	2
	Sept	22:40	19:50	3:20	-	3
	Oct	38:00	34:42	3:41	3	3
	Nov	15:15	14:30	-	1	1
	Dec	28:05	25:40	8:21	2	2
TOTALS		1,468:30	1,115:16	108:16	20	42

* Unit No. 1 Not In-Service

- Conical Tips - manufactured from hardened tool steel, tungsten carbide coated tool steel, boron heat treated molybdenum cemented tungsten carbide, and three ceramics were evaluated in the 100 hour test program. Hardened tool steel, tungsten carbide coated steel, boron heat treated molybdenum and one ceramic material exhibited excessive wear.

- Two ceramics exhibited good wear resistance but were subject to cracking. The cemented tungsten carbide tip showed good resistance to wear but after 120 hours in operation suffered mechanical damage. No tip material lasted more than about 200 hours.

TABLE 2.4

CHATHAM FRONT FIRED BOILER EFFICIENCY (UNIT NO. 1)
OIL AND CARBOGEL FIRING
(NB POWER DATA)

		PERCENT LOSSES						
TEST DATE	UNIT MW LOAD	DRY GAS	MOISTURE* IN FUEL	UNBURNT COMB.	MOISTURE IN AIR	RADIATION	UNMEAS.	TOTAL BOILER EFFICIENCY
No. 6 Oil								
83.07.19	9.8	7.94	6.15	0.36	0.26	0.50	1.00	83.80
83.07.19	7.4	8.70	6.15	0.36	0.20	0.65	1.00	82.94
83.07.18	5.0	6.07	6.02	0.36	0.20	0.85	1.00	85.51
Carbogel								
84.01.19	9.8	7.75	6.95	4.10	0.19	0.55	1.50	78.97
84.07.16	9.7	6.68	8.00	2.11	0.20	0.50	1.50	81.00
84.01.19	7.7	9.00	7.23	2.81	0.23	0.60	1.50	78.64
84.06.27	7.5	6.93	7.34	10.87	0.21	0.55	1.50	72.60
84.01.20	5.4	8.81	6.81	3.78	0.21	0.75	1.50	78.14
84.06.27	5.2	8.52	7.37	14.68	0.19	0.80	1.50	66.94
84.07.17	5.4	10.55	7.51	3.91	0.26	0.70	1.50	75.56

REMARKS: * Total loss from moisture in fuel plus H_2O from combustion of H_2

TABLE 2.5

CWF PROJECT - CHATHAM PLANT OPERATING DATA

CORNER FIRED BOILER (UNIT NO. 2)

Date	Total Hours On-Line (Hrs-Min)	Total Hours CWF Guns In Service (Hrs-Min)	CWF Guns In-Service Without Support (Hrs-Min)	Starts	
				Hot	Cold
1983 Oct	226:00	65:50	-	2	2
Nov	225:00	163:57	-	1	4
* Dec	-	-	-	-	-
1984*Jan	-	-	-	-	-
* Feb	-	-	-	-	-
* March	-	-	-	-	-
* April	-	-	-	-	-
* May	-	-	-	-	-
June	16:00	8:20	1:12	1	1
July	50:30	25:25	0:39	3	2
Aug	18:15	12:35	-	1	1
* Sept	-	-	-	-	-
* Oct	-	-	-	-	-
Nov	141:15	39:15	-	2	3
Nov	CE Test	22:30	4:25	-	-
* Dec	-	-	-	-	-
TOTALS	677:00	337:52	6:16	10	13

* Unit No. 2 Not In-Service

Note: No Hot or Cold Starts with Coal Water Fuel

Burner Demonstration Corner Fired (Unit No. 2)

- CWF was successfully burned in the corner-fired Chatham Unit No. 2 achieving 100% of rated boiler capacity. Sustained and stable fires were obtained without support ignition.

- Boiler efficiencies were lower when burning CWF than for baseline testing of the unit on heavy fuel oil. Three efficiency tests were conducted by NB Power while the unit burned CWF at various loads. This data and the corresponding heavy fuel oil boiler efficiencies are presented in Table 2.5.

- Two major factors contribute to lower boiler efficiencies when burning CWF. One is unburned combustibles indicating poor combustion, and the second is dry gas loss. These two account for 90% of the difference between heavy oil and CWF boiler efficiencies.

- On Unit No. 2, the minimum time required from light-off to 4 burners unsupported was 3 hours.

TABLE 2.6

CHATHAM CORNER FIRED BOILER EFFICIENCY (UNIT NO. 2)
OIL AND CARBOGEL FIRING
(NB POWER DATA)

		PERCENT LOSSES						
TEST DATE	UNIT MW LOAD	DRY GAS	MOISTURE* IN FUEL	UNBURNT COMB.	MOISTURE IN AIR	RADIATION	UNMEAS.	TOTAL BOILER EFFICIENCY
No. 6 Oil								
83.10.27	20.3	6.74	6.18	0.45	0.13	0.40	1.00	85.10
Carbogel								
84.11.07**	18.2	11.08	7.47	7.47	0.17	0.45	1.50	71.86
		+6.97	+7.47	+7.48	+0.11	+0.45	+1.50	+76.03
84.11.08	19.6	11.88	7.37	10.71	0.16	0.40	1.50	67.99
		+7.20	+7.37	+10.71	+0.09	+0.40	+1.50	+72.74
84.11.09***	20.2	13.34	7.35	7.09	0.18	0.40	1.50	70.14
		+7.48	+7.35	+7.09	+0.16	+0.40	+1.50	+76.02

REMARKS: * Total loss from moisture in fuel plus H_2O from combustion of H_2
** Two ignitors required for flame stability - Heat Input credited for 57.5 IGPH of No. 2 Oil
*** Test employing steam atomization - approximately 3840 PPH steam used on 4 burners. Air atomization employed on previous Carbogel tests.
+ Based on theoretical CO_2 values

NOTE: Both % CO_2 and CO quantities in flue gas estimated for oil fired test and % CO estimated for all Carbogel tests

- All ignition of CWF was done in a preheated furnace, no experience was obtained in cold starting on CWF for this unit.
- Switching of fuels from heavy oil to CWF and back was achievable and repeatable although the switching times were considerably longer than for Unit No. 1 due to the physical size and weight of Unit No. 2 guns.
- The burners tested on Unit No. 2 operated equally well on either air or steam atomization.
- The burners tested on Unit No. 2 operated at fuel and atomization pressures up to 150 psig for air and 200 psig for steam.
- Although a television monitoring camera provided surveillance on the unit, the Unit No. 2 configuration provides much less opportunity for the operators to observe combustion. In addition, the testing was undertaken for a shorter duration, therefore a more conservative approach was taken to Unit No. 2 test work.

Material Erosion Corner Fired Burners (Unit No. 2)

The atomizer tips for this burner were manufactured in one piece with cemented tungsten carbide inserts.

Two sets were tested with the first set remaining in service for approximately 230 hours. No visible signs of wear were detected. The second set had a revised spray angle and were in service for 125 hours without visible signs of wear.

Environmental Aspects

- Coal cleaning during the manufacture of CWF reduces the ash and sulphur content as compared to the parent coal. Resulting improvements in the quality and quantity of air emissions can be expected relative to burning pulverized coal or residual oil.
- Coal water fuel could be expected to present a lower environmental hazard in the event of spillage as compared to heavy oil.
- Incomplete combustion of CWF during burner demonstration tests resulted in very high flue gas particulate emissions. This was a result of fuel variations, burner design and burner adjustment.
- Dust collectors on the Chatham units performed with mixed success owing to the experimental nature of combustion during the demonstration period. Large amounts of unburned carbon were observed in collected fly ash.
- Under conditions of good combustion, little or no bottom ash was observed in the furnaces.
- Cleaning of equipment used in the handling of CWF was readily accomplished, however, the disposal of wastes required very significant settling time and thus sizeable ponds owing to the fineness of fuel solids.
- Routine spills of CWF were easily cleaned up. Spills on dry ground can be left to dry and then shovelled up.

DEVELOPMENTS IN CANADA'S COAL-LIQUID FUEL PROGRAM

P.J. Read*
H. Whaley**
D.M. Rankin***

Achievements in medium-scale demonstrations of coal-water fuel combustion in eastern Canada have answered basic questions as to the practicability of manufacture, transport and combustion but have not defined the constraints applying to the use of such fuel in boilers designed to burn oil. The Canadian program is going ahead to relate pilot-scale experience to oil-designed boilers and to quantify the effects of coal-liquid fuel quality on boiler operation. Factors to be investigated include ash levels, ash fusion, and effectiveness of sootblowers. Specifications are being developed to ensure that coal-water fuels meet the requirements of potential transporters and users.

INTRODUCTION

The use of coal to replace imported oil is a goal of Canadian energy policy but this replacement has been inhibited by the inconvenience of handling solid fuel and by its environmental implications. Canada's strategy for energy aims to remove this inhibition by bringing new coal utilization technologies that have both economic and environmental advantage over the oil alternative to a stage of development useful to industry. A program of development and commercialization of fuels made from mixtures of coal with liquids, with the twin objectives of easy, economic coal handling and minimized environmental impact has therefore formed an integral part of Canada's energy strategy for the last eight years.

The first phase of the program has brought the development of coal-liquid fuel technologies well beyond laboratory scale but they are still too immature for widespread commercial application. The aim of the present, second phase of the program is to define equipment performance, fuel and combustor specifications, and capital and operational costs for the manufacture and delivery of coal-water fuel and for the conversion of boilers originally designed to burn oil. This information will enable potential coal-water fuel producers, transporters and users to determine where, and under what circumstances, its use would be commercially attractive. The work of the second phase includes a demonstration of combustion of coal-water fuel in a 20 MW_e boiler designed to burn oil in a compact space and definitive, site-specific, cost estimates for a coal-water fuel manufacturing plant and for the conversion from oil to coal-water fuel of an electric utility boiler, both fuel plant and boiler in the 100-150 MW_e range.

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The second phase of the program starts with the selection, during the first four months of 1985, of burners suitable for the 20 MW_e demonstration to be undertaken in Charlottetown, Prince Edward Island. Modifications to the boiler also start in early 1985 and should be complete by August, in coordination with the selection, manufacture and installation of burners. Fuel preparation continues throughout the Spring and Summer months of 1985 and the combustion demonstration follows this with a target of completion by the end of the year. At the end of the Charlottetown demonstration and the definitive estimates for commercial coal-water fuel production and conversion of a large electric utility unit, the following information will be known on a site-specific basis:

1. Fuel specifications;
2. Means of manufacturing, transporting and using coal-water fuel;
3. Cost of fuel production plant;
4. Operation, maintenance and feed cost for fuel production;
5. Cost of fuel transportation, handling and storage;
6. Cost of conversion from oil to coal-water fuel;
7. Cost of and constraints on boiler operation using coal-water fuel.
8. Possible low-cost modifications to enhance boiler performance.

POTENTIAL

Potential users of coal-water fuel fall into three main categories:

a) Kilns and furnaces with high tolerance for sulphur and ash in fuel such as cement kilns and processors or smelters for metal ores;

b) Coal-Boilers i.e., boilers designed to burn coal but currently burning oil because of space limitations or handling costs; new boilers required by electric utilities or by industry may face similar constraints and could be included in this category;

c) Oil-Boilers i.e., boilers designed to burn oil.

Coal-water fuels can be tailored to meet the requirements of each of these categories and the overall development program covers all three. It is impossible to generalize costs of fuel delivered to the user since these will depend on transportation, but, in view of the current prices of alternative fuels, targets can be set as criteria for prices of coal-water fuels for each user category.

Table 1 illustrates typical Canadian price criteria, based on an assumption that a coal-water fuel would have to be at least 20% cheaper than its current competitor to achieve pay-back on conversion costs within a commercially attractive time frame.

It is obvious from Table 1 that the requirements for replacement in kilns are included in those for coal- or oil-boilers. Therefore definition of the capital and operational costs for coal- or oil-boilers will enable kiln operators to determine whether economic criteria can be met by elimination of unwanted features. The approach selected by the Department of Energy, Mines and Resources (EMR) for Canada aims to treat the use of coal-water fuel at the more critical level, i.e. for oil-designed boilers.

Table 1: PRICES OF COAL-WATER FUEL FOR VARIOUS APPLICATIONS

USER CATEGORY	PRICE OF FUEL PER GJ	REQUIRED FEATURES OF COAL-WATER FUEL
Kilns	\$2.50	Combustibility
Coal-boilers	\$3.00	Combustibility, stability, low ash
Oil boilers using No. 6 oil	\$3.60	Combustibility, stability, very low ash, reduced sulphur
Oil boilers using No. 2 oil	\$4.50	Enhanced combustibility, extended stability, very low ash, reduced sulphur.

Studies supported by EMR and by the Canadian Electrical Association, as well as in-house investigations by EMR have indicated that there is a potential gross annual market for coal-water fuel of 10 million tonnes in the Atlantic and New England region, given an appropriate price, which exceeds the potential productive capacity for coal-water fuel in eastern Canada by almost ten times. A very substantial potential market by 1990 for coal-water fuel is also indicated in Pacific Rim countries. More detailed analysis of this latter market is currently being undertaken by western Canadian industries and supported by the government of the Province of Alberta. The existence of the currently underutilized Trans-Mountain oil pipeline, located in the proximity of coal mines in central Alberta and running from Edmonton to Vancouver, may offer opportunity to transport western Canadian coal to tide-water more economically as a coal-water slurry by pipeline than as a solid fuel by rail.

The work of Phase Two will enable market studies to reach firm conclusions resulting in commitments to trade in coal-water fuels. Preliminary indications are that this trade could reach 1.5 to 2 million tonnes per year in eastern Canada and 5-7 million tonnes per year in the West.

PROBLEMS

The achievements listed above are substantial but they are not enough to allow potential users to invest in conversion from oil to coal-water fuel without significant risk: problems remain in the domains of economics, boiler derating, boiler tolerance to ash, fuel transportation, storage and handling, and, the suitability of different coals to make coal-water fuels.

The economic target is a two-year pay-back. As phase two of the program begins, several of the major elements which determine whether this target can be reached are unknown, also the program cannot answer two further economic questions which will be major determinants in any decision to convert from oil to coal-water fuel i.e. the relative prices of coal and oil, and the utilization factor. These crucial factors will be determined by potential users on a time- and site-specific basis. Target prices for coal-water fuels delivered to users might vary from as low as \$2.50/GJ in the case of a kiln which can accept a high ash, high sulphur fuel and where the alternative is natural gas or residual oil on the spot market, to as high as \$4.50/GJ in the case of an industrial boiler which needs a very easily combustible, low ash, low sulphur fuel and where the alternative is No.2 oil.

By the end of Phase two of the program, the capital and operational costs associated with coal-water fuels at moderate utility scale (100-150 MW_e) will be known. This phase incorporates two matched definitive estimates, one for the capital cost of conversion of a specific oil-designed utility boiler, the other for construction of a site-specific fuel preparation plant to manufacture the quantity and quality of fuel needed by the given boiler. The demonstration component of phase two provides the technical data and the operational cost of running an oil-designed boiler on coal-water fuel. Thus, any unresolved problems at the end of phase two will be specific to the site and the fuel required by a potential user.

Predictive Studies commissioned by EMR (1,2), have attempted to forecast the derating, i.e. loss in maximum power output, to be expected when coal-water fuels are burned in oil-designed boilers. In these generic studies, two sizes (60 and 200 MW_e) of typical oil-designed utility boilers found in Canada were studied for potential derating or loss of generating capacity, and the limiting factors which produced these effects. The table below shows the results:

Table 2: POTENTIAL DERATING OF TYPICAL CANADIAN UTILITY BOILERS

Boiler Type and Size	Derating by %	Limiting Parameter
Small compact Frontwall fired	59	furnace exit gas temperature
Large compact Frontwall fired	39	tube bank gas velocity
Small liberal Frontwall fired	40	tube bank spacing
Large liberal Frontwall fired	56	tube bank spacing
Small compact Tangential fired	65	furnace exit gas temperature
Large compact Tangential fired	45	furnace exit gas temperature
Small liberal Tangential fired	49	tube bank spacing
Large liberal Tangential fired	58	tube bank spacing

These forecasts assume no boiler modifications and are based on models which use empirically derived formulas but the basis for derivation does not extend to the use of very low ash coal nor to coal fired in an atomized water slurry. Consequently the models extrapolate empirical formulas beyond the domains over which they were derived. The demonstration at Charlottetown will provide data to extend the basis for derating estimates to one of the most severe situations (high gas velocity, narrow boiler tube spacing, small boiler volume) that coal-liquid fuels are ever likely to encounter.

The level to which ash must be controlled for different applications of coal-liquid fuels has not yet been determined but it is expected to vary widely. Such uses as cement kilns, highly tolerant of ash and sulphur, probably require no beneficiation of coal beyond that needed to achieve a satisfactory calorific value: more critical applications are likely to require at least some beneficiation. Developers of coal-water fuels are generally proceeding on the assumption that tolerance to slagging, fouling or erosion by ash in boilers is specific to individual boilers. There may, however, be some generally applicable considerations, such as ash stickiness under fouling conditions, that can be influenced more by manufacturers of coal-liquid fuel than by boiler configuration. Observations to date have indicated that, in general, ashes from coal-water fuels (not coal-oil fuels) are light and soft and can easily be removed from boiler tubes by normal soot-blowing techniques. However the parameters which influence ash stickiness and abrasiveness have not yet been quantitatively defined for coal-water fuels as they have for the firing of pulverized coal.

There is a general perception among potential users of coal-water fuels that substantial modifications to deal with bottom ash would be required in conversion of oil-designed boilers. Such modifications would be expensive and might form an unnecessary deterrent to the use of coal-water fuels. All experience to date has shown that, when combustion is taking place properly, all the ash produced remains entrained in the hot gases until trapped by a flue gas dust collection device (cyclone, fabric filter) and does not fall to the bottom of the furnace as does a substantial fraction of the ash formed during the firing of pulverized coal. Further evidence of ash behaviour, particularly where soot-blowing is necessary, is needed to establish if modification of the furnace bottom is needed for a site-specific application.

Two features of the parent coal may cause problems during the manufacture of a coal-water fuel: the mineral matter and the surface characteristics of the coal. High proportions of organic sulphur or dispersion of very fine mineral matter can make beneficiation to the quality required for some purposes impossible or uneconomic. The microsurface quality of coals influences their floatability and, even more important for coal-water fuels, influences their predispositon to accept adsorption of the dispersing agents essential to the control of fuel viscosity. Phase one of the program has defined reagents (collector, dispersant, defoamer, stabilizer and biocide) suitable for coal from Cape Breton, Nova Scotia, and Phase two includes the use of alternative coal-water fuels in addition to the major demonstration which uses coal-water fuel made by the Carbogel process from Cape Breton coal. It remains to define, on a coal-specific and use-specific basis, reagents suitable for any new coal intended for use in a coal-water fuel.

The coal-water fuel pilot production plant and burner demonstration has been described in detail previously3,12). The project, which was undertaken by the New Brunswick Electric Power Commission (NBEPC), Cape Breton Development Corporation (CBDC) and EMR, demonstrated the continuous production of coal-water fuel and its combustion in two utility boilers at the Chatham generating station.

CHATHAM DEMONSTRATION PROJECT

The major tasks in the project were (a) the construction, startup and operation of a continuous pilot production plant for the manufacture of coal-water fuel (b) the rail transportation of the coal-water fuel to the Chatham Thermal Electric Generating Station approximately 700 km from the production plant (c) the demonstration of burners using the coal-water fuel in both a front wall-fired boiler and a tangentially-fired boiler.

Fuel Production

The design, erection and commissioning of the coal-water production plant was undertaken by CBDC assisted by their licensor AB Carbogel of Sweden and was completed in mid 1983. The pilot production plant site was chosen adjacent to CBDC's Victoria Junction coal preparation plant and therefore has access to a variety of services. The basic process flow sheet, material balances and equipment refinement and specifications were developed with the assistance of AB Carbogel. The present flow sheet is shown in figure 1 and comparison with that shown earlier3,12) will indicate the changes that have been made during the program.

The basic steps in the preparation process are as follows:

1) Feed coal is supplied by a hopper and conveyer belt.

2) An open circuit primary grinding of the raw feed coal is by wet milling in a 1.5 m by 2.5 m ball mill.

3) Size classification of the primary discharge is by a sieve bend.

4) Close circuit secondary grinding of the classification oversize is by wet milling in a 1.5 m by 2.5 m ball mill.

5) Size classification of the secondary discharge in a Hydro Cyclon; the cyclon underflow goes directly to the secondary ball mill while the cyclon overflow goes to the sieve bend.

6) Two stage flotation roughing and cleaning of the sieve bend underflow for cleaning of the ground coal.

7) The dewatering of the clean coal to about 25% moisture by rotary drum vacuum filters.

8) Chemical addition and slurry mixing in two mixing tanks operated in series.

9) Slurry conditioning with the addition of stabilizer in two 70 tonne viscosity control tanks with mechanical stirring.

10) Fuel storage in two 130 tonne storage tanks with mechanical stirring.

The coal used through the program has been metallurgical grade coal from the Harbour seam from the Sydney Coalfield, Nova Scotia which has been processed in the CBDC Victoria Junction coal preparation plant. However, a lower quality feed stock from the Hub Seam from the same coal field will be used to produce coal-water fuel on a commercial basis. Table 3 gives a comparison of the coal as received by the pilot plant compared to the coal-water fuel produced. Table 4 gives a comparison of the ash and sulphur in these two feedstocks.

Table 3: PILOT PLANT FUEL ANALYSES

	Washed Coal		Coal-Water Fuel	
	As Rec'd. Basis	Dry Basis	As Rec'd. Basis	Dry Basis
Moisture%	8	Nil	30	Nil
Ash %	2.8	3	1.2	1.7
Sulphur %	1.1	1.2	0.6	0.9
Volatile %	33.6	36.5	26.	37.
MJ/Kg	31.5	34.3	24.4	34.9

Table 4: COMPARISON OF COAL FEED STOCKS FOR COAL-WATER FUELS

	Harbour Seam			Hub Seam
% (Dry Basis)	As Mined	Benef.	Coal-Water Fuel	As Mined
Ash	5 to 8	2.8	1.7	16.0
Sulphur	1.8	1.2	0.9	4.5

Although some initial problems were encountered in maintaining quality control of the fuel, improvement in mixing procedures and better particle size control in the pilot plant have largely overcome these problems. The beneficiation in the pilot plant achieved levels of ash and sulphur in the fuel which have the potential to be attractive to users, particularly where the application requires a very clean product.

Fuel Transportation

The Chatham Generating Station is located near the mouth of the Mirimichi River in northeastern New Brunswick. The station is served by two major highways, the Canadian National Railway System, and is accessible throughout the year. A wharf is located on NBEPC property adjacent to the plant.

A study was undertaken to investigate the most economical and suitable method of transporting the required 6000 tonnes of coal-water fuel from Sydney, to Chatham. Road transportation seemed to be convenient; however it proved to be less flexible and more costly for this type of project. Investigation of water transportation indicated that, to be economical, major storage was required both at the pilot plant and at the Chatham Station. The most economical method of transportation of the coal-water fuel was determined to be rail.

Twelve rail cars operating in four groups of three were required to transport coal-water fuel. A weight restriction on the rail line to the Chatham Station limited the amount of fuel each car could carry to 70 tonnes. The rail cars were also used as storage to act as a buffer against interruptions either in production of fuel or testing at Chatham. Normally, delivery of fuel from Victoria Junction, Sydney, to the Chatham Plant took about one week. Although some shipments took much longer, minimal problems were encountered with the fuel transportation or unloading. Uninsulated tank cars were used initially because the burner demonstration was scheduled to be completed prior to the onset of cold weather. However, the project was extended into the winter months and the uninsulated rail cars presented some problems in handling because of freezing, especially on the outside shell of the tank and the tank outlet. As a result one insulated rail car was added to the fleet. This rail car was able to move fuel from Sydney to Chatham over approximately a two week period in midwinter, without problems in freezing of the fuel or unloading.

Temporary receiving and unloading facilities were constructed at the Chatham Plant to accommodate shipments of fuel. This involved placing temporary pipelines adjacent to the rail siding with three unloading points. The pipelines carried compressed air for pressurizing the rail cars to assist unloading and water for prewetting the fuel lines prior to use and to flush the lines out. In addition a 100 mm diameter line was used to move fuel from rail cars to the in-plant storage. As cold weather approached, a steam line was added to the facilities to provide heat for thawing of the rail cars and outlets and to keep the fuel lines from freezing during winter operation. All pipes were then wrapped in a bundle inside a blanket type insulation.

In general no unexpected problems were encountered when handling fuel in below freezing temperatures. It was found that, if the fuel was loaded at the plant in Sydney at a relatively warm temperature (25°C) and the outlet valves were thawed, the fuel could be discharged at Chatham without problems.

Air lances were used to agitate the fuel in the tank cars with limited success. Internal heating coils in several of the cars interfered with the removal of all of the fuel from the cars and made the cleaning of the interior of the cars much more difficult.

Through a series of delays which aggravated cold-weather problems several rail cars ended up with varying quantities of settled fuel in them. The problems of removing this settled fuel from the rail cars and, even worse, disposing of it in an environmentally acceptable manner, proved to be much greater than originally anticipated. The very fine coal which is used to manufacture coal-water fuel was found not to settle easily, therefore, care had to be taken to provide adequate settling time. The settling time was not adequate in the ash ponds normally used. Ultimately a hydraulic process was used. Water was pumped from a coal wash plant tailings pond at high pressures (of the order of 1.2 MPa) and the discharge routed back to the pond. This, combined with agitation at first and finally with scraping, enabled the rail cars to be cleaned effectively.

The only suitable location within the Chatham plant for fuel storage facility was a coal bunker. This bunker was suitably modified for storage of the coal-water fuel. In addition, connections were installed in the bunker to provide a means of agitating the fuel in the bunker by means of compressed air. Experience at Chatham indicated that this type of storage is not the most suitable configuration for coal-water fuel. The shape of the bunker proved to be a disadvantage in that it induced the fuel to channel from fuel delivery point or the recirculating line discharge to the inlet to the burner fuel pumps.

Future fuel storage should be designed in such a manner that the fuel within the storage can be mixed in a very slow and thorough manner with paddle mixers. Channeling in the storage bunker tended to magnify small fluctuations in consistency between different rail cars of fuel. This showed up as unpredictable changes in the quality of the flames at the burners.

As the particular coal-water fuel used is very sensitive to overheating, it was difficult to warm the fuel in the rail cars prior to unloading because the only source of heat available was steam. In future installations, care should be taken to ensure that a heating medium is available at an unloading station which will provide heat for the fuel within the temperature limits established by the fuel manufacturer.

The fuel was unloaded from the rail cars through a progressive cavity transfer pump located in the basement of the power house. From there it was pumped directly to the storage tank. From the storage tank the fuel was pumped to the burner front of either boiler by a second progressive cavity pump. The input side of this latter pump was always under static pressure from the fuel in the storage bunker. The pumps were sized for 125% of maximum flow so that some fuel could always be recirculated.

The flow to the burners was controlled by a valve station located downstream from the burner front. This valve station controlled the fuel pressure at the burner front to the level desired and allowed a fraction of the fuel to be recirculated back to the storage system. Pipelines were generally carbon steel run in straight lines with right angle bends. No bends or curved pipe were used. Flexible braided lines were used from the main headers to the burners. In general, very little problem was experienced with the fuel lines.

The fuel pressure for the front wall-fired unit was controlled by a pinch valve. These valves worked extremely well where the fuel was required at a pressure of less than 700 kPa.

On the tangentially-fired unit the fuel was required at a higher pressure of approximately 1 MPa. In this area the pinch valve did not last as expected and therefore the system was modified to include a variable speed drive on the fuel pump as well as a pressure control valve. In general the fuel systems were operated in a similar manner to a bunker oil system on a large utility boiler. One of the main design criteria for the delivery system was to minimize deadend lines and to keep the fuel moving through the system. A schematic of the overall distribution system in the Chatham station is shown in figure 2.

Fuel Combustion

Contracts were awarded for the development, design and supply of burners for each of the two boilers in the Chatham Plant. One contract was awarded to Foster Wheeler Canada Limited, for the supply of burners for the No. 1 unit. This unit is a front wall-fired Foster Wheeler Balanced Draft Boiler designed with a capacity of 12.5 MW_e when burning New Brunswick coal. It was converted to No. 6 oil in the early sixties.

A detailed inspection was conducted on the No. 1 boiler to identify potential problems. No attempt was made to bring the unit to a new condition but, emphasis was placed on being able to obtain reproducible results during the extended period of testing on oil and coal-water fuel. The boiler and air heater gas passages were cleaned, the soot blowers were examined but were not operational and were not used in the tests due to problems in obtaining replacement parts.

Four independent burner wind-box assemblies were supplied and installed on the boiler. Modifications were required to both the front wall and combustion air duct. Five front wall tubes were replaced to accommodate the larger burner throats. Brick work and refractory around the throats were modified and the combustion air ducts were changed to fit the deeper burner wind boxes. Balancing dampers were removed from the duct work and incorporated in sleeve type damper burner registers. The new burners were each rated at 40 GJ/h thermal output. Ignition and support energy was provided by two light oil pilots each rated at 6 GJ/h. Each burner is provided with controls to allow precise adjustment of air or fuel flow as necessary to optimize burner performance.

The same burner gun was used to fire heavy oil by changing the fuel gun tip and position of the primary air damper. No other modifications were necessary. The changeover normally took less than fifteen minutes per burner while the unit was on line. The boiler was operated manually by operators located directly in front of the burners. No burner management system or flame supervisory system was provided other than viewing ports at each burner.

All burner valves and controls are manual and were arranged for ease of changeover from coal-water fuel to No. 6 oil and vice-versa. The fuel flow is controlled by manual pinch valve on a recirculation line from the burner front. A second small valve in parallel to the main control valve is used to adjust the flow of fuel according to minor changes in boiler load. Recirculated fuel returns to the main storage.

The initial test program was developed by NBEPC in consultation with the burner supplier. This program included an oil base line test and performance test while firing coal-water fuel. An initial test program was established to select materials for the coal-water fuel burner atomizer. This test program involved a series of tests on seven different materials for periods up to about 125 hours. The materials tested included hardened tool steel, Tungsten carbide spray coating, boron heat treatment on tool steel, cemented Tungsten carbide and three different ceramic materials. From the initial wear test, 1000 hours wear predictions were made. The components of atomizer for the performance testing of the unit were a combination of cemented tangstem carbide and hardened tool steel.

A series of performance tests were conducted by NBEPC on the front wall-fired unit using No. 6 oil and coal-water fuel. In summary, as shown in Table No. 5, the unit burner was shown to operate on coal-water fuel with an average performance of 78% and a maximum performance of 81%; the burners were shown to operate on No. 6 oil with oil nozzles with an average performance of 84%.

Normal operation of the boiler included: light-off with No. 2 oil; warm the boiler up; switch to bunker oil to bring the boiler to operating load; and, switch (while on load) one burner at a time to coal-water fuel. The switching of the unit from CWF fuel; to bunker oil and back while on load proved to be a very straightforward routine operation.

Lightoff also proved to be straightforward and although two 6 GJ/h igniters were provided on each burner, in actual practice it was found that only one was required. It was also possible to light-off the unit using coal-water fuel without the preliminary warming step using No. 6 fuel oil. Normal procedures used by the operators when starting up the unit with bunker oil were followed. Although performance tests were not conducted with fuels at many different viscosities, the unit was operated quite successfully with fuels at viscosities between 500 centipoise Brookfield and 1200 centipoise Brookfield. These burners were designed air atomizing at less 800 kPa air pressure and atomizing with steam was attempted but was totally unsuccessful when firing coal-water fuel.

Table 5: SUMMARY/COMPARISON CHATHAM NO. 1 BOILER EFFICIENCY OIL AND CARBOGEL FIRING

					Percent Losses				
Firing Mode	Test Date	Unit MW Load	Dry Gas	Moisture* In Fuel	Unburnt Comb.	Moisture In Air	Radiation	Unmeas.	Total Blr. Efficiency
No. 6 oil	83.07.19	9.8	7.94	6.15	0.36	0.26	0.50	1.00	83.80
	83.07.19	7.4	8.70	6.15	0.36	0.20	0.65	1.00	82.94
	83.07.18	5.0	6.07	6.02	0.36	0.20	0.85	1.00	85.51
Carbogel	84.01.19	9.8	7.75	6.95	4.10	0.19	0.55	1.50	78.97
	84.07.16	9.7	6.68	8.00	2.11	0.20	0.50	1.50	81.00
	84.01.19	7.7	9.00	7.23	2.81	0.23	0.60	1.50	78.64
	84.06.27	7.5	6.93	7.34	10.87	0.21	0.55	1.50	72.60
	84.01.20	5.4	8.81	6.81	3.78	0.21	0.75	1.50	78.14
	84.06.27	5.2	8.52	7.37	14.68	0.19	0.80	1.50	66.94
	84.07.17	5.4	10.55	7.51	3.91	0.26	0.70	1.50	75.56

Remarks: * Total loss from moisture in fuel plus H_2O from combustion of H_2

Performance calculated by NBEPC using their standard procedures.

The ash that formed in the No. 1 unit when the burners were atomizing the fuel properly tended to be very light fluffy ash which did not deposit in the cyclones or in the furnace bottom.

Although the burners work well with fuels at different viscosities; they were found to be extremely sensitive to adjustment of atomizing, primary and secondary air and to minor fluctuations in fuel characteristics.

A second contract was awarded by NBEPC to Combustion Engineering Canada for the development, testing and supply of burners for the No. 2 Unit. This unit is a 22 MW_e tangentially fired Combustion Engineering balanced draft unit. It was designed to burn New Brunswick coal and subsequently was converted to burn No. 6 fuel oil.

The coal-water fuel burner gun initially developed by the burner manufacturer required high pressure fuel and atomizing air. These pressures were considered too high for application in utility boilers, so the burner manufacturer was provided with maximum pressure limits for both atomizing media and fuel which were in the range of 825 to 1035 kPa. Subsequent development of an atomizer meeting these requirements in the manufacturers test facilities indicated good fuel atomization quality with both air and steam4).

Since the maximum wind box air pressure on the Chatham unit was about 0.5 kPa, a booster fan was installed. New burners were supplied and installed on the unit by October 1984. At each burner location there is a supply of purge water, compressed air for atomizing and purging, steam for atomizing No. 2 fuel oil for ignition, No. 6 fuel oil and coal-water fuel.

The No. 2 boiler is operated manually by the operators located adjacent to the boiler. There is no burner management system or flame supervisory system other than viewing ports and a television camera which views all four burners from above. All burner valves and controls are manual and arranaged for ease of changeover from coal-water fuel to No. 6 fuel oil.

The fuel is controlled by a manual pinch valve on the recirculation line from the burner front. A second manual valve in parallel with the main control valve is used to adjust the fuel flow according to minor changes in load. In addition, a manually operated variable speed drive was installed on the fuel pump to minimize the amount of fuel passing through the bypass valves and to provide better fuel flow control. Several performance tests were conducted by NBEPC on the unit. The preliminary test results are summarized in Table 6.

It must be noted that these are the results of the performance tests conducted by NBEPC using their standard procedures and do not include data from Combustion Engineering at the time of writing (January 1985).

Achievements on unit No. 2 were as follows:

The unit was operated at loads from 50% to full capacity with all four burners using coal-water fuel and with no support ignition required.

It was possible to switch at full load from No. 6 fuel oil to coal-water fuel. The fuel switching took approximately 20 minutes per burner because of the weight and size of the burner guns. It is expected that future coal-water burners will weigh less and be less cumbersome and the switching will then take much less time.

Table 6: SUMMARY CHATHAM NO. 2 BOILER EFFICIENCY OIL AND CARBOGEL FIRING

			Percent Losses						
Firing Mode	Test Date	Unit MW Load	Dry Gas	Moisture* In Fuel	Unburnt Comb.	Moisture In Air	Radiation	Unmeas.	Total BLR. Efficiency
No. 6 Oil	83.10.27	20.3	6.74	6.18	0.45	0.13	0.40	1.00	85.10
Carbogel**	84.11.07	18.2	11.08 (6.97)	7.47 (7.47)	7.47 (7.48)	0.17 (0.11)	0.45 (0.45)	1.50 (1.50)	71.86 (76.03)
	84.11.08	19.6	11.88 (7.20)	7.37 (7.37)	10.71 (10.71)	0.16 (0.09)	0.40 (0.40)	1.50 (1.50)	67.99 (72.74)
***	84.11.09	20.2	13.34 (7.48)	7.35 (7.35)	7.09 (7.09)	0.18 (0.16)	0.40 (0.40)	1.50 (1.50)	70.14 (76.09)

Remarks: * Total loss from moisture in fuel plus H_2O from combustion of H_2

** Two ignitors required for flame stability - heat input adjusted for 260 l/h No. 2 oil.

*** Test using steam atomization - approximately 1750 Kg/h steam used on 4 burners. Air atomization for previous coal-water fuel tests.

Note: Both CO_2% and CO% in flue gas estimated for oil fired tests and CO% estimated for all coal-water fuel tests.

All numbers in brackets are theoretical calculations based on carbon dioxide readings.

These are preliminary figures calculated by NBEPC using their standard procedures.

Table 6 shows that the unit operated at about 85% boiler efficiency (ASME indirect method) compared to between 68 and 72% when using coal-water fuel (based on NBEPC data).

A notable achievement with respect to these burners is that it was possible to operate using steam as atomizing media. The results with steam atomization were significantly better than with air. It must be noted however that in general the burners appear to be very sensitive to minor variations in coal-water fuel properties.

The atomizers were of T design with tungsten carbide inserts and showed negligible indications of wear during the cumulative burner operation.

Boiler startups were straight forward; the unit was warmed up on light oil then switched to No. 6 fuel oil until the furnace was hot. When adequate steam pressures and temperatures were reached, the burners were switched to coal-water fuel individually and adjusted until the flame stabilized.

ONGOING WORK

The ongoing program of demonstration of coal-water fuel in utility boilers has generated interest in Canada in the industrial sector. A 1981 survey5) conducted by the Montreal Engineering Company on behalf of EMR showed that industrial boilers and process combustors consume about 46 X 10^6 bbl/year compared to 15 X 10^6 bbl annual consumption of fuel oil for power generation, the latter all in eastern Canada. Therefore it is not surprising that coal-water fuels have generated interest in industry across Canada.

Canada Cement Lafarge, one of the largest cement producers in Canada, has been following the Chatham demonstration program with interest and has also been involved in a short coal water fuel test at Sete, France by its affiliated company Lafarge. In collaboration with EMR, a program has been developed which will lead to a 38-week test program in a wet process cement kiln in Richmond, British Columbia. The program which started in late 1984 has as its main objectives:

(i) to develop and optimize on-site coal-water fuel preparation using surplus wet process grinding capacity;
(ii) to observe the impact on the cement manufacturing process of replacing natural gas with coal-water fuel;
(iii) to develop and optimize durable burners for coal-water fuels.

During 1982, the Iron Ore Company of Canada became interested in coal-oil mixtures as an option for replacing fuel oil in its iron ore induration operations in Labrador City, Newfoundland. In order to assess the feasibility of using coal-oil mixtures they approached EMR for financial and technical assistance to convert an iron ore dryer located in Sept Iles, Quebec, to a coal-based fuel. The conclusions6) of the 50 h test burn in the dryer confirmed that the use of coal-oil mixture was technically feasible but only marginally so on an economic basis.

During 1983 and 1984, the company evaluated many other options for alternate fuel and finally approached EMR for technical support of a project to evaluate coal-water fuel. The first phase, now completed, was a single burner test in an iron ore induration furnace. A number of coal-water fuels and burners were evaluated in this phase. The second phase is scheduled to be a full zone conversion of eight burners, four each on opposed walls of the kiln. The third phase will be a full conversion of the furnace. If, at the conclusion of phase 3, the economic and technical feasibility is attractive, then the Iron Ore Company will proceed with conversion of the entire induration operation in Labrador City to Coal-water fuel.

As part of a continuing program on the evaluation of the combustion and heat transfer characteristics of coal-liquid mixtures, a program has been initiated at the Centre for Energy Studies (CES), Technical University of Nova Scotia to study the effects of fuel ash level on ash deposition from coal-water fuel flames. One of the possible major factors influencing the potential derating of boilers is the composition of the ash which may cause slagging and fouling of heat transfer surfaces. Obviously, even without these effects, the amount of ash passing heat transfer surfaces can lead to significant tube erosion. There are a number of interactive technical and economic parameters which give rise to two main questions: What are the economics of cleaning and grinding a particular fuel? and, How much of the ash of this particular fuel can be tolerated in a boiler in view of problems which prevent the boiler from operating efficiently, i.e. incomplete combustion, ineffective transferring of heat, and detriment to equipment? A study has therefore been designed to determine the effects of ash level in a series of coal-water fuels made from the same parent coal. The fuel manufacturing process is the same in all cases and the testing is being conducted in the CES 4GJ/h flame research tunnel.

The study of combustion characteristics, corrosion-erosion and evaluation of slagging and fouling in a flame tunnel, while simple in concept, is made difficult because of the length of time required to make comprehensive measurements. Particularly, corrosion-erosion measurements require long exposure time leading to high fuel use requirements and expense. The calculation of boiler efficiency is also more difficult under simulated conditions than it would be in an actual boiler. Modifications are therefore being made to the flame tunnel. The exit flue gas breeching from the flame tunnel is being modified to house simulated superheater and reheater tube bank assemblies. In addition, corrosion-erosion probes are inserted into the hot, particulate laden gas flow. This makes possible a realistic assessment of the impact of fuel ash content on deposition on the simulated heat transfer surfaces. Once this phenomenon is quantified, it will be possible to combine technical results from the test program with an economic model which will include the breakdown costs of coal-water fuel manufacture, and to determine what ash-level is appropriate for the given boiler application and coal supply and processing scenario.

EMR, together with the National Research Council of Canada (NRC), has been involved in the development of a wear-resistant ceramic atomizer for coal water fuels8,9). More details of this project will be given in another presentation at this symposium7). The nozzle was developed originally from a metallic annular atomizer which showed some promise because the most susceptible wear components were protected by an atomizing medium boundary layer. (See figure 3). Further development led to an adjustable ceramic atomizer which could be made to suit most burner and windbox configurations, and which had been shown to exhibit almost negligible wear in extensive spray and combustion tests. Since that time a comprehensive combustion characterization program has been undertaken on the atomizer in the CES flame tunnel7). Preliminary tests on a single burner in Unit No.1 boiler at the Chatham Generating Station have shown the versatility of the atomizer in being able to switch from heavy fuel oil to coal-water fuel by a simple in situ burner-gun adjustment. Most other coal-water burners require their atomizers to be exchanged to allow fuel oil to be burned in the boiler. These tests have shown the potential of the NRC atomizer and EMR plans to operate Unit No.1 entirely with the atomizers and coal-water fuel for performance testing in the spring of 1985. It is expected that this will lead to commercialization of the atomizer.

In addition to the NRC atomizer, EMR has been supporting the development of an alternative second generation coal-water fuel atomizer. The Lezzon atomizer concept has been described earlier10) and is illustrated in figure 4. In combustion tests of this atomizer at CES, oil, coal-oil- water and coal-water fuel have been burned in short test programs. It is now planned to embark on a comprehensive optimization and combustion characterization program using the CES facilities in Halifax. Ultimately the program will follow the same type of development as that of the NRC atomizer, through testing, demonstration and commercialization.

EMR is an active member of the International Energy Agency Coal-Liquid Mixtures Implementing Agreement, an agreement in which cooperative exchange of technical information in various areas takes place between the members. As part of this technology exchange, EMR's Canada Centre for Mineral and Energy Technology (CANMET) and the Dutch Energy Agency, Nederlandse Energie Ontwikkelings Maatschappij, BV have undertaken a collaborative combustion and heat transfer evaluation of several coal-water fuels. The studies covered a range of coal type ranging from low to high volatile bituminous coals, and fuels were supplied by four manufacturers. The results of this work which was undertaken by the International Flame Research Foundation (IFRF) in Ijmuiden, the Netherlands, have been discussed previously11). The results showed the importance of good atomization in optimised coal-water fuel flames and concluded that the fuel manufacturing process introduced variation into atomization quality which was difficult to elucidate with the information available. The work at IFRF complements that ongoing at CANMET's Canadian Combustion Research Laboratory7), and at CES.

The Nova Scotia Research Foundation has commenced a rheological study of coal-water fuels which is in support of the utility boiler demonstration program. The objectives of this study are as follows:

1) To measure the rheological properties of the coal-water fuel from the Sydney pilot-plant. These measurements would include apparent viscosity versus shear rate, shear stress versus shear rate and yield stress. The shear rates would cover a range which might be expected in typical burner front liquid fuel handling systems including the atomizer.

2) To examine the spray pattern and measure the droplet size distribution for various atomizers over a range of recommended operating parameters.

3) To quantify pressure drops through piping using coal-water fuel and to correlate these with fluid flow theory.

4) To correlate rheological properties with spray test results if possible.

It is anticipated that this study will enable better understanding of the relationship between coal-water fuel properties and atomization phenomena at the high shear rates which apply in twin-fluid atomizers. It will also lead to more meaningful fuel specifications for coal water fuels in the longer term.

CHARLOTTETOWN DEMONSTRATION

The 20 MW_e boilers at the Maritime Electric Company's generating station in Charlottetown, P.E.I., are most suitable for continuation of the program to the demonstration of coal-water fuel in an electric utility boiler designed to burn oil. These boilers are not in regular use, their compact nature is a challenge to the new fuel which will indicate its potential for most other units designed to burn oil, they are of an appropriate size for the demonstration, and, the modifications (conversion from forced to balanced draught and addition of a bag-house) needed for demonstration will be beneficial to station operation and to the local environment whatever fuel may be used in the future.

The boiler chosen for the demonstration has capacity to raise 24 kg of steam per second at a pressure of 6 MPa and a temperature of 480°C and the distance from its first bank of boiler tubes to the burner throats is only about 5 m. It has five front-wall burners, three in a lower horizontal row and two in an upper row. Bidders for conversion were given choice of using as many of these burner ports as they wished provided that sufficient fuel could be burned to raise 24 kg/sec of steam as a maximum and that 6 kg/sec of steam could also be raised on a continuous basis, without ignition support for the coal-water fuel under either circumstance. This range was required because the boiler derating due to the change from oil to coal-water fuel was unknown. A further requirement was that the carbon conversion during combustion be above 98%.

Boiler derating may be caused by insufficient heat generation or by insulation of the heat generated from the water and steam in the boiler tubes. Insufficient heat may be generated because flame temperature or position may be inappropriate, because gas velocities have to be kept low enough to avoid tube erosion, or because flames have to be restricted in size to avoid impingement on furnace walls and consequent slagging. Heat transfer may be restricted by accumulation of slag on boiler water walls or by fouling of boiler tubes by ash. It may be possible to minimize the deleterious effects of fouling or slagging by the use of soot blowers. The Charlottetown demonstration is investigating all of these effects. By the end of the demonstration 15 000 tonnes of Carbogel fuel from Cape Breton and up to 5000 tonnes of other coal-water fuels will have given reliable indication of how these fuels behave and how operators can cope with start-up, operation at various levels and ash disposal; knowledge of boiler performance, wear and associated economics will also be available.

CONCLUSIONS

The Chatham demonstration has proved that coal-water fuel can be used to heat up and to fuel electric utility boilers for full-load operation. Steam and air have been used as atomizing media and means of pumping, handling and metering the fuel have been defined. Toward the end of the test it became possible to define limits on fuel specifications which were achievable by the manufacturer and meaningful to the customer. Difficulties in manufacturing and transportation which caused inconsistent fuel to arrive at the customers' premises at the outset of the demonstration were all resolved.

Derating was proved non-existent for the boilers used but this left open the question of derating in boilers conservatively designed to burn oil. This will be resolved in a small (20 MW_e) boiler at Charlottetown in the near future. Scale-up of the technology to modern utility sizes greater than 100 MW_e was not attempted but will be feasible as a result of the program.

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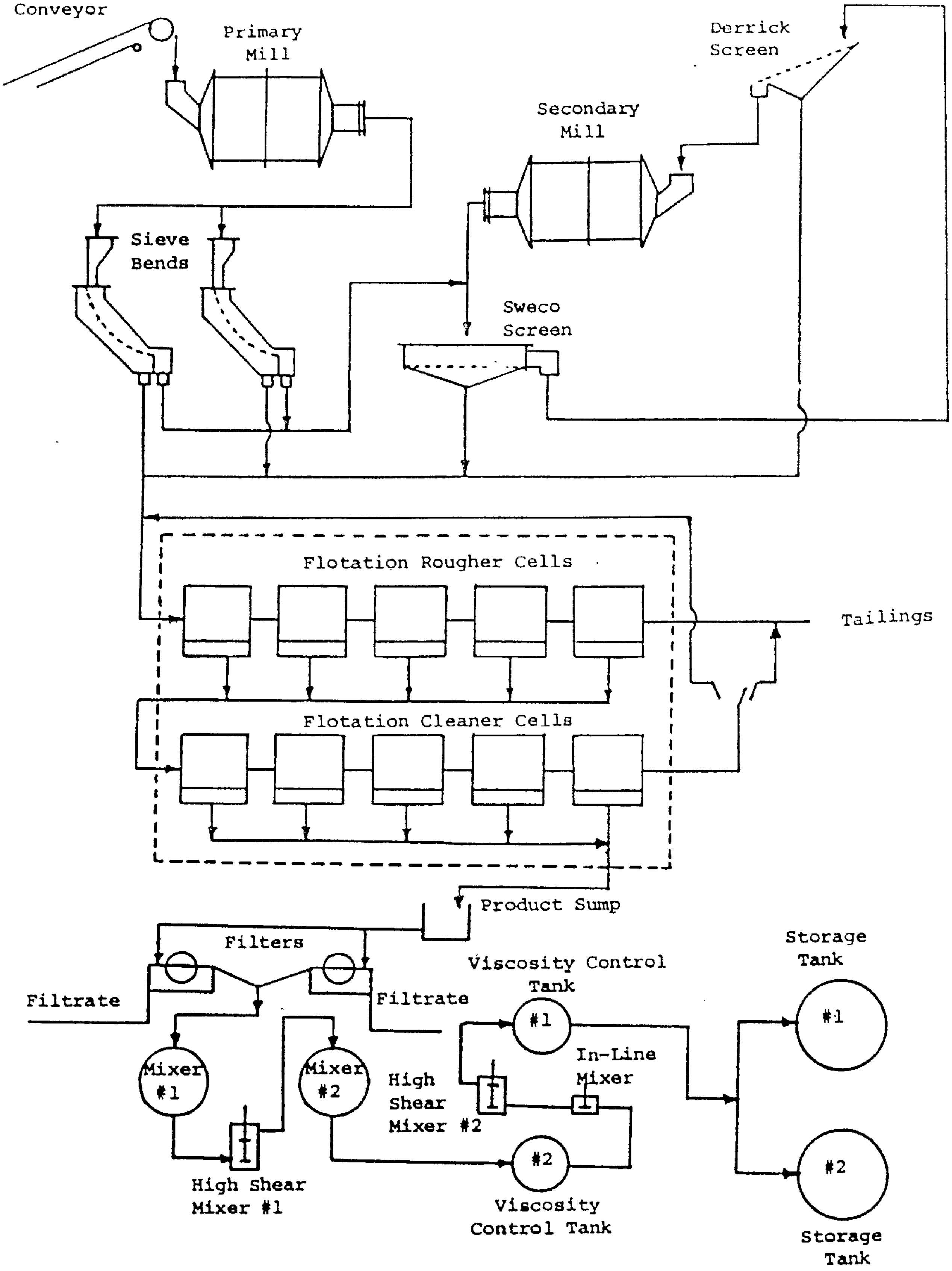


Figure 1: The Modified Coal-Water Fuel Pilot Plant Flow Diagram 1984

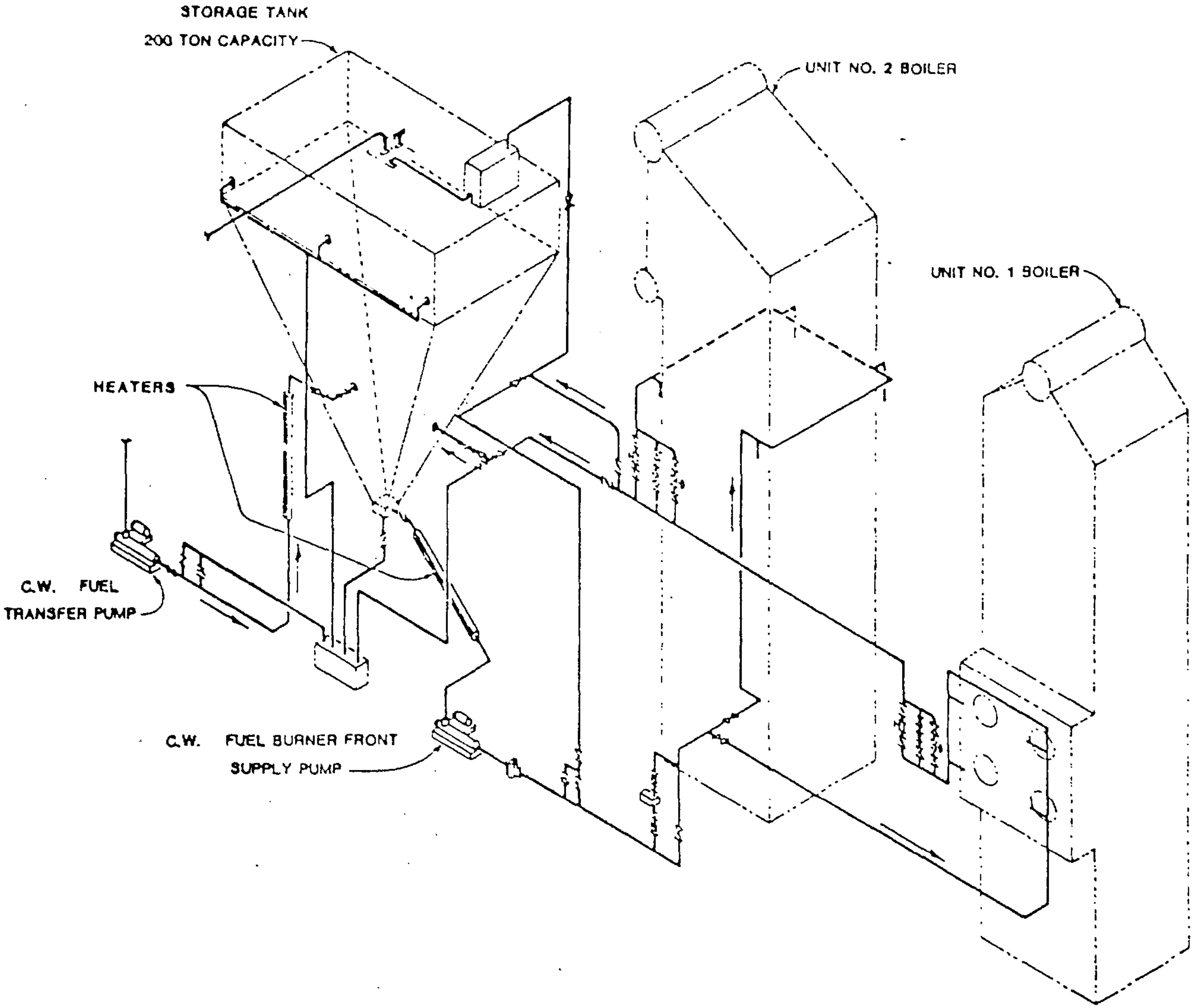


Figure 2: Schematic Illustration of Coal-Water Fuel Arrangement in the Chatham Station

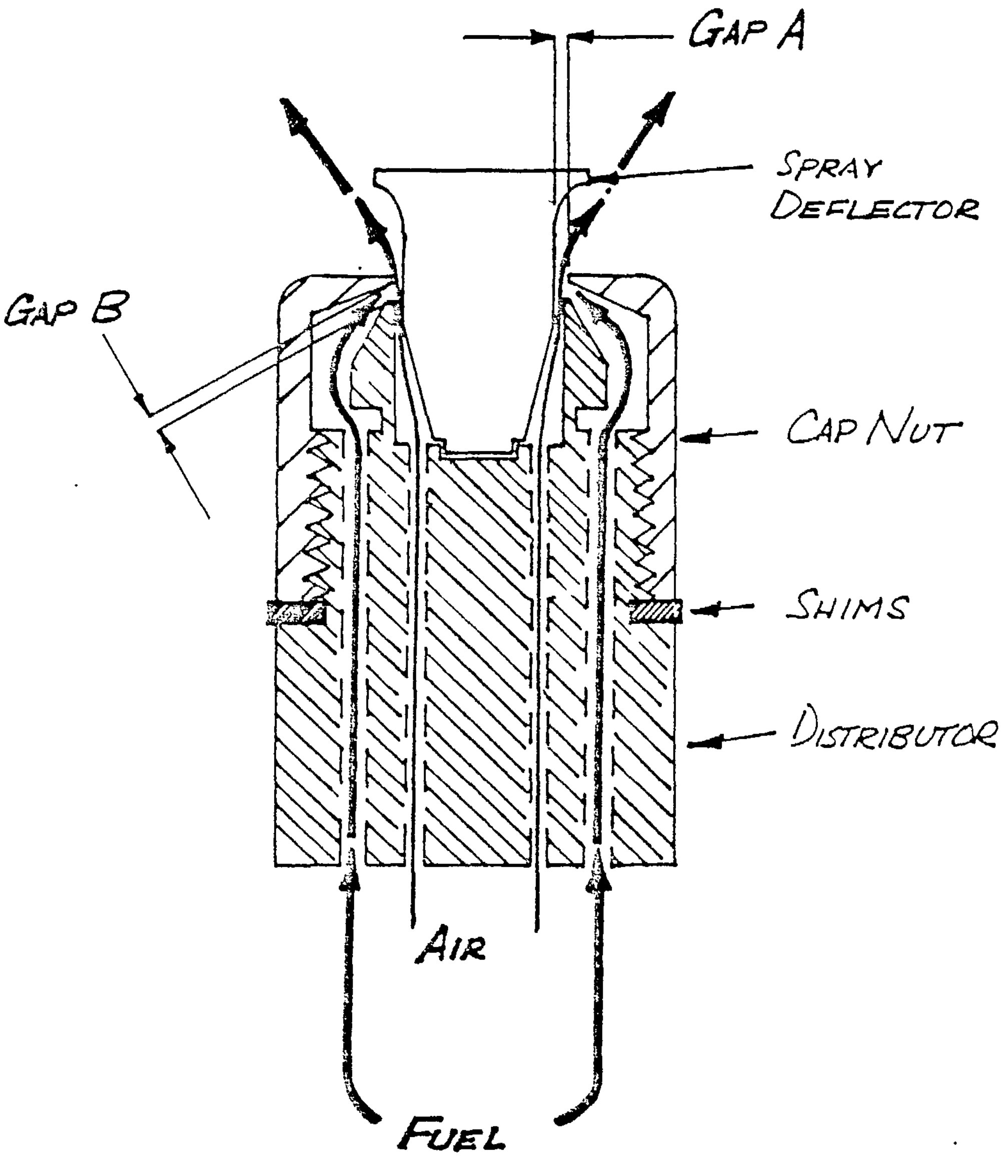
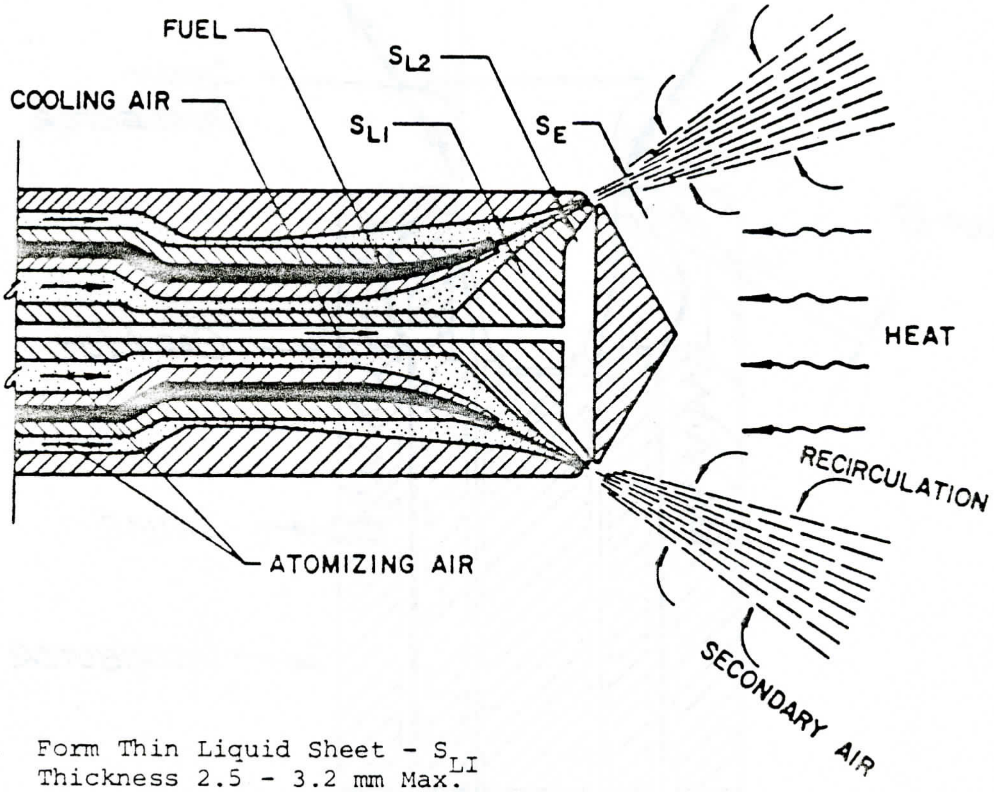


Figure 3: Schematic Illustration of the NRC Atomizer



1. Form Thin Liquid Sheet - S_{LI}
   Thickness 2.5 - 3.2 mm Max.

2. Sheet Thins in Conical Flow - S_{L2}

3. Two Air Annuli - Common Flow Channel

4. Atomize at Elongated Throat

5. Gas Throat Width: S_T $S_E - S_{L2}$

Figure 4: Schematic Illustration of the Lezzon Atomizer

CIMENTS CANADA LAFARGE LTÉE– CANADA CEMENT LAFARGE LTD.

CONVERTING A CEMENT PLANT FROM NATURAL GAS TO COAL WATER FUEL

MICHAEL A. NISBET

7 JANUARY 1986

ACKNOWLEDGEMENT

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CCL'S EXPERIENCE WITH COAL WATER FUEL

Introduction

Canada Cement Lafarge is approaching the end of a successful coal water fuel development program at its cement plant in Richmond, near Vancouver, British Columbia. The work which began in 1984 should be completed by mid-1986.

Chronology of Events:

1984 August - 4 week preliminary test in one kiln

1984 December - plant winter shutdown

1985 March - plant start-up: no CWF fired while product inventory was being built up

1985 June - CWF firing restarted in one kiln

1985 September - second kiln switched to CWF

1985 December - winter shutdown

1986 March - both kilns to be fired with CWF while optimization work is done

The objective of this paper is to outline the conditions which led to the decision to go to CWF, to describe the CWF firing system and technical results, and to present our preliminary economic findings.

Background

In the Portland cement manufacturing process, the various raw materials, typically limestone, chalks, shales, clays and sands, depending on the local sources, are blended in the correct proportions and ground to a fine powder or slurry. The resulting raw mix is further homogenized and stored prior to being fed to the kiln.

The raw mix is heated in a large rotary kiln, some equipped with cyclones, to a temperature of approximately 1370°C to decompose the calcium carbonate and recombine the resulting calcium oxide with the silica, iron and alumina. The intermediate product, called clinker, is a gravelly, abrasive material consisting of calcium silicates. The clinker is then ground in a ball mill, with a small amount of gypsum which controls the setting time.

Portland cements with different properties are produced by varying the raw mix composition, by adding small amounts of chemical agents and by changing the fineness of the product. The quality of the product is very sensitive to small changes in the chemical composition of the clinker, such that the raw mix must be corrected to compensate for the coal ash if coal is fired in the kiln. The ash, in fact, becomes another raw mix component.

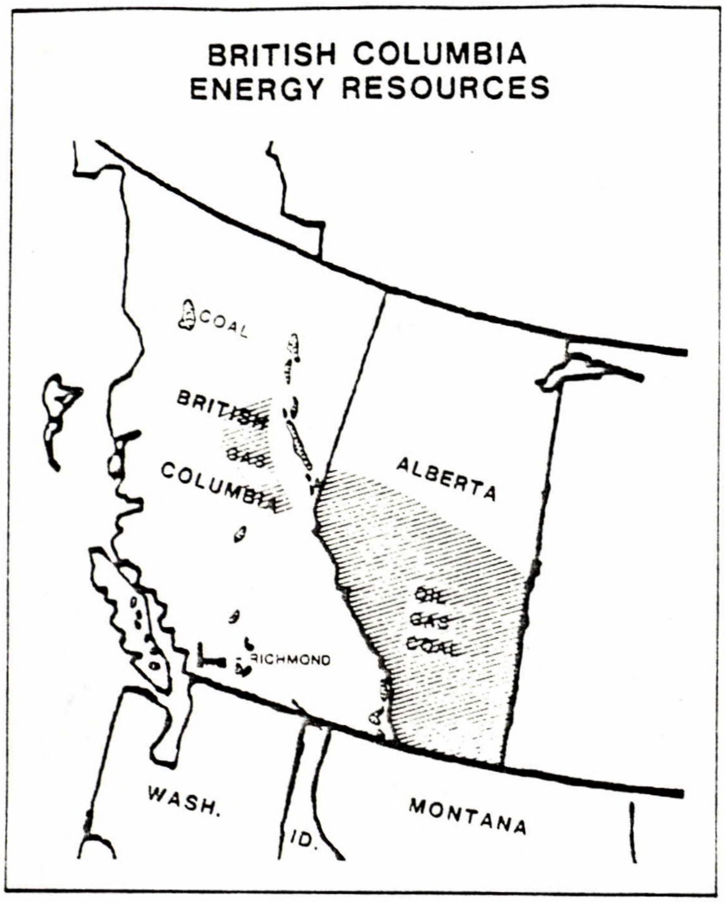
The rotary kiln is the principal user of thermal energy, consuming between 3.2 GJ for modern dry process plants and 6.4 GJ per tonne of product for older wet plants. Typically, kiln production capacities range from 20 tph to 500 tph. Fuel oil, cokes, natural gas, and coal are the principal fuels, the choice being determined by price, availability and processing equipment.

As coal is often lower in price and very available, it is the preferred fuel in North America. However, coal firing requires a higher capital investment in handling and milling equipment as compared to that required for oil or gas.

The Richmond plant was started in 1958 as a single kiln operation. A second kiln of slightly larger capacity was added in 1967. The capacities of the major equipment are summarized in the table below.

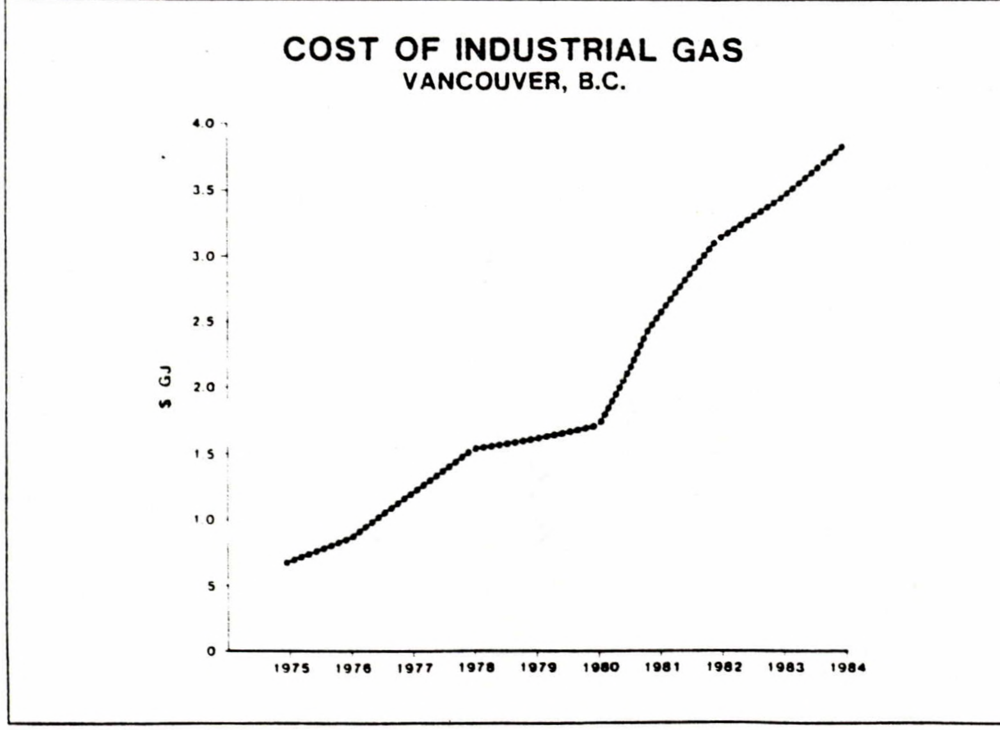
RICHMOND PLANT
MAJOR EQUIPMENT

Annual capacity		490,000 tonnes cement
Process		wet
Raw mills	1	1400 HP (60 t/hr)
	2	1600 HP (60 t/hr)
Kilns	1	654 t/24 hrs clinker
	2	753 t/24 hrs clinker
Finish mills	1	1400 HP (24 t/hr)
	2	1600 HP (24 t/hr)


BRITISH COLUMBIA ENERGY RESOURCES

The major kiln fuel has traditionally been natural gas from the reserves in north-eastern British Columbia. The province also has extensive coal resources, with most of the exploitation taking place in the south-east corner near the Alberta and Montana borders.

Prior to mid-1985, natural gas prices were controlled by the Provincial Government, and, despite falling industrial demand during the recent recession, continued to rise.


COST OF INDUSTRIAL GAS
VANCOUVER, B.C.

Faced with the prospect of an energy source, whose price had become uncoupled from the market, CCL directed its attention to converting the plant to coal, whose cost was about 54% that of natural gas. Since most cement plants use pulverized coal, the technology is well established so there would have been no technical risk involved.

However, there was a reluctance for economic reasons to spend an estimated US$5.0 million on a dry coal firing system because:

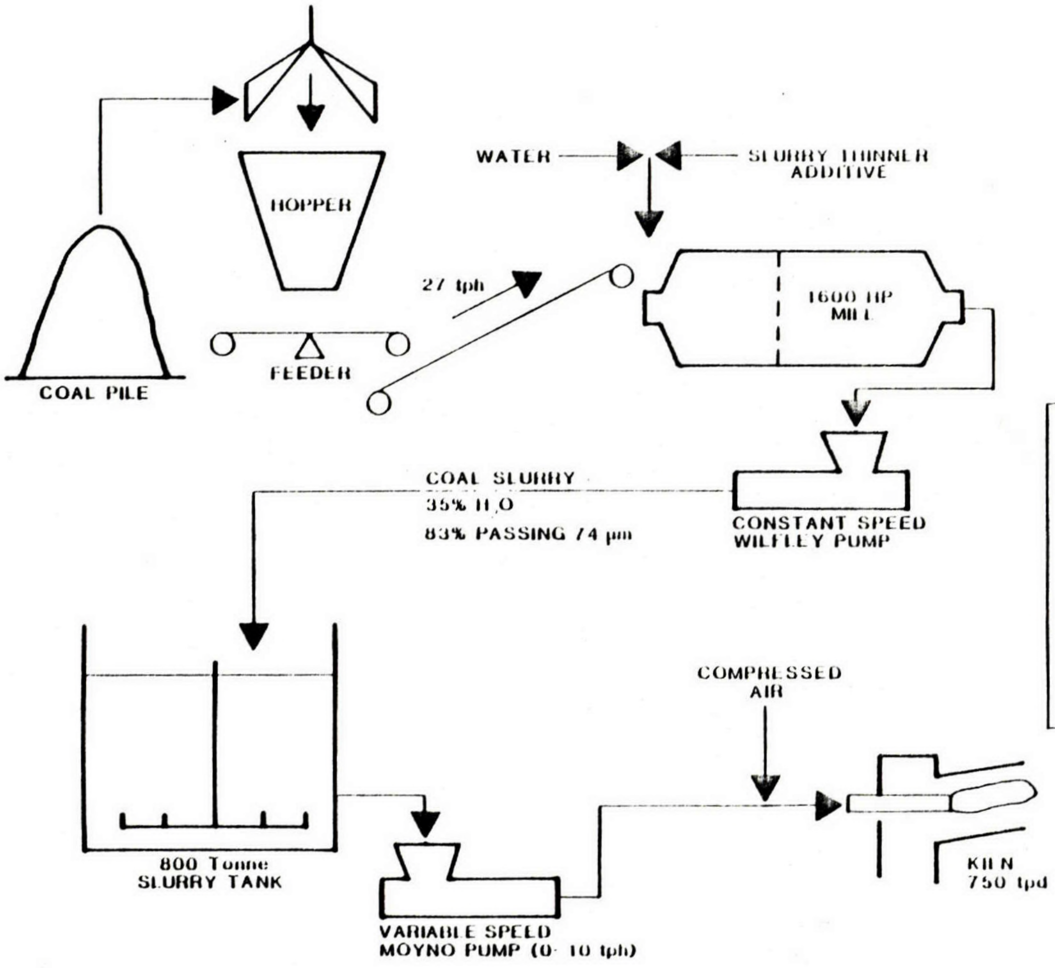
- the plant is relatively old,
- local cement markets were weak and expected to recover slowly,
- capacity utilization had been low from 1982 to 1984,
- the recession had limited the availability of capital within the corporation.

Thus, though coal water fuel was an unexplored technology as far as cement manufacture was concerned, a decision was made to test it in one of the kilns. The initial investment was low because a wet mill used to make raw mix slurry, and also an 800 tonne slurry storage could be made available. The main additions were a transport line to carry the CWF from storage to the kiln, a pump, a compressed air source and a burner.

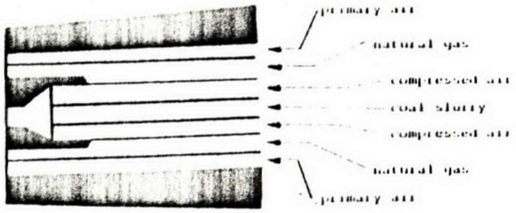
The Coal Water Fuel Project

The coal is handled with existing equipment in exactly the same manner as the raw materials. A 1600 HP open circuit ball mill with two compartments grinds the coal to 17% rejects on a 200 mesh sieve. The only additive, calcium lignosulfonate, is added at the mill as a slurry thinner or dispersant at the rate of 1.5% solids. The water content of the fuel is about 35% on a wet basis. The coal slurry is pumped through the slurry line by a Wilfley pump to an 800t slurry tank, equipped with slowly rotating plows with compressed air for additional agitation. Up to this point, all the equipment already existed in the plant for the production of raw mix slurry. In fact, calcium lignosulfonate was already being used to reduce the water content of the raw mix. The process flow is shown in the diagram on the next page.

COAL WATER FUEL SYSTEM



Coal Slurry Process Flow



Burner Arrangement

From the storage tank, the coal slurry is pumped approximately 500 feet to the burner platform through a 4 inch line, using a variable speed Moyno pump rated at 265 psi. The burner pipe was modified to carry CWF, compressed air, natural gas and primary air through successive annular spaces with coal slurry at the center. The Moyno pump, piping and burner are new installations for the CWF firing. Compressed air is provided at present by a 1000 CFM mobile compressor.

The firing rate of the coal is controlled by varying the speed of the Moyno pump. The flow of compressed air, used to atomize the CWF, is controlled with a manual valve on the burner floor.

Results

CWF has been used as the main heat source in one kiln for close to six months and in the second kiln for one month. CWF is providing about 80% of the heat requirement. The major findings are:

- Agitation in the slurry tank is sufficient to keep coal in suspension.
- Nozzle dimensions are critical for good atomization. Good success with a 1.5 inch diameter nozzle.
- Nozzle wear is high unless special materials are used. Ceramic inserts have solved this problem.
- Kiln operation, always a concern of cement makers, is not adversely affected. Scale formation (important as it protects the refractory) is good.
- Secondary air temperature is important. If it falls too low, the flame becomes unstable.
- High initial wear rate of the Moyno pump stator has been reduced by eliminating rejects in the slurry.

- The quality of the cement has not been affected.

- Environmental standards have been met.

Three types of coal have been used in the CWF. Proximate analyses are given in the table below.

COAL ANALYSES			
	GREENHILLS	WOLF MOUNTAIN	ELKVIEW
% Ash	14.7	12.3	9.8
% Moisture	9.5	6.5	7.3
% Volatiles	25.0	37.0	20.0
% Sulphur	0.4	0.5	0.3
Thermal Value (GJ/t)	26.33	27.21	29.77
(BTU/lb)	11,320	11,700	12,800
Hardgrove Index	75	53	86

During the initial phases of the program, Greenhills coal was used exclusively. Water content of the fuel ranged between 35-40% with a viscosity averaging 1200 cps.

When stable operation of the CWF system and kiln had been achieved, a test was made with the higher volatile Wolf Mountain coal. The findings were disappointing. The water required to maintain a viscosity of 1200 cps with a constant level of water reducing agent (1.5% solids) rose to 40%, and because of the lower Hardrove Index, mill output dropped from 29 to 21 tph.

The Wolf Mountain coal was followed by the Elkview product which was lower in volatiles, had a higher heat content, and was more easily ground. The result was a CWF which burned satisfactorily and met the viscosity requirements with 34% water.

Preliminary Economics

CWF is not optimized yet at Richmond. Further work remains to be done on reducing the water content of the fuel and on decreasing the percentage of gas in the kiln fuel mix. Ideally, gas should only be used for start-up.

However, enough data is available to make a preliminary economic evaluation of the project by estimating the savings flow generated by replacing gas with CWF and by comparing it to the savings which could be expected from using dry pulverized coal as fuel.

The capital investment in converting the CWF at Richmond was low because milling and storage capacity was already available. Thus, the capital for the CWF installation was about 13% of a dry coal preparation system.

CAPITAL ESTIMATES

CWF	US$ 630,000
Dry Coal	5,000,000

Estimation of the savings flow from CWF assumes:

- CWF will provide 90% of the heat; gas 10%,
- the kiln heat consumption will increase by 5%,
- dry coal would supply 100% of the kiln's heat requirement without an increase in heat consumption.

The savings flow at three different levels of plant utilization are summarized in the following table.

ANNUAL SAVINGS STREAM ESTIMATES			
	Utilization of Practical Capacity		
	60%	80%	100%
Plant output (tonnes)	298,000	398,000	496,000
SAVINGS (US$000)			
From Gas to CWF 90% / Gas 10%	1,501	2,005	2,498
From Gas to Dry Coal	2,108	2,815	3,508

On the basis of these estimates, it is clear that under the conditions existing at Richmond where capital investment was low, and natural gas prices were relatively high compared to coal, conversion to CWF has been very profitable, with a payback period of less than 6 months at 60% capacity utilization. If the cost differential between natural gas and coal remains at current levels, a sustained savings flow of US$1.5 to 2.5 million per year should be realized depending on capacity utilization.

Had a conventional coal mill been installed, the savings would have been greater than those achieved with the CWF because of:

- cost of the water reducing agent in the CWF,
- 5% increase in thermal consumption in the kilns,
- 10% high cost natural gas fired with the CWF.

But, the greater savings are conditional upon an expenditure of US$5 million. At 60% capacity utilization, the payback period on this investment would be 2.6 years and the ROI 30.1%. While this return is financially satisfactory, it is considerably below that obtained on the CWF investment.

Conclusions

At the Richmond plant, coal water fuel has been found to be a technically satisfactory and economically viable alternative to natural gas as a kiln fuel.

The CWF was put into use relatively easily because of the Plant's knowledge of grinding and handling cement raw mix slurries.

Capital investment was minimized by using existing equipment.

CWF is budgeted to provide 80-90% of the kilns' heat requirements in 1986.

A CWF optimization program is needed in 1986, aimed at:

- lowering the water content of the fuel from the current level of 36% to 30%,
- reducing natural gas to 10% or less of the kiln fuel,
- gaining more experience with different coals.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

84-JPGC-FU-6

COMBUSTION TRIALS OF COAL-WATER MIXTURE FUEL IN TWO SMALL UTILITY BOILERS IN EASTERN CANADA

by

H. Whaley[1], D.M. Rankin[2] and P.J. Read[1]

ABSTRACT

Interest in coal-liquid mixtures as potential oil replacement fuels has been continuing in Canada since the early seventies. The initial motives for this interest were the rapidly rising cost of oil coupled with an insecurity of supply. The possibility of the recurrence of extreme energy price and supply fluctations is the reason for continued efforts in the development of coal-liquid mixtures and in particular coal-water mixtures for utility boiler applications.

A brief description is given of an early program undertaken at Chatham, New Brunswick in which coal-oil mixtures were used in a small utility boiler. This program showed that burner and equipment wear was a significant impediment to coal-oil mixture utilization and led to the inclusion of coal cleaning in the preparation process as a means of reducing the sulphur and abrasive ash content of the coal.

Currently, under a co-operative agreement between Energy, Mines and Resources Canada, the New Brunswick Electric Power Commission and Cape Breton Development Corporation, a 7 tonne/h preparation facility has been built to produce fuel for testing in two small utility boilers located at Chatham N.B. An update is given of the status of this program as well as plans for the future program in eastern Canada.

1. Introduction

Coal-water mixtures offer a means of replacing oil by coal where direct substitution of a solid fuel is impossible or uneconomic. There is a potential for this replacement in many stationary combustors and in some mobile uses provided that they can be burned reliably, cleanly, safely and economically. This paper reports the progress in the development of coal-water mixture technology to meet these requirements.

In eastern Canada, the only part of the country where electricity is generated from oil, natural gas has not been generally available and local coal tends to be both expensive and high in sulphur. This situation leads to the potential for replacement of oil by coal-water mixtures being highest in New Brunswick and the other Altantic provinces. Coal-water mixtures may ultimately find use in the West or for export but the decision was taken to investigate their potential in eastern Canada because of the most urgent need, because of the possibility of environmental benefits, and because there are more smaller utility boilers of a suitable size for demonstration in the East.

Utilities and other industries which might use coal-water mixtures are generally not in a position to switch to such a fuel or even to assess the economics of switching until there is proof that it can be burned reliably and safely. The present program therefore seeks to demonstrate the combustion of coal-water mixtures at small utility scale in two small coal-capable units. Then it is planned to proceed to demonstrations in a small oil-designed unit and ultimately in oil-designed units of normal utility scale. Once all these demonstrations have been completed it is expected that normal commercial practice will take advantage of the technology wherever it is economic to do so.

2. Background

In 1972 the Canadian Combustion Research Laboratory conducted an in-house program to study the combustion and heat transfer characteristics of several coal-oil mixtures in a pilot-scale research tunnel furnace. The results of this work were presented at a joint industry/government seminar in 1972(1) in order to stimulate interest in coal-oil mixture technology. Subsequent evaluations of the data were presented at the International Flame Research Foundation, IFRF, 4th Members Conference(2) and the ASME winter annual

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1) Energy, Mines and Resources Canada.

2) New Brunswick Electric Power Commission

meeting(3), both in 1976. This early research into coal-oil mixture combustion was discontinued because the availability of cheap fuel oil did not make coal-oil mixture attractive to industry. However, following the rapid escalation of oil prices in the late seventies there was renewed interest in coal-oil mixture technology and Energy, Mines and Resources, Canada, as part of its program to reduce reliance on foreign oil supplies, encouraged this interest by financial and technological support through demonstration projects and R and D.

The first demonstration project was undertaken in three phases from 1977 to 1980 to study the potential for utilization of coal-oil mixtures in a small utility boiler at Chatham N.B.(4,5,6,7,8). The Chatham Thermal Generating Station, Unit No. 1 of 10 MW(e) generating capacity was selected for this earlier project, due to its small size, coal design, and the fact that it is rarely required to supply electricity to the grid. Thus the unit had the operational flexibility required for the coal-oil mixture study.

After more than 1500 hours of operation on coal-oil mixtures ranging from 10 wt percent to 40 wt percent coal, it was concluded that:

> The erosion of burner tips was the main obstacle preventing the successful utilization of coal-oil mixture technology in this boiler;
> The erosion which resulted in progressive flame deterioration could be attributed to the use of a highly abrasive coal in the coal-oil mixture;
> This problem still persisted even when incorporating an in-line coal cleaning process to reduce the ash and pyrites content of the coal;
> Pumps, valves and secondary grinding equipment also suffered signficant wear-related damage which resulted in deteriorating performance but it was felt that this problem could be eliminated by appropriate materials and equipment design considerations;
> Pipework was relatively unaffected by wear, essentially due to the low prevailing fluid velocities.

It was deduced that the major problem of burner tip erosion could be solved by choice of a less abrasive coal, improved coal cleaning by ash and pyrites rejection, further reductions in coal particle size, materials selection, or the use of externally atomized burners with low coal-oil mixture efflux velocities and a simple configuration. These findings have been subsequently reinforced by a CANMET study of atomizer wear undertaken at the Ontario Research Foundation(9).

3. Economic and physical requirements

The price range which coal-water mixtures can command is determined by competing fuels. In large industries and electric utilities these fuels are usually residual oil, Bunker 'C' or coal. Smaller energy consumers use No. 2 or No. 4 fuel oil or natural gas which, in Canada, may also be used in larger industries and utilities. For most of these users, the prices per unit of energy for the competing fluid fuels are approximately two-thirds that of crude oil. In order to attract customers by pricing significantly below that of the competition, coal-water mixtures must sell for less than 50 percent of crude oil prices on a heat value basis. On this basis the most expensive Canadian thermal coal sells for somewhat less than 50 percent of the crude oil price, so where direct use of coal is possible it is the most attractive fossil fuel. However, where solid fuel cannot be used, even if the starting material for a coal-water mixture is one of the more expensive Canadian coals, there is nearly a 50 percent margin above its regular price available to cover additional costs of preparation by the supplier and of operation by the user as well as reasonable return on investment.

Feedstock costs all but preclude the use of coal-oil mixtures since, at the upper physical limit (about 50 percent) of coal concentration, the cost of coal, oil and preparation exceed the price of competing fuels. There may be an exception to this generalization in the case of proprietary fuels containing about 25 percent oil, 15 percent water and 60 percent coal, particularly for modest-scale heating plant and marine use, but overall the Canadian program has veered away from its early interest in coal-oil mixtures on economic grounds.

Canada has the objective of decreasing its atmospheric emissions of sulphur oxides by 50 percent between 1980 and 1990 and the substitution of low sulphur coal for residual oil can materially assist in reaching this objective. The multistage cleaning process associated with coal-water mixtures can reduce medium-sulphur coal to this desirable state. However, even where such mixtures might be chosen as an oil substitute preferable to coal on environmental grounds alone, such as in a furnace originally designed to burn coal but later switched to oil (to minimize particulate as well as sulphur emissions), the competitiveness of clean-burning natural gas sets an upper limit to the price.

Removal of mineral matter from coal is important for boiler performance, for economy of distribution, for ash disposal, and for environmental protection. Conventional coal beneficiation removes much of the adventitious mineral matter but cannot extract minerals that are very finely interspersed or are part of the molecular structure of the coal. In the case of sulphur, the occurrence may be in pyritic, sulphatic or organic form. Very finely divided pyritic sulphur is often reported as organic because it is so difficult to remove by physical means. In Canada most beneficiation is currently applied to coarser coking coals, however, where coals will be burned as a slurry and fine grinding is essential, advantage can be taken of this grinding to liberate sulphur compounds and other minerals. Therefore in the preparation of coal-water mixtures, conventional washing is followed by milling and froth flotation which separates coal from mineral matter on the basis of surface characteristics. Coal from the Sydney coalfield in Nova Scotia is particularly amenable to this treatment and shows promise of good yields with mineral matter in the 1.5 to 3 percent range and with about two-thirds of the original sulphur removed.

In utilizing coal-water mixtures in utility boilers, particularly those designed for oil firing, there are many problems to be overcome. Usually an oil-designed boiler is smaller, the steam-raising tube banks are configured differently and the gas velocities in the banks much higher than for an equivalent capacity coal-fired unit. In addition, coal-based fuels may contain ash which poses problems of tube erosion and slagging and/or fouling. The ignition, flame and heat transfer characteristics of coal-water mixtures are quite different from those of heavy fuel oil and therefore the heat release pattern from the flame may not be suitable for an oil-designed unit. The combination of all these factors means that an oil-designed unit may be derated; that is it may not be able to attain the maximum generating capacity for which it was designed when firing oil. Studies have indicated that such derating may be very significant but this remains yet to be shown in practice(10,11). In addition to depending on the design of the boiler and its operating characteristics, the extent of this loss of electrical output will also depend on the coal, its rank and reactivity, (volatile matter, inert macerals content, degree of oxidation) as well as its ash content and composition, and the slagging/fouling propensity of the ash.

Several estimates have indicated that deposition of slag on the tubes of boilers conservatively designed for oil firing would contribute very substantially to boiler derating which could be more than 50 percent when coal is used as fuel(10,11). The site chosen for preliminary coal-water fuel tests was again the generating station at Chatham, New Brunswick since it has two boilers originally designed to burn coal but recently adapted to burn oil, one front-wall fired and one tangentially fired, and of 10 and 22 MW(e) capacity respectively. The results obtained at Chatham, where coal-water mixture burners have replaced oil nozzles, are giving us, at a small utility scale, virtually all the data required to assess burners and fuel without risk of outages or of seriously interrupting electricity supply.

4. Objectives of Present Program

The development of the Canadian coal-liquid mixture program through its early stages and the rationale behind the Canadian approach have already been described(12). The ultimate objective of the program is to derive enough data concerning the fuels and how to burn them that potential users will be able to make decisions to replace oil, based on economics and without abnormal technical risk. An essential component of the program is the establishment of a quality-cost-price relationship. Obviously it costs more to prepare a high quality (i.e. low sulphur, low ash) mixture than a low quality one. For coal-water mixtures, conventional cleaning applied to the highest quality coal can reduce mineral matter to 3 percent and sulphur to 1.2 percent: grinding and multistage flotation can reduce these levels to 1.5 percent and 0.8 percent respectively: if lower quality (less expensive) coals are used, the same process is expected to attain about 3 percent ash and 1.5 percent sulphur.

The program includes preparation and assessment of the combustion characteristics of a range of fuels from the cleanest coal-water mixtures that can be manufactured to those containing more ash and sulphur. These tests will help to determine the extent and cost of physical cleaning needed to achieve satisfactory boiler operation.

Use of coal-water mixtures by utilities requires a delivery and storage system, including agitation, and pumps which can deal with fluctuations in diurnal and seasonal demand. The program is demonstrating methods of transportation which would be applicable to industrial users and one of the combustion tests has been carried out in freezing weather so that the problems due to low temperature operations have been identified and solved.

5. Details of Present Program

The present program comprises several elements now virtually complete which combine to achieve the objectives set out above. These are the construction of a 7 tonne per hour pilot plant at Sydney, Nova Scotia, for preparation of a coal-water mixture containing over 70 percent coal, the design of burners suitable for reliable combustion of this fuel, the demonstration of the use of the fuel and burners at Chatham in both units. The pilot plant treats clean coal (-3 mm) from an adjacent conventional dense-medium coal preparation plant which reduces the mineral matter content from about percent to 3 percent. The pilot plant, schematically illustrated in Fig. 1, comprises two stages of grinding, particle size control, two stages of froth flotation (further reducing the mineral matter to about 1.5 percent), and the mixer to add a stabilizer followed by holding tanks. The flow sheet is based on the proprietary CARBOGEL process. The target solids content is 75 percent with viscosity in the 800-1500 centipoise range at low shear rates. It is also a requirement that the fuel shipped is not dilatant. The prepared fuel is held in day storage tanks for regular delivery by rail tanker about 750 km to Chatham: a storage tank of 250 m^3 capacity already in existence at Chatham forms the buffer to match demand with production capacity.

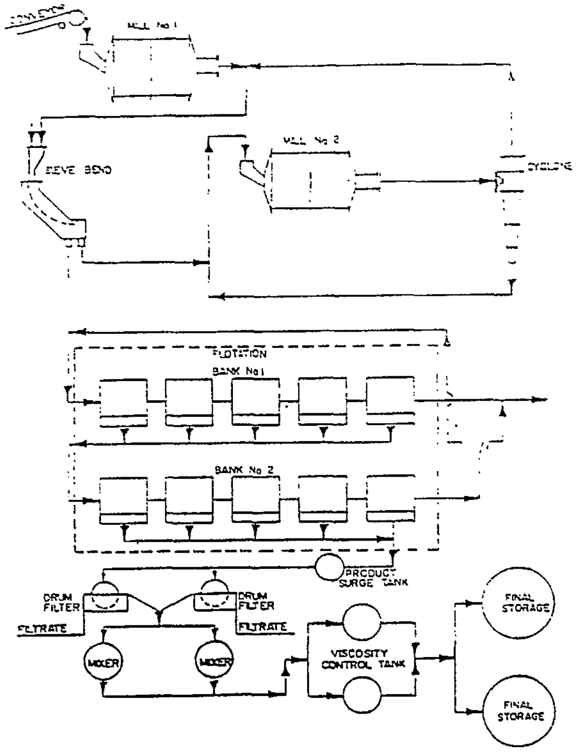


Fig. 1 - Coal-water mixture, pilot-plant flow diagram

Fuel production costs are recovered by the producer through the price charged to the electric utility. After a credit for the value of the electrical energy produced, the remaining cost of the demonstration, including combustion of the fuel, is borne by the federal government. Construction of the pilot plant began in November 1982 and was completed in July 1983.

Concurrently with the construction of the pilot plant, a program to develop coal-water mixture burners for the 10 MW(e) front-wall fired and 22 MW(e) tangentially fired units at Chatham NB was undertaken. The two phases of the coal-water program were as follows:

Phase 1:

Design, testing and evaluation of a burner rated at approximately 30 GJ/h thermal input, of a type suitable for coal-water slurry fuel combustion in the 10 MW(e) front-wall fired Chatham Unit No. 1. A testing and evaluation program for the burner together with a boiler performance assessment program were developed for the performance trials in Chatham Unit No. 1, and undertaken during Phase II. Similar programs for tangentially fired units were also undertaken leading to performance trials in Chatham Unit No. 2 of 22 MW(e) capacity. Burners for both units were designed and tested prior to installation at Chatham.

Phase II:

Assessment of burner and boiler performance when firing coal-water mixtures in front-wall and tangentially fired boilers, with special emphasis on reliability of equipment. At the time of writing it is anticipated that 6000 tonnes of fuel will have been burned by the end of the performance trials. The fuel contains about 1.6 percent ash, 0.9 percent sulpur, and is similar to that used in Phase I for burner development. The Phase II performance trials began in late Summer of 1983 and should be completed by Summer 1984. It is expected that these two phases should lead to the testing of burners for demonstrations of coal-water mixture technology in oil-designed utility boilers up to the 50 to 150 MW(e) capacity range and of both basic configurations typical of eastern Canada.

6. Current Progress

Formal contracts have been signed among the Cape Breton Development Corporation, the New Brunswick Electric Power Commission and Energy, Mines and Resources to conduct the program. The Cape Breton Development Corporation has entered a licensing agreement with A.B. Carbogel to use their patented process and the plant is now designed and built and supplying fuel to Chatham on an as needed basis. The original plant schedule specified July 1st 1983 for completion of equipment installation and start-up and in fact the first fuel was produced in late July.

New Brunswick Electric Power Commission has issued burner development and boiler modification contracts to Foster-Wheeler Ltd. and Combustion Engineering Ltd. for their respective boilers at Chatham. The current schedule for burner testing and development for the two units is shown in Fig. 2. This schedule shows that, at the time of writing, burners have been developed for Unit No. 1 by Forney Engineering the burner manufacturing subsidiary of Foster-Wheeler. These were installed on the unit during July and a preliminary evaluation was conducted in late July 1983.

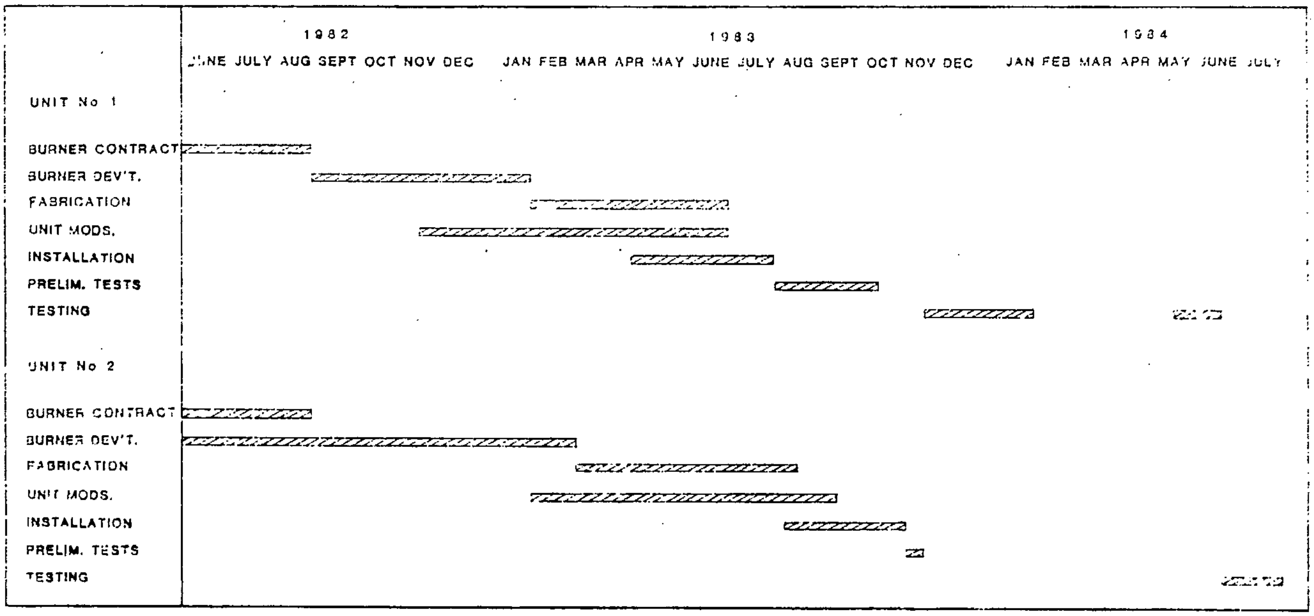


Fig. 2 - Schedule for burner development and testing at Chatham

6.1 Unit No 1. Boiler Description and Test Program

The Chatham Unit 1 boiler was originally installed in the late 1940's and was designed to fire pulverized coal. The boiler is a balanced draft, type SA Unit with the following nameplate data:

Manufacturer:	Foster Wheeler
Steam Flow at superheater:	63,600 kg/h
Operating Pressure:	4170 kPa
Steam Temperature:	450°C
Feedwater Inlet Temperature:	177°C
Number of Burners:	4 (2x2) Front Fired

Steam from the boiler is used to drive a turbine generator with an output of approximately 12.5 MW (e). The boiler was converted to heavy oil and was used for coal-oil mixture program mentioned earlier.

A schematic side view of the boiler is shown in Fig. 3.

The burner and windbox shown in Fig. 4 are specifically designed to burn coal-water mixtures. They consist of two combustion air passages and a specially designed atomizer. A primary air-fuel mixing zone is created along the burner centerline at the exit of the primary retractory throat. Low velocity air passes through this zone to generate strong recirculation and long fuel residence times. Secondary air passes through an outer rotating air register for further stabilization and mixing. The atomizer is of a conical internal mix design for low pressure operation. Each burner is rated at approximately 40 GJ/h.

Ignition and support energy are provided by a single high energy spark igniter and two light-oil pilots rated at 6 GJ/h each. Experience at Chatham has, however, shown that for light-off and low load support only one light-oil pilot is necessary.

The burners were supplied as four independent burner/windbox assemblies. To accommodate the new burners, modifications were required to both the boiler front wall and combustion air ducting adjacent to the burners. A total of five wall tubes were replaced to accomodate the larger burner throats. Brickwork and refractory around the throats were modified accordingly. The combustion air ducts were also modified to fit the deeper coal-water mixture burner windboxes. Balancing dampers were removed from the duct and incorporated as sleeve type dampers over the outer burner registers.

Each burner is designed to allow a wide range of adjustments, some of which are not normally present on commercial burners. These adjustments allow the precise positioning necessary to optimize burner performance. Some of the adjustable features include the following:

- Inner throat position.
- Swirler position.
- Atomizer position
- Igniter and HESI positions.

The burner is easily adapted to heavy oil firing by changing the fuel gun tip and the position of the primary air damper. No other modifications have been found necessary.

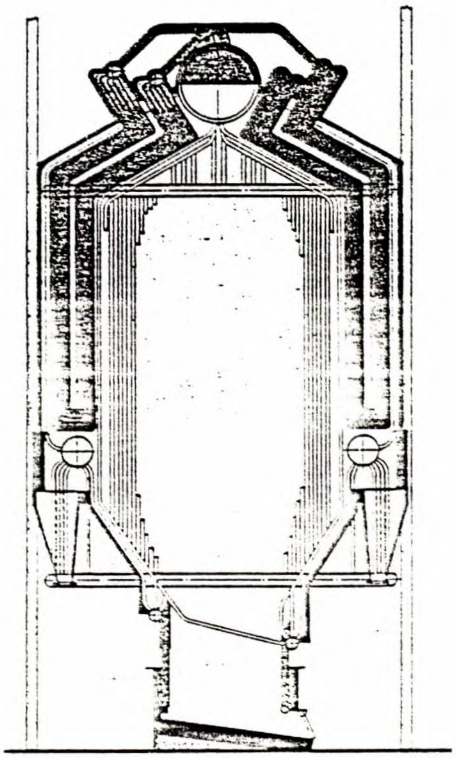
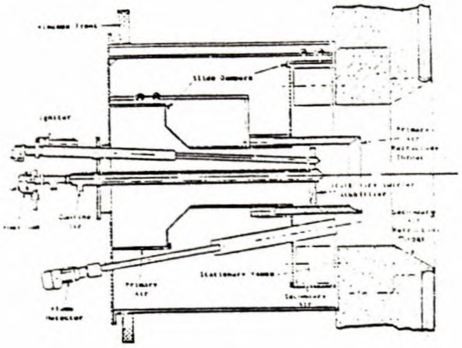
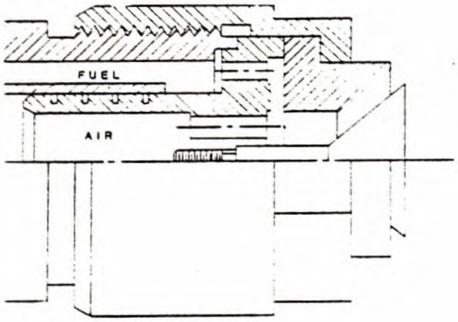


Fig. 3 - Illustration of Chatham Unit No. 1, front-wall fired



a) Burner Assembly



b) Atomizer

Fig. 4 - Schematic Illustration of burner and atomizers for Chatham Unit No. 1

A test program was developed to evaluate both burner and boiler performance on CWM and oil. The basic objectives of the program were:

1) To investigate the wear characteristics of various burner nozzle materials.

2) To evaluate burner performance with respect to carbon burnout, excess air, NO_x, SO_x and CO_2 emission.

3) To evaluate boiler performance, efficiency and changes in heat transfer characteristics.

The current status of the project is that all baseline oil tests and approximately 300 h of the wear evaluation have been completed. The full test program is expected to be completed by the Summer of 1984. The unit has been fired at full load on coal-water mixture without support energy being required. Light-off and start from cold has proved to be routine as was transfer to fuel-oil. 20 percent load was achieved without support fuel. To date about 3000 tonnes of fuel have been used on Unit No. 1.

It has been found possible to operate both the burners and the fuel handling equipment over a wide range of fuel rheological properties. Variations in slurry quality required burner adjustments to be made to ensure optimum combustion performance. Under optimum conditions carbon conversion efficiency proved to be about 99 percent and no furnace bottom ash was observed. At the time of writing tests are almost completed but detailed data are not yet available.

6.2 Unit No 2 Boiler Description and Test Program

Chatham Unit No. 2 is of the same vintage as Unit No. 1 and was designed to fire pulverized coal. The boiler is a balanced draft, type VU Unit with the following nameplate data:

Manufacturer:	Combustion Engineering
Steam Plan:	95,500 kg/h
Operating Pressure:	6040 KPa
Steam Temperature:	480°C
Feedwater Inlet Temperature:	180°C
Number of burners:	4 corner-fired

A Schematic view of the boiler is shown in Fig. 5 and of the burner windbox and fuel atomizer system in Fig. 6.

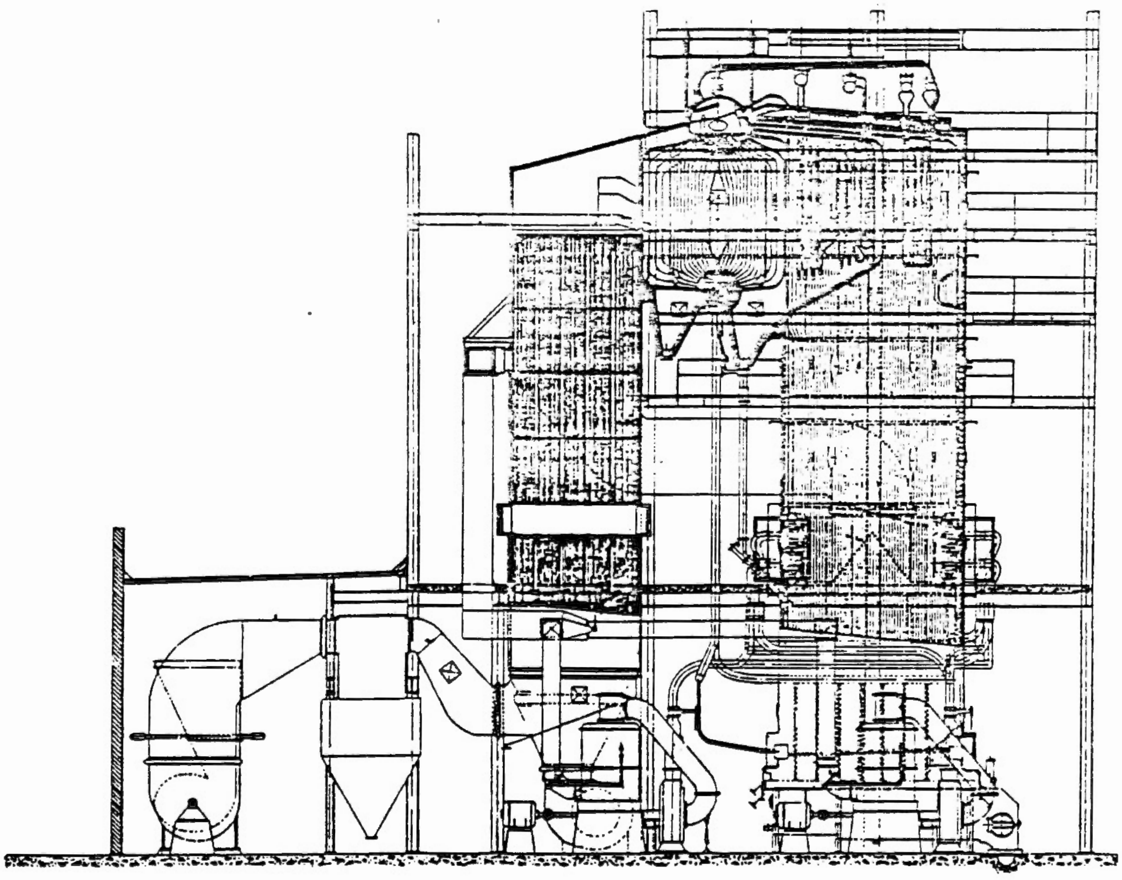
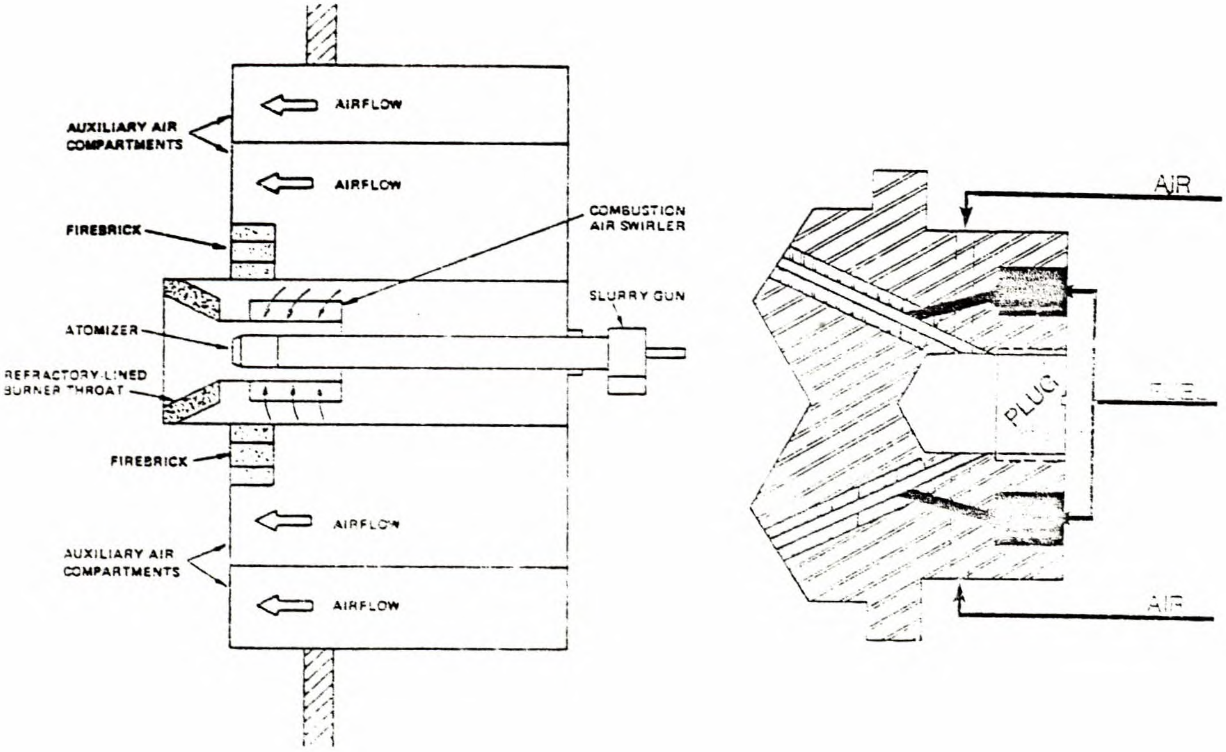


Fig. 5 - Illustration of Chatham Unit No. 2, tangentially-fired boiler



a) Burner Assembly

b) Atomizer

Fig. 6 - Schematic illustration of burner and atomizer for Chatham Unit No. 2

The initial nozzle development program called for a four step approach. The first step consisted of bench-scale characterization of the CWM in parallel with the basic development of the different atomizer alternatives. Next, the developed burner tips were tested to establish atomization quality. The most promising alternative was selected and this tip was then full-scale combustion tested at 70GJ/h at the CE test facilities in Windsor CT.

In order to fire the coal-water mixture in Unit No. 2, windbox modifications were carried out. The top and bottom air registers were removed, along with the two adjacent coal buckets. The oil compartment was also removed and replaced with a refractory-lined bucket. Also, in order to supply combustion air to the centre compartment at a higher pressure, a booster fan and associated ductwork had to be added to the system as shown in Fig. 6.

The total ignition system capacity was 6GJ/h. This ignition energy is considered necessary to ignite and stabilize the CWM.

Initial tests at Chatham were undertaken in November 1983. These proved unsatisfactory and some modifications to the burner system were subsequently made. After the modifications the boiler was operated at virtually full load without support fuel. These tests are ongoing and it is expected that the complete coal-water mixture performance test on Unit 2 will be completed by Spring 1984 as shown in the Schedule (Fig. 2).

7. Future Program

The performance of utility boilers designed for oil is expected to be significantly different when using coal-water mixtures. The problem of unit derating has already been mentioned and each unit to be converted will need a detailed individual assessment to ascertain its loss in electrical generating capacity when firing coal-water mixture. One of the objectives of the current program is to provide data for the determination of the inter-relationship between properties and quantity of mineral matter in the coal-water fuel, the flame, and unit derating. It must be noted that a significant requirement of the coal-water mixture program is that the burners be compatible with the retention of fuel oil capability to attain full generating capacity during peak demand periods.

The next immediate step in the program as planned is to conduct tests in an oil-designed boiler of similar size to the larger Chatham boiler. After these demonstrations, the next steps will be to design systems for burning coal-water mixtures in oil-designed and larger utility units. In eastern Canada there are several front-wall and tangentially-fired units designed for oil-burning. The current program embraces the design of coal-water systems for both configurations.

The major emphasis of the current program is to assess whether coal-water mixtures are feasible for use in utility boilers. There will obviously be many side benefits of the program in the industrial sector, particularly in the area of burner development for coal-water mixtures. Because of the much wider variety of types of industrial boilers and process combustors it is clear that the non-utility development of coal-liquid mixture technology will be much more difficult. However, whilst much scale-up information will be generated as larger utility demonstrations proceed, the small Chatham units are typical of many industrial boilers which may directly utilize the operating experience gained there. Consequently, at the conclusion of the coal-water mixture program in Canada, some of the industrial sector, particularly large kilns and boilers, may convert to coal-water mixtures as fuels. There will be a need for significantly more R and D support for the penetration of coal-liquid mixtures into the industrial, marine and diesel markets.

The next stage planned for the coal-water mixture utility demonstration program in eastern Canada is the selection and testing of burners for the 20 mW(e) oil-designed, front-wall fired boiler located in Charlottetown, Prince Edward Island and operated by Maritime Electric Company Ltd. This will not only test burner technology as at Chatham, but will indicate boiler-side feasibility of the fuel in more compact oil-designed units. It is hoped that the Charlottetown demonstration will be completed by early 1985.

Following the Chatham and Charlottetown demonstrations, scale-up is the next obvious step. Design of burners for front-wall or tangentially fired boilers in the 50 to 150 MW(e) range is planned as a third phase of the coal-water mixture program. A start has been made on a generalized derating study which uses modeling techniques to predict boiler performance when boilers designed for oil are fired with coal-water mixtures.(10,11) A priori reasoning cannot predict specific derating effects because there is insufficient experience connecting the formation of ash from coal-water flames burning finely ground coal in an atomized spray to slagging or erosive effects on boiler tube surfaces. Also, it appears that the emissivity and the combustion characteristics of coal-water mixtures are unlike those of coal and this will significantly influence derating. When more information concerning ash properties, ash formation, and combustion characteristics is available from the current work, the program will go on to include specific application studies to 100 and 150 MW(e) oil-fired boilers in Atlantic Canada. These studies will determine the minimum overall cost, by balancing the costs of boiler operation and derating against those of fuel preparation and beneficiation.

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Progress in CWF Technology Development For Utility Boilers in Eastern Canada

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The use of coal to replace imported oil is a goal of Canadian energy policy but this replacement has been inhibited by the inconvenience of handling solid fuel and by its environmental implications. Current decreases in world oil prices are likely to delay the commercial implementation of new coal combustion technologies. However, it is worthwhile to bring coal-water fuels (CWF) and their use to a state of commercial readiness so that if economic or environmental reasons so demand, these technologies can be implemented quickly. Canada's strategy for energy therefore aims to bring new coal utilization technologies that have both economic and environmental advantage over the oil alternative to a stage of development useful to industry. A program of development and commercialization of fuels made from mixtures of coal with liquids, with the twin objectives of easy, economic coal handling and minimized environmental impact, has therefore formed an integral part of Canada's energy strategy for the last nine years.

The first phase of the program has brought the development of CWF technologies well beyond laboratory scale but they are still too immature for widespread commercial application. The aim of the present, second phase of the program is to define equipment performance, fuel and combustor specifications, and capital and operational costs for the manufacture and delivery of CWF and for the conversion of boilers originally designed to burn oil. This information will enable potential CWF producers, transporters and users to determine where, and under what circumstances its use would be commercially attractive. The work of the second phase includes a demonstration of combustion of CWF in a 20 MWe boiler designed to burn oil in a compact space and definitive, site-specific, cost estimates for a CWF manufacturing plant and for the conversion from oil to CWF of an electric utility boiler, both fuel plant and boiler in the 100-150 MWe range.

The second phase of the program began with the selection and testing, during 1985/86, of burners suitable for the 20 MWe demonstration to be undertaken in Charlottetown, Prince Edward Island. Solicitations were made to six burner suppliers, five responded with acceptable bids, and four were selected for testing. The burners ultimately selected were those proposed by COEN CANADA Burners of Montreal, and designed by COEN Corporation of Burlingame, California. Prime reasons for the selection were the quality of combustion during testing and the guarantee of combustion performance. Modifications to the boiler began early 1986 and should be complete by June, as should the manufacture and installation of burners. Fuel preparation continues throughout the Spring and Summer months of 1986 and the combustion demonstration follows with a target of completion by November, see Figure 1. The information which will be

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obtained as a result of this demonstration was discussed at the previous symposium. (1)

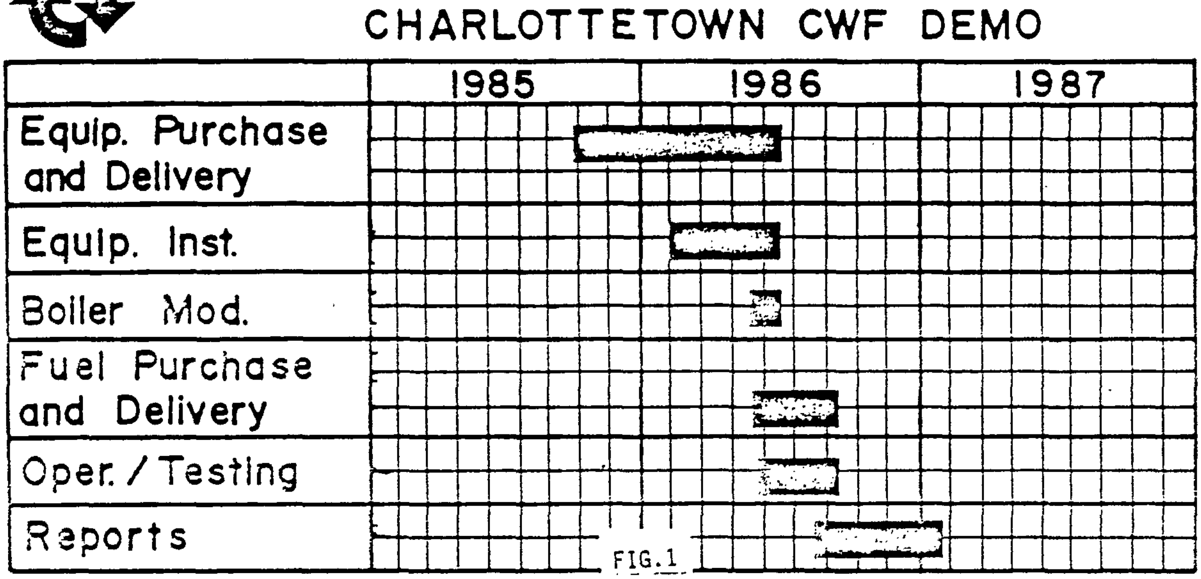

FIG.1

The first major demonstration was initiated in 1982 though a cooperative agreement between Energy, Mines and Resources Canada (EMR), The New Brunswick Electric Power Commission (NB Power) and the Cape Breton Development Corporation (CBDC), to demonstrate the preparation and combustion of coal-water fuel in two utility boilers at Chatham which were originally designed to burn coal. (2)

This first major demonstration of CWF has been described in the literature (1), (2). Its results prompted the continuation of the program with the testing of burners and a demonstration in a 20 MWe compact oil-designed utility boiler.

The Charlottetown CWF Utility Boiler Demonstration

The 20 MWe boilers at the Maritime Electric Company's (MECL) generating station in Charlottetown, P.E.I., are the most suitable boilers in Atlantic Canada for the demonstration of CWF in an electric utility facility designed to burn oil. These boilers are not in regular use, their compact nature is a challenge to the new fuel which will indicate its potential for most other units designed to burn oil, they are of an appropriate size for the demonstration, and, the modifications (conversion from forced to balanced draught and addition of a baghouse) needed for demonstration will be beneficial to station operation and to the local environment whatever fuel may be used in the future.

Boiler derating may be caused by insufficient heat generation or by insulation of the heat generated from the water and steam in the boiler tubes. Insufficient heat may be generated because flame temperature or position may be inappropriate, because gas velocities have to be kept low enough to avoid tube erosion, or because flames have to be restricted in size to avoid impingement on furnace walls and consequent slagging. Heat transfer may be restricted by accumulation of slag on boiler water walls or by fouling or slagging by the use of soot blowers. The Charlottetown demonstration is investigating all of these effects. By the end of the demonstration up to 15,000 tonnes of Carbogel fuel from Cape Breton will have given reliable indication of how these fuels behave and how operators can cope with start-up, operation at various levels and ash disposal. Knowledge of boiler performance, wear and associated economics will also be available.

In August 1985 a collaborative agreement was signed among EMR, NB Power, CBDC, and MECL to convert a 20 MWe oil-fired utility boiler to burn CWF and to assess the performance and economics of that conversion. Under the agreement, EMR provides financial and technical support for the production of CWF and the conversion and demonstration of that fuel in the MECL's No. 10 boiler at Charlottetown.

CBDC is supplying the CWF to the project from their plant in Sydney, Nova Scotia. Locations of the plant and the boiler are shown in Figure 2.

NB Power is providing technical support and management expertise based on their experience during the burning of about 6000 tonnes of CWF in the Chatham boilers. Also NB Power has arranged for a detailed study of the cost of converting a 100 MWe facility, designed to burn oil, to burn CWF.

MECL is providing the utility boiler, plant and support facilities for the demonstration.

The Electric Power Research Institute is represented on the Steering Committee which manages the demonstration.

The main features of the Charlottetown Demonstration include the following:

1. Manufacture and transportation to Charlottetown of up to 15,000

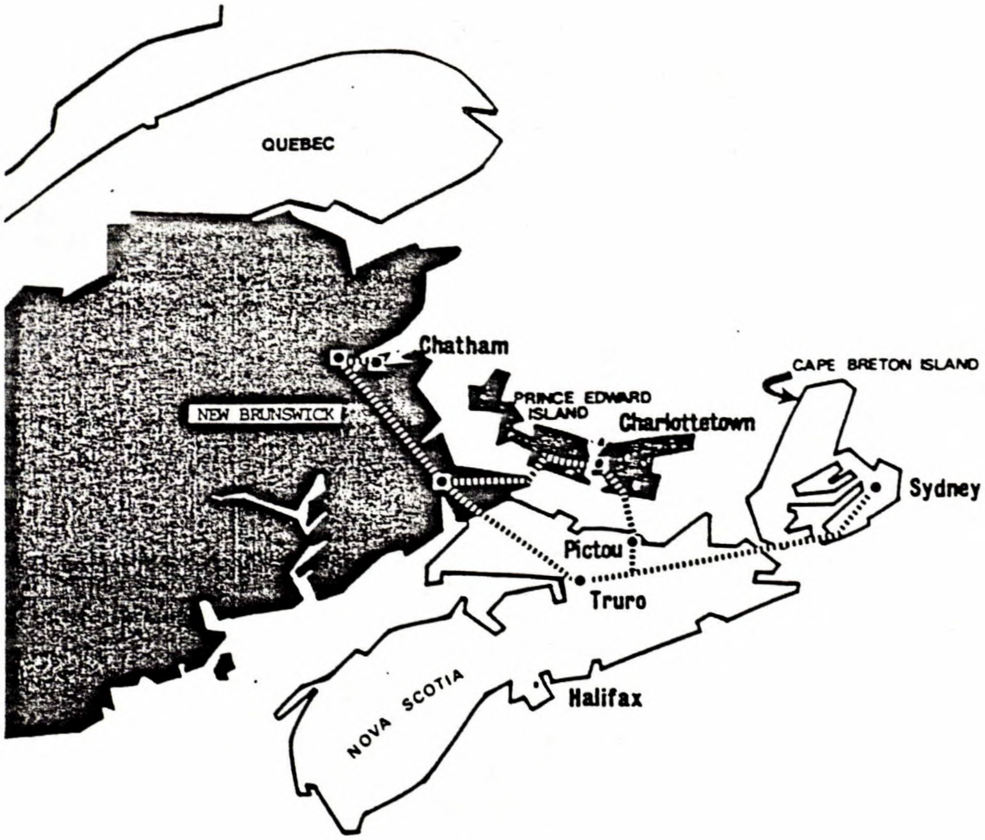

FIG.2

tonnes of high quality (low ash) Carbogel fuel (a coal-water fuel manufactured by CBDC).

2. Transportation and burning of a limited quantity of lower quality fuel.

3. Transportation, unloading, storage and handling of fuel delivered by both truck and rail, including transportation of the fuel from the storage tank to a day tank.

4. Selection of burners and proving of prototype burners prior to installation in the boiler.

5. Expansion of the storage facilities and upgrading of the instrumentation in the CBDC fuel processing plant.

6. Engineering assessment of conversion of a 100 MWe oil-designed electric utility boiler to fire CWF.

7. Control of sulphur oxide emissions through fuel cleaning and through sulphur containment during and after combustion.

8. Testing of a pilot scale fabric filter for the purpose of developing operating parameters for the Charlottetown demonstration.

9. Installation of a fabric filter dust collector on the Charlottetown unit.

10. Theoretical predictions of the capacity achievable by the unit on a continuous basis.

11. Collection of data which will allow the evaluation of the economics performance and capacity of the unit when using CWF.

These areas are considered to be the most serious questions with respect to any commercial conversion to CWF.

Fuel Transportation and Storage

A preliminary study of the economics of transporting the fuel from the Sydney to Charlottetown was undertaken. After a detailed assessment it was concluded that the most economic transportation would be by truck.

Several investigations were undertaken to assess the most suitable and economical means of storing a reasonable quantity of fuel at the MECL Plant. The fuel cannot be manufactured at the same rate that it can be burned by the boiler at rated capacity. Storage facilities have therefore been designed to provide a buffer between manufacture and use.

Provisions have been made to store up to 1000 tonnes of fuel at Sydney. The most economic means of storing the fuel at Charlottetown is to rent rail tank cars and to fill these from trucks while they remain in a siding. On an as-required basis, fuel will be withdrawn from these tank cars to fill a day tank of approximately 200 tonnes capacity from which the fuel will be transported to the burners by a progressive cavity pump.

In general the overall concepts and details of the fuel storage, handling and transportation system have been developed as a result of experience gained during the Chatham CWF demonstration. Special features are being built into the system to accommodate the many variables which may be expected during long term operation of a CWF system. These concepts will be proven or modified as experience is gained at Charlottetown.

Boiler

MECL's Charlottetown No. 10 unit (Fig. 3) is a Babcock and Wilcox, two drum, forced draft, pressurized Stirling design. The unit is rated at 20 MWe and produces a guaranteed steam output of 24 Kg/s (190,000 lb/h) when burning heavy fuel oil. Steam temperature and pressure at the turbine inlet are 480°C (900°F) and 6 MPa (850 psig) respectively at the rated load.

The superheater type is two-stage, pendant, with an interstage attemperator. The air heater is Ljungstrom regenerative package type arranged for horizontal air and gas flow. The furnace bottom is flat and covered with refractory brick. No special provision has been made for the removal of furnace bottom ash. The rear furnace wall screen tubes are 26 mm (1 in.) diameter with 76 mm (3 in.) clear tube spacing perpendicular to the gas flow. The superheater tube rack at the flue gas inlet has 60 mm (2 in.) clear tube spacing.

One of the main objectives of the Charlottetown CWF demonstration is to determine the boiler capacity which is achievable on a long term continuous operation and then to compare this performance with predictions. Two separate empirical derating studies have been undertaken (3), (4). Both predict substantial but very different derating estimates based on the hypothesis that boiler tube fouling and tube erosion would be similar to that caused by firing the parent coal in pulverized form. Neither study appears to have taken account of the analyses of combustion, heat transfer or ash abrasives and fouling characteristics of CWF reported in the literature (5), (6), (7) and (8). The demonstration will show whether any reliance can be placed on such estimtes and what in fact the limitations to capacity are, if any!

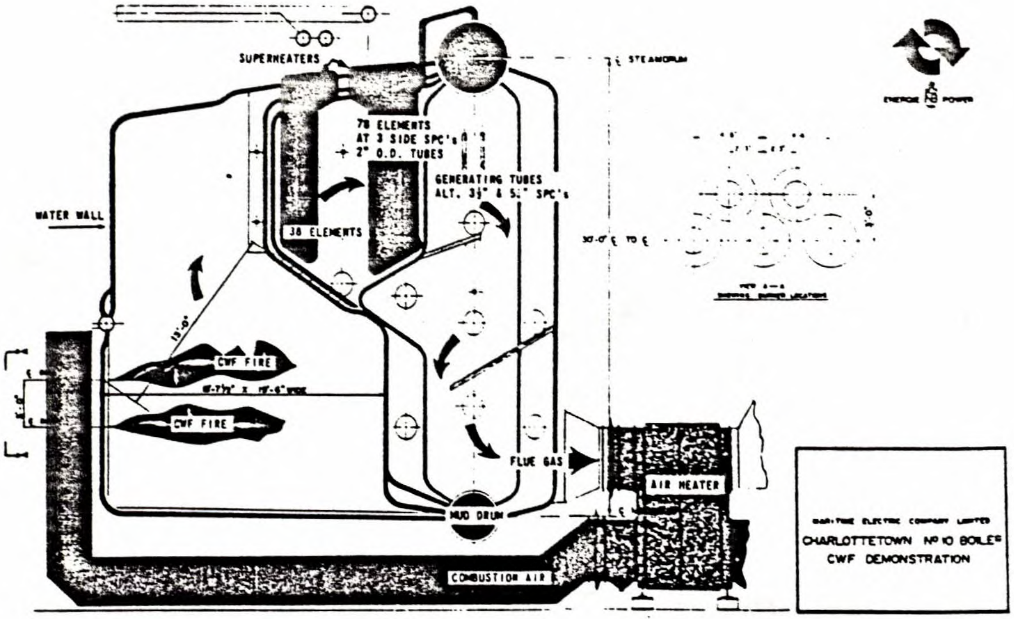

FIG.3

Preliminary tests of ash-fouling and abrasivity characteristics from CWF for fuels of varying ash content at the Centre for Energy Studies, Halifax, N.S., have shown that all fouling deposits can easily be controlled by conventional soot-blowing. These tests were arranged to simulate the temperature, velocity, and heat flux conditions for the reheater and superheater at Tufts Cove Unit No. 2 and the primary superheater section of Unit No. 10 at Charlottetown. Furthermore, no evidence of erosion has been detected to date. This corresponds to experience in Sweden (8).

It is presently planned to operate the unit with minimal modifications to the steam pressure parts. Burners sized for full-rated capacity have been specified for installation in the existing burner ports without changing the wall tubes and with some modifications to the refractory throats. The boiler at present has five burners in two rows with three in the bottom and two in the upper row.

Additional viewing ports will be installed and possibly some additional soot-blowers. The boiler will be changed from pressurized to balanced draft.

Environmental Protection

Since the Charlottetown Thermal Plant is situated in a downtown location, sulphur oxide and particulate emissions are a prime concern. Therefore steps have been taken to select equipment and institute operating procedures and concepts which will adequately contain these emissions.

A fabric filter system has been selected and is being installed on the unit. The ash from the filter will be collected and disposed of locally in a manner acceptable to the regulatory authorities.

Filter bags made from three different fabrics (fiberglass, Nomex, polyster) have been tested on CWF fly-ash at Chatham. All three were effective in collecting the fly-ash which contained high and variable proportions of carbon. Actual data on collection efficiencies are being evaluated at present. Pulsing was used to good effect to remove the filter cake and no excessive pressure drops were encountered. Polyester bags showed deterioration after a few days of operation but fiberglass and Nomex withstood the conditions satisfactorily. The test unit at Chatham was operated satisfactorily on CWF alone and on combinations of CWF and heavy oil. It is intended to operate the Charlottetwon unit in this manner to meet local environmental specifications. It is also proposed to investigate the use of solvents for the capture of sulphur in the fuel. Beneficiation during fuel manufacture has already reduced sulphur emission to half those associated with heavy oil: solvents have the potential to reduce this even further.
In view of the short duration of the test and small quantities of bottom ash expected, no special provisions has been made for its removal. It is planned to remove this ash from the furnace by hand or by vacuum. During operations at Chatham, experience has shown that less than one percent of the ash passing through the boilers has been retained in the furnace bottom.

Engineering Estimates

One of the objectives of the program is to prepare an engineering assessment of converting a larger oil-fired thermal generating unit to CWF.

Nova Scotia Power Corporation's Tufts Cove Generating Station, a three unit - 350 MW total output oil fired station, is located in a metropolitan area on the Dartmouth shoreline of Halifax harbour. After a preliminary technical review, the number 2 unit, 1 100 MW Babcock and Wilcox oil designed El Paso type boiler generating 668,800 lbs per hour of steam on an 1800 psig/1000°F/1000°F cycle, was selected as the candidate for a detailed technical and economic evaluation.

Two scenarios are being considered. The first, that of minimum, least cost modification to the boiler and its auxiliaries, to enable efficient combustion of the fuel; but, with whatever derating penalty might result. Second, conversion to the prescribed CWF to achieve as near full load operation as practical, within the physical and technical limitaitons imposed by the existing plant installation. Full load on oil is to be retained for both options.

The study is proceeding in two stages.

Phase I includes the necessary basic site investigation and examination of the existing plant design, followed by a preliminary evaluation of the plant and building additions and modifications, waste handling and disposal, environmental concerns, plant derating and rough budget estimates of cost. An interim report will then be prepared, the technical and costing content of which, will be used by NSPC and the Program Steering Committee to determine which of the alternatives will be selected for further study.

Assuming a positive assessment of the results of Phase I, Phase II will follow with a detailed analysis of the selected option to provide a definitive design, cost estimates, work definitions, design and construction schedules, layout drawings and a comprehensive final report.

Although still incomplete, the preliminary findings from Phase I suggest that the minimum change option will result in derating the boiler by 48%, a cost of $14 million for a Jan. 1 - 1989 in service date. Since furnace enlargement is highly impractical and not seen as a viable option, improvement in derating can only be achieved by adjustment to the convection pass superheater elements. The cost of such a change approximates $18 million with a derating reduction to 31%. Projected coal-water fuel costs compared to the present forecast prices of bunker 'C' make neither alternative attactive.

The prime boiler design limitation generating these large derating estimates is the allowable convection pass gas velocity of 65 feet per second. This velocity is based on the 1% ash coal-water fuel having the same tube metal erosion characteristics as the parent coal. Ongoing ash characterization test work at the Technical University of Nova Scotia may provide some adjustment to this constraint, as may the combustion test demonstration at Charlottetown later this summer.

The detailed work planned for Phase II of the investigation has therefore been deferred until the results of these tests are available.

In addition, in collaboration with CBDC, an economic evaluation is being made of a fuel production plant with a capacity of about 50 tonnes/hour on a dedicated basis which might supply the candidate boiler.

CBDC Fuel Production Plant

Part of the program is to upgrade the throughput and instrumentation and to expand the fuel storage at the CBDC Sydney Fuel production plant. The technology has been developing very rapidly and new, more flexible, instrumentation has been installed in order to improve operation and quality control and it is expected to be able to achieve specification fuel production of 7 t/h during the Charlottetown program.

Conclusion

It is expected that the Charlottetown Demonstration will give a much better understanding of the techniques, economics and environmental impact of operating an oil-designed utility boiler of CWF as well as more reliable information on derating and the ability to predict derating on other units.

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PILOT-SCALE COMBUSTION STUDIES OF COAL-WATER FUELS: THE CANADIAN R AND D PROGRAM

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Pilot scale studies undertaken as part of the Canadian coal water fuels program are presented.These studies included a comparison of the combustion and heat transfer characteristics of a domestic coal-water fuel, pulverized coal and No.6 fuel oil, and combustion tests to evaluate the performance of a new wear resistant atomizer that was developed for coal water fuels. Detailed results from these studies and its relevance to industrial and utility processes are described.

1. INTRODUCTION.

The department of Energy Mines and Resources (EMR) Canada has identified coal-water fuels(CWF) as a priority, and has directed substantial efforts towards the development of CWF technology. Major initiatives have included the construction of a 4 tonne per hour CWF preparation plant in Sydney, Nova Scotia, the development of CWF fuel burners and the demonstration of CWF combustion in two utility boilers (10 MW(e) front wall fired and a 22 MW(e) corner fired) in Chatham, New Brunswick(1). It is expected that the CWF demonstration in these coal-designed boilers will be followed by the scale-up and demonstration of CWF technology in oil-designed utility boilers in the 20-150 MW(e) capacity range(1,2). As a spin-off from these initiatives, a number of industrial demonstrations and applications of CWF in cement kilns, iron ore induration furnaces and nickel smelters are also being pursued(2).

In their role as federal government research agencies, both the Canada Centre for Mineral and Energy Technology(CANMET) and the National Research Council of Canada(NRCC) are engaged in R & D activities in support of the above developments. The work reported in this paper describes some of the pilot scale studies undertaken by contract and in-house research to address the

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following key issues: i) Assessment of the combustion and heat transfer characteristics of CWF, pulverized coal and No.6 fuel oil in order to delineate critical hardware and fuel-related parameters relevant to CWF substitution; ii) Combustion tests for a performance evaluation of a prototype wear-resistant ceramic tip atomizer developed by NRCC.

2. COMPARATIVE EVALUATION OF THE COMBUSTION AND HEAT TRANSFER CHARACTERISTICS OF CWF,PULVERISED COAL AND NO.6 FUEL OIL.

2.1 Experimental Procedures

The experimental study on the combustion and heat transfer characteristics of the domestic CWF, the parent pulverized coal (Lingan Coal; Cape Breton Harbour Seam) and No.6 fuel oil was carried out in a pilot-scale flame tunnel furnace at CANMET's Energy Research Laboratories. A schematic of the flame tunnel is shown in Fig.1. The main chamber of the flame tunnel is made up of 28 cylindrical calorimetric sections 1m I.D. and 4.2m long. Sealed water-cooled doors with circular probe holes are located in the gaps of the cooling segments. The probe holes provide radial and axial access to the furnace environment for the measurement of flame properties. The main furnace chamber is preceeded by a 0.83m I.D., 1m long refractory-lined adiabatic pre-chamber. The burner quarl used in the study was a 0.54m deep, 2.3° half angle, divergent conical refractory quarl with a 0.18m inlet throat and a 0.23m exit hole. The burner installed at the inlet of the quarl was a dual fuel gas/oil burner. The fuel nozzle assemblies shown in Figs.2 and 3 were specially adapted for CWF and No.6 oil firing. When firing pulverised coal, the nozzle assemblies for the liquid fuels were replaced by a 0.05m I.D. pipe injector. Flue gases leave the flame tunnel via a converging section and a 0.3m square duct connected to a water cooled heat exchanger with an induced draft fan to the stack. During normal operation, a balanced draft is maintained at the furnace exit to minimise in-leakage of ambient air into the furnace.

Aside from routine measurements of input and output variables to monitor furnace performance, the following parameters were also measured; in-flame gas temperatures, axial distributions of the total and cooling load heat fluxes, in-flame and exit gas compositions and the total flue particulate loadings. Details of the flame probes used for the temperature measurement, total heat flux measurement and in-flame gas sampling have been described previously(3). In addition, particle size distributions were analysed by a Coulter Counter and small samples of the solids were analysed by SEM for qualitative determinations of the particle morphology.

2.2 Operating Conditions and Fuel Properties.

The input and operating conditions of the flame tunnel are summarised in Table 1. The fuels were fired at a nominal thermal input of 0.46 MW, with excursions in the firing rate between 0.42 and 0.48 MW noted for the CWF and pulverized coal. For each fuel, three tests were carried out at 1, 3 and 5% excess O2 concentration in the flue gas in order to investigate the effect of excess air and residence time on fuel conversion. The coolant flowrates in the furnace segments were maintained at identical values for all test runs so that the differences in the heat flux profiles between fuels were determined by the combustion and heat transfer characteristics of the flames.

The mass ratios of the atomizing air to fuel flowrates, shown in Table 1 are significantly higher than the 0.2-0.4 ratio that is desirable for an optimized fuel nozzle(4). The fuel nozzle assembly for No.6 fuel oil (Fig.3), was initially selected for both CWF and oil firing. However, a number of difficulties were experienced with CWF atomization and ignition using this nozzle, and the internally atomized nozzle shown in Fig.2 was chosen as a replacement. The dimensions selected for the fuel and air outlet diameters and the final dispersion gaps in the internally and externally atomized nozzles were optimised values necessary to produce symmetrical stable flames, and without fuel dripping or coking. The high atomization airflowrates had a significant influence on axial fuel-air mixing and is described in section 2.3. Significant erosion was noted for the CWF nozzle, and overall wear data are summarised in Fig.2.

Tables 2 and 3 summarise data on the physical and chemical properties of the fuels. The CWF had an average composition of 70 wt% coal, 29 wt% water and up to 1 wt% of proprietary surfactant additives, viscosity modifiers and an algicide. Viscosity data supplied by the fuel manufacturer show that the fuel is thixotropic. The CWF had excellent handling characteristics with very little evidence of solids separation or settling. The particle size distribution in the CWF, with size data expressed as the volume equivalent spherical diameter are shown in Table 2 and Fig.12. The coal particles in CWF had a mean diameter of 36 μm with 86% less than 75 μm. The parent pulverized coal used in the tests had a virtually identical fuel composition, but the size grinds used in runs PC1 and PC2 (table 2) were finer than the size distribution of coal in the CWF.

2.3 Ignition Stability and Flame Type.

The most significant early problem encountered in the experimental trials was achieving stable ignition of the CWF. Early experience with a wide divergent quarl, in which a flame could only be stabilized with gas support, showed that significant energy feedback to the fuel spray was required for moisture evaporation, heating and devolatilization of the coal particles(5,6). In order to provide this energy, the narrow quarl described in section 2.1 was adopted. Pulverized coal and No.6 oil were fired using the same quarl. This was necessary in order to obtain flames with similar mixing patterns that would permit a valid comparative evaluation of the fuels.

The ducted quarl, secondary airflow distribution pattern, and the fuel nozzles produced confined jet turbulent diffusion flames, with combustion and heat transfer properties that are determined by axial mixing gradients between the fuel jet and the secondary combustion airflow(4). Axial mixing arises from momentum exchange between the fuel jet and the secondary airflow caused by frictional entrainment of fluid across the boundaries of the jet. In the ducted quarl, the availability of a secondary airflow less than that which the jet can entrain, promotes an axial recirculation eddy within the quarl(4). The recirculation eddy transfers hot gas back to the core of the flame and the concentric hot refractory surfaces also provide radiant feedback. Axial fuel-air mixing is more rapid for the pulverized coal flames (large nozzle inlet with a high air-fuel mass ratio), intermediate for CWF and lowest for No.6 oil. The latter is because external fuel atomization produces a more confined fuel jet with slow radial dispersion characteristics.

Visual inspection of the flames showed that the pulverized coal and CWF flames expanded radially filling the discharge hole of the quarl, while the oil flames were of a smaller diameter. From these observations, it was concluded that a recirculation eddy was not formed in the quarl for the oil flames, resulting in some discharge of the secondary airflow into the adiabatic pre-chamber. For the coal flames, the convective heat transfer of recirculated hot gas within the quarl and radiant heat transfer from the refractory walls improved ignition stability. Besides flow recirculation in the quarl, flame discharge into the larger furnace chamber also induced a secondary recirculation flow, due to frictional entrainment caused by the large radial and axial velocity gradients within the flame envelope. The secondary recirculation eddies were external and located in an area between the flame envelope and the furnace walls, extending over an axial distance from the quarl exit to the flame tip (flame lengths of 2-2.5 m).

2.4 Gas Temperatures.

Radial temperature profiles for the 1% excess O_2 runs measured at the 1.87 and 2.92 m axial stations are shown in Figs.4 and 5. At the 1.87 m station the temperature profiles are very nearly identical for No.6 oil and pulverized coal, but are lower by as much as 200°C for CWF. A similar trend is obvious at the 2.92 m station but with slightly lower temperatures for pulverized coal when compared with oil. The radial temperature profiles at the 1.87 m station located between the quarl exit and the flame tip are parabolic, with a 300-400°C temperature drop between the furnace axis and walls. The large temperature gradients are caused in part by the high temperatures within the flame envelope and the recirculation flow outside that transfers cooler gases from a downstream to an upstream location in the furnace. At the 2.92 m axial station (beyond the measured flame lengths), the temperature profiles are of a plug flow type with the net forward movement of gases in the furnace.

Peak temperatures at the furnace axis plotted as a function of the axial distance from the burner are shown in Fig.6. The centreline temperatures for all three fuels show a general trend of decreasing temperatures with increasing axial distance, but appear to approach limiting values at positions close to the burner and at the flue duct. The high limiting temperatures represent the maximum flame temperatures achieved with fuel combustion in the adiabatic refractory zones in the furnace, whereas the lower limit is caused by the absence of a cooling load at the flue exit section. At intermediate positions, the temperatures drop by gas dilution from flow recirculation and by heat loss to the furnace cooling loops. The axial temperature profiles show the highest measured values for No.6 oil, intermediate for pulverized coal, and lowest for CWF (200°C < No.6 oil). Highest temperatures measured for the oil stem from the high fuel conversion efficiencies, and the accompanying high heat release rates per unit volume of gas (lower combustion air volumes) when compared to coal. Applying similar arguments to the CWF for which the fuel reactivity is identical to pulverized coal, it can be seen that the lowest gas temperatures are caused in part by the energy initially required to evaporate the water in the fuel. From these observations, it appears that the lower flame temperatures for CWF results in a penalty on fuel conversion efficiencies (section 2.7), in addition to the estimated 3% heat loss incurred by the water present in the fuel.

2.5 Heat Flux.

Fig.7 shows the axial distribution of the total heat flux for the 1% excess O2 runs measured by conductivity plug type heat flux meters (3). The axial distribution of the heat flux removed by the furnace cooling circuits for the same conditions are shown in Fig.8. The total heat flux and the heat flux removed by the cooling circuits are the sum of the radiant and convective heat flux. However, the radiant component in the former is the radiant energy absorbed by a black body ($\varepsilon = 1$), whereas the radiant component in the latter is the energy absorbed by a real surface ($\varepsilon < 1$). Similarly, the convective driving force measured by the heat flux probe does not include the cooling liquid boundary layers which are barriers to heat transfer. Hence, the total heat flux is the potential driving force for energy transfer, while the cooling load heat flux is the actual energy absorbed by the heat transfer surface.

The total and cooling load heat flux profiles decrease exponentially with increasing axial distance from the burner with lowest measured values for CWF. Besides the clearly identifiable trend for CWF, values of the total heat flux measured at four axial positions are not sufficiently accurate to delineate relative trends between the oil and pulverized coal. Examination of the cooling load heat fluxes (Fig.8) shows that the values are highest for oil, intermediate for pulverized coal and lowest for CWF close to the burner, with a switch in the relative positions for oil and pulverized coal at locations more than 3 m from the burner. A comparison with the axial distribution of centreline temperatures (Fig.6) shows that at positions close to the burner, the gas temperatures and the cooling load heat fluxes maintain identical trends relative to fuel type. With the dominant influence of temperature on radiant heat transfer and the higher flame emissivity expected for an oil flame, the higher values for No.6 oil at positions close to the burner are caused by higher radiant heat transfer. With more complete radial mixing of the gases beyond the flame tip and the higher gas throughputs in the furnace relative to oil, the cooling load heat flux is higher for pulverized coal due to higher convective heat transfer. In all cases, lower temperatures and gas throughputs for CWF produced lowest measured values of the cooling load heat flux. With sufficiently detailed measurements, the same trends should be apparent for the total heat flux due to the similarities noted in the component heat flux terms.

2.6 Gas Compositions.

Radial profiles of the in-flame O2 and NOx concentrations for the 1% excess O2 runs measured at the 1.26 m axial station are shown in Figs.9 and 10. The concentration profiles are symmetrical about the furnace axis with characteristic minima or maxima measured within the flame envelope. Similar profiles were measured for the in-flame CO2 and CO concentrations. As expected, the in-flame CO2 profiles were usually exact mirror images of the corresponding O2 profiles. The CO concentration profiles in all cases peaked at the flame axis. With increasing excess O2 in the flue gas, or with increasing axial distance along the flame, the radial gas concentration profiles maintained identical shapes, albeit at different equilibrum gas concentrations.

As shown in Fig.9, the O2 profiles for CWF and pulverized coal peak at the flame axis, whereas the corresponding curve for No.6 oil shows a characteristic minimum. The difference in O2 profiles for the coal and oil flames stem from characteristic differences in the axial fuel-air mixing patterns and the reactivity of the fuels. The formation of internal and external eddies for the coal flames causes flow recirculation and mixing of gases outside the flame envelope which originate from different axial locations within the flame envelope. The mean O2 concentration outside the flame envelope is thus lower, and peaks within the flame envelope because the heterogenous reactions with the coal particles are not sufficiently rapid to cause a significant radial decay in the in-flame O2 concentration. For the oil flame on the other hand, discharge of the secondary combustion airflow into the furnace chamber and mixing of this higher O2 concentration airflow with spent gases recirculated by the secondary eddies, causes a higher measured O2 concentration outside the flame envelope. With gas phase combustion of a more volatile and reactive fuel within the flame envelope, the oxygen concentration drops to a minimum at the flame axis because the flame temperatures also peak at that location (Figs. 4,5 and 6).

Fig.10 shows that the high flame temperatures at the furnace axis also cause a peak in the in-flame NOx radial profiles. NOx in the flame originates from the high temperature fixation of atmospheric N (thermal NOx) and from the oxidation of N chemically bound in the fuel (fuel NOx). Experimental studies on NOx formation in pulverized coal flames show that at least 70% of the total concentration formed originates from fuel N(7). Fuel compositions in Tables 2 and 3 show that the fuel N content is lowest for No.6 oil and highest for CWF, so that a similar trend should be apparent for the measured NOx. The data in Fig.10 are in good agreement with the expected trend for oil, but show lower concentrations for CWF relative to pulverized coal. However, the energy consumed by water evaporation for CWF produced lower flame temperatures, and lower fuel and thermal NOx formation may be expected in comparison to pulverized coal. NOx concentrations in the flue gas shown in Table 1 maintain an identical trend with fuel type as that noted for the in-flame NOx. With increasing excess air, the volume concentrations go through a characteristic maximum at intermediate excess air levels. This trend is equivalent to combustion air staging, which at low excess air diminishes NOx production, increases with excess air and decreases once again with volume dilution and lower combustion temperatures at high excess air(7).

2.7 Fuel Burnout, Flue Particulates and Furnace Deposits.

Fig.11 shows a plot of the fractional fuel burnout efficiency, Cx, versus the excess O2 in the flue gas. The fractional fuel burnout efficiencies for the oil runs were calculated from a carbon balance on the fuel, with measured levels of the soot particles in the flue gas taken as the total unburnt carbon. For CWF and pulverized coal, the burnout efficiency was calculated by an ash tracing technique(8), with the unburnt fuel taken as the complementary weight fraction of the ash in the flue particulates.

The results in Fig.11 show that the fuel burnout efficiencies are highest for oil, marginally less for pulverized coal and lowest for the CWF. The burnout efficiencies for oil increase with increasing excess oxygen in the flue (see Table 1), due to improved fuel conversion with a higher oxidant concentration in the flame. The corresponding results for CWF and pulverized coal show a similar trend at low and intermediate excess air, but decrease at high excess air. The lower measured efficiencies for pulverized coal and CWF (despite improved fuel-air mixing), are caused by the slower mass transfer and chemical rate limited gas-solids reactions that require a longer residence time in the furnace for good carbon burnout(9). The crucial effect of the solids residence time is also demonstrated in the measured fuel burnout efficiencies at high excess air for the coals. Compared to pulverized coal, the lower flame and gas temperatures for CWF are mainly responsible for poorer fuel burnout efficiencies.

Figs. 12 and 13 show the particle size distributions of the flue solids and the coal in the fuels for the 1% excess O2 CWF and pulverized coal runs. The flue ash particles have a smaller volume mean diameter than the coal particles in the fuel due to a pronounced reduction in the volume concentration of coarse particles in the particle size distribution. The reduction in the mean diameter of flue particulates, despite the high free swelling index of the coal (Table 2), is caused by the size reduction with carbon burnout, particle attrition and deposition of some large particles in the furnace.

SEM analyses of the flue particulates showed a large population of cenosphere type char and ash particles with a high bulk concentration of unburnt carbon (see Table 1). The solids from pulverized coal combustion were highly fused cenospheres due to higher flame temperatures experienced by the particles. A porous skeletal ash matrix within the particles and a highly porous surface with a large number of small blow holes was observed. Some of the cenospheres from CWF combustion had similar characteristics, but a major proportion of the particles were cenospheres with a small number of large blow holes with empty cavities within the particles. A number of these particles were oblate and appeared to have been formed by the fusion of two or more coal particles. A significant amount of broken cenospheres exposing large internal cavities and smaller pieces from these cenospheres were also evident.

In order to characterise CWF agglomeration, samples of the pre-chamber, middle and rear furnace deposits were subjected to similar analyses. The particle size distribution of the pre-chamber deposits in Fig.12 show a marginally smaller volume mean diameter than that for the coal particles in the fuel. However, below 25 µm, the size distribution of the pre-chamber deposits are coarser than the fine coal and ash particles in the fuel. A large number of fine ash particles are expected because of fuel beneficiation by water flotation. Attempts to analyse the particle size distribution of the middle and rear furnace deposits met with limited success, due to rapid plugging of the aperture tube in the Coulter Counter by some of the larger particle agglomerates in these deposits.

The SEM analyses of the pre-chamber deposits showed a very large population of very fine irregular reddish brown ash particles, the majority of which appeared to have bonded together into medium and large clusters of multi-particle agglomerates. The middle and rear furnace deposits were mainly char particles with unburnt carbon 5-10 wt% higher than the carbon in the flue particulates. Most of the char particles were agglomerates that appear to have originated from a number of coal particles in large fuel droplets that have fused together to form single hollow cenospheres during the heating, devolatilization and ignition stages of fuel combustion. Some of these cenospheres were very large with particle sizes at least 300 µm in diameter. It is clear from these observations that most of these particles were dropped in the furnace by inertial separation from the gas flow. Other studies on CWF combustion have also identified similar deposits(5,8) and show that atomization is critical for good CWF combustion. In addition to the lower flame and gas temperatures caused by the water present in the fuel, the agglomerates formed also affected carbon burnout through a slower mass transfer limited reaction rate expected for larger char particles (9).

Some deposition in the furnace was also noted for the pulverized coal which raises the possibility that the fuel burnout efficiencies reported in Fig.11 may be suspect, because of the unaccountability of the carbon in these deposits. For verification, carbon burnout was calculated using measured values of the CO2 concentration in the flue gas. These values ranged from 2% lower for oil, 2% lower and 6.3% higher for pulverized coal and 10% higher for CWF when compared to the ash tracing values. However, the calculation requires very accurate measurements of fuel and air throughputs with no leakage of gas in or out of the furnace chamber.

3. CWF AND HEAVY OIL COMBUSTION TESTS WITH THE NRCC ATOMIZER.

Combustion tests to evaluate the performance of the prototype NRCC ceramic tip atomizer were undertaken in a pilot scale flame tunnel furnace at the Centre for Energy Studies (CES), Technical University of Nova Scotia. The CES flame tunnel has a 1.17 m I.D. and 3.0 m long combustion chamber made up of five water cooled segments with access holes for flame probing. The bottom of the furnace has a refractory lined hearth covering 45% of the internal surface area. The flame tunnel is equipped with a modified Babcock-Duiker swirl register and a divergent 35° half angle refractory quarl. The combustion air flow to the furnace is admitted into a plenum, and enters the quarl through the swirl register which has adjustable swirl vanes for tangential air entry, and adjustable concentric openings in the back face of the register for axial air entry. The gases leave the furnace through a concentric 0.4 m i.d duct at the end of the furnace chamber. Combustion air is delivered by a forced draft fan with indirect steam heating and/or direct propane firing for air pre-heating. The exit gas is evacuated by an induced draft fan connected to the stack. The furnace is operated with a balanced draft at the furnace exit. The gas sampling and flame probing equipment used in these tests were essentially identical to those described in section 2.

The NRCC atomizer is a conical spray twin fluid atomizer with an outer annular fuel stream and an inner axial atomizing fluid stream. The atomizing fluid emerges via tangential slots in a stem holding a ceramic cone and flows outwards in a conical stream at an angle to the nozzle axis determined by the included angle of the spray cone. The annular fuel stream goes through a 90° change in its flow direction, flows horizontally towards the spray cone where the diverging conical air stream impinges on the fuel sheath. A ceramic wear ring which forms the upper surface of the fuel sheath has an angled hole in the centre which matches the spray angle of the ceramic cone. The gap between the wear ring and cone over the thickness of the wear ring forms the mixing chamber and exit gap from the atomizer. The wear ring and cone are changeable parts for the alteration of the fuel spray angle. The thickness of the horizontal fuel sheath can be adjusted by spacers of different thicknesses to match fuel rheology to atomization and to control fuel throughputs at the desired pressure. Similarly, the vertical position of the stem holding the cone can also be adjusted for alteration of the atomizing medium and final dispersion gaps, and this provides an independent control of the atomizing medium throughput and pressure. The assembly below the spray head described above is equipped with a heat exchanger for fuel pre-heating or cooling depending on the application desired. A thermocouple inserted in the same assembly is used to monitor the fuel temperature. At the time of writing, a schematic diagram of the NRCC atomizer could not be included for proprietary reasons.

Table 4 summarises the test conditions in the furnace for the CWF and No.6 fuel oil runs. The fuels were fired at a nominal throughput of 1.8 MW(th) with a 5% excess O_2 concentration in the flue gas. Both air and steam atomization were employed. The furnace cooling load of 0.81 MW(th) maintained in these tests corresponded to 45% of the thermal input. The atomizing medium to fuel mass ratios were between 0.23-0.33 for the CWF and 0.41-0.42 for heavy oil and were comparable to those levels desired for an optimized fuel atomizer (section 2). Fuel compositions and properties were not significantly different to those reported in

Tables 2 and 3. When firing heavy oil the fuel was heated to a temperature of 104°C. Cooling to maintain a temperature of 30-31°C was used for the CWF. In all cases, the combustion air to the furnace was heated to maintain temperatures between 230-260°C.

Swirling combustion air jets are used to promote mixing between the fuel stream and combustion airflow and to improve the ignition stability and combustion intensity of flames(4). When a rotating motion is imparted to the combustion airflow upstream of the burner quarl, the fluid flow emerging from the quarl has tangential, axial and radial velocity components. The tangential velocity spins the airflow outwards on emergence from the burner quarl,and induces a large internal torroidal vortex reverse flow region at the flow axis. In addition, the velocity gradients in the swirling air jet also create an external recirculation zone between the jet and the constraining walls of the burner chamber. The strength and size of the internal recirculation zone (IRZ) is, amongst other factors, mainly dependent on the angle of divergence of the burner quarl and the swirl numbers (the ratio of the tangential and axial momentum of the combustion airflow). At intermediate or high swirl numbers, the combustion airflow is stably attached to the divergent walls of the quarl, producing highly stable flames with fuel ignition close to the exit of the fuel nozzle due to the reverse flow of hot combustion products promoted within the IRZ. This flow pattern enables close matching of the zones of high turbulence intensity and mixing at the interface of the IRZ, with those of high fuel concentration (the spray trajectory), producing short flames with a high combustion intensity.

Figures 14 and 15 show the flame flow boundary maps measured for the CWF and heavy oil tests with the NRCC atomizer. The experimental points of the forward and reverse flow regions (of zero axial velocity) were measured using and oxy-acetylene flame boundary probe for the CWF and a Hubbard probe for the oil. These measured points, together with the loci of the in-flame peak radial temperatures in the burner near-field region, show flame aerodynamic patterns identical to those described above. For the quarl, furnace geometry and spray momentum of the NRCC atomizer used in these tests, a 50° and 60° spray angle for CWF and heavy oil respectively were found necessary to produce the shortest flames with the highest combustion intensity. Fuel ignition occurred close to the atomizer exit with flow recirculation and location of the spray trajectory within the IRZ. For CWF, this recirculation flow provided the convective heat flux necessary for moisture evaporation, ignition and devolatilization of the coal particles. The combination of these optimized mixing patterns and the combustion air pre-heat, also permitted easy light-off of the CWF in a cold furnace, together with a short period of ignition support.

The loci of the peak radial in-flame temperatures, which corresponded to the fuel rich zones, show a diverging trajectory in the near field region with flow divergence of the swirling jet. Further down the furnace, re-convergence of the gas flow towards the exit flue duct causes a fuel rich zone to develop on the flow axis, with peak temperatures measured at that location. With the flow convergence, the axial profiles of the centreline temperatures in Figs. 16 and 17, provide a rough guide of the relative performance of the fuels. In the near field region, lower axial temperatures for CWF suggest lower combustion efficiencies and heat flux profiles relative to oil, but increase at the back-end of the furnace due to the longer residence time required for char combustion. For CWF and heavy oil, steam atomization produced lower axial temperatures, but the data for the radial temperature profiles at positions between x/L=0.17 and x/L=0.53 showed higher measured peak temperatures relative to the air atomized runs. Hence, the average fuel burnout efficiencies reported in Table 4 show no significant change with the type of fluid used for fuel atomization. Good atomization of the CWF also produced fuel burnout efficiencies in the high nineties, being marginally lower then the corresponding oil values (Table 4). No wear was detected in the NRCC atomizer throughout the estimated 200 hr total duration of the tests with CWF.

4.RELEVANCE OF THE WORK TO INDUSTRIAL AND UTILITY PROCESSES.

The turbulent co-axial diffusion flames described in section 2, were designed to simulate flames encountered in industrial kilns and ore processing furnaces. Attempts to disperse the CWF by a single hole externally mixed oil atomizer used in iron ore induration machine burners showed poor fuel dispersion and ignition characteristics, while a substitute internally mixed oil nozzle showed significant erosion wear with a marginal improvement in fuel atomization. The laboratory work also showed that the water present in the fuel causes some difficulties with fuel ignition, requiring a high convective and radiant heat flux to the core of the flame to sustain a stable and well ignited CWF flame. In the absence of combustion air swirl to promote axial fuel-air mixing, the convective and radiant heat flux is provided by a fuel jet-assisted recirculation flow in a ducted quarl located close to and concentric with the fuel spray.

In field trials on a 0.6-3.5 MW(th) iron ore induration machine burner(10), high preheat temperatures (800-900°C) of the co-axial combustion air stream was sufficient to ensure rapid moisture evaporation, devolatilization and ignition of the coal particles in the fuel spray. However, the NRCC atomizer used in this field trials showed that a CWF atomizer with good fuel dispersion characteristics, a high spray momentum and a wide spray angle, which is sufficient to promote rapid axial fuel-air mixing, was necessary in order to achieve fuel combustion within the refractory zone of the induration machine burner(10).

For industrial process burners with fuel jet-assisted mixing, the foregoing example shows that the ignition stability of CWF, the degree of combustion air pre-heat, atomization characteristics, spray momentum and angle are the critical factors affecting heavy oil substitution by CWF. However, the comparative evaluation of fuels in the laboratory work shows that a thermal penalty is incurred by the water present in the fuel. Similarly, carbon burnout may be lower, and would depend on the actual process gas temperatures and the residence time of the char particles in the furnace.

Combustion tests with the protype NRCC atomizer in a swirling combustion air jet produced turbulent diffusion flames typical of some utility boiler burners. Good CWF atomization, matching of the spray momentum and angles to direct the fuel spray trajectory into a zone of high turbulence intensity and mixing at the interface of the IRZ and the swirling combustion airflow, produced short intense flames with good carbon burnout. Flow recirculation of hot gases in the IRZ greatly aided the ignition stability of CWF, but the carbon burnout was lower relative to heavy fuel oil because of the longer residence time required for the complete combustion of char particles. In marked contrast to the laboratory tests comparing the relative performance of CWF, heavy fuel oil and pulverized coal, better atomization of the CWF produced higher gas temperatures in the back-end of the furnace relative to the temperatures measured for heavy fuel oil. These higher gas temperatures show that the combustion and heat transfer characteristics of CWF would be similar to that expected for pulverized coal burning in a utility boiler, with some differences arising in the front-end of the boiler due to the lower flame temperatures caused by the water present in the fuel. The improved combustion performance of CWF in the tests with the NRCC atomizer, with a rated firing capacity of 0.6-3.5 MW(th) and no erosion wear, also showed it to be an ideal candidate for an application as a fuel atomizer in utility plant burners. Work is now proceeding on the development and testing of two 12 MW(th) atomizers at the Chatham generating station in New Brunswick. This work is being undertaken in preparation for the CWF demonstration trials in an oil-designed utility boiler in Charlottetown, Prince Edward Island (2).

ACKNOWLEDGEMENTS.

The authors wish to express their gratitude to the Laboratory Manager Mr.G.K.Lee and to the staff of the Industrial Combustion Processes Section, Combustion and Carbonization Research Laboratory, Energy Research Laboratories, CANMET for carrying out the pilot-scale experiments described in the early sections of this paper. Significant contributions from Mr.W.Thayer and Mr.A.Bennet of the National Research Council of Canada, who are deeply involved in the NRCC atomizer development, is also gratefully acknowledged. Lastly, the authors wish to express their thanks to Dr.M.J. Pegg and staff at the Centre for Energy Studies, Technical University of Nova Scotia for the work performed in the combustion tests with the NRCC atomizer under a CANMET contract.

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Table 1. Furnace Operating Conditions; CWF, P.Coal and No.6 Oil

Fuel Type	CWF			Pulverised Coal			No.6 Fuel Oil		
Run No.	CW1	CW2	CW3	PC1	PC2	PC3	O1	O2	O3
Rate MW(th)	0.44	0.43	0.42	0.46	0.47	0.48	0.46	0.46	0.46
Atomizer	Figure. 2			Pipe Injector			Figure. 3		
AFR (kg/kg)	0.60	0.68	0.89	8.53	8.82	8.98	1.76	1.12	1.10
Atomizer Pres. (kPa)	467	494	536	Near Ambient			343	246	253
Comb. Air (cu.m/kg)	6.9	7.4	7.8	9.8	10.7	11.6	11.8	12.9	14.0
Air Temp(°C)	70	64	61	59	61	53	64	61	57
Flue									
O2 (%)	0.9	2.9	4.9	0.9	3.0	5.1	0.9	3.0	4.8
CO (ppm)	117	102	100	151	227	91	63	46	18
CO2 (%)	16.2	15.0	13.7	17.0	15.2	13.2	14.8	13.1	12.0
N2 (%)	82.9	82.1	81.4	82.1	81.9	81.7	84.3	83.9	83.2
NOx (ppm)	454	582	457	698	776	688	343	340	323
SO2 (ppm)	852	734	654	886	710	658	1358	1463	1042
SO3 (ppm)	0.4	-	-	0.8	-	-	-	0.1	0.7
Temp.(°C)	434	513	479	459	579	546	536	551	571
P'(gm/cu.m)	7.4	3.0	3.3	6.4	2.4	2.2	0.18	0.16	0.04
Flue Solids									
Carbon (%)	90.4	73.5	79.1	77.3	44.0	62.0	100	100	100
Cx (%)	84.0	95.3	93.6	90.2	97.7	95.3	99.7	99.8	99.9

All volume flowrates at 15.5 °C and 101.3 kPa.
AFR atomizing air fuel ratio
P' flue particulate loading
Cx Carbon burnout from ash or soot tracing.

Table 2. Fuel Analysis CWF and Devco Lingan Pulverised Coal.

	CWF	Pulverised Coal		
S.G. at 20 °C	1.16	-		
Moisture wt%	29.8-32.4	0.35-0.74		
Viscosity(Pa.s;20 °C)	Thixotropic	-		
Shear Rate (1/s)				
154	0.971(0.459)	-		
452	0.842(0.514)	-		
Free Swelling Index	7	7		
Gross C.V.(dry;MJ/kg)	37.67	34.9		
Proximate (dry;wt%)				
Volatiles	35.73	36.88		
Fixed Carbon	62.60	60.32		
Ash	1.67	2.80		
Ultimate (dry;wt%)				
C	84.24	83.48		
H	5.47	5.32		
S	0.99	1.27		
N	1.93	1.79		
O	5.70	5.34		
Size Distribution		PC 1	PC 2	PC 3*
µm; cumulative wt%				
>75	14.0	1.0	2.4	11.0
>64	20.0	3.2	7.0	19.0
>40.3	45.0	21.5	29.0	47.0
>25.4	65.0	61.0	55.0	70.0
>16.0	81.0	74.0	79.0	87.5
>10.1	92.5	92.5	93.0	96.5
> 5.1	99.6	100.0	100.0	100.0

* See Table 1.

Table 3. No.6 Fuel Oil Analysis

S.G. at 15.5 °C	0.986
A.P.I. at 15.5 °C	12.01
Pour Point (°C)	5.0
Flash Point (°C)	102
Viscosity (Pa.s)	
at 40 °C	1.080
54 °C	0.355
70 °C	0.146
100 °C	0.039
Gross C.V. (MJ/kg)	42.48
Ultimate (wt%)	
C	85.60
H	10.40
N	0.37
S	2.46
Ash	trace

Table 4. Furnace Conditions for Swirling Jet CWF & No.6 Oil Flame

Fuel	No.6 Oil		CWF	
Atomizing Medium	Air	Steam	Air	Steam
Thermal Input (MW)	1.8	1.8	1.8	1.8
Atomizer Type	NRCC	60° Cone	NRCC	50° Cone
AFR (kg/kg)	0.42	0.41	0.33	0.23
Atomizer Pres.(kPa)	721	722	754	696
Comb.Air (cu.m/kg fuel)	15.77	16.28	9.70	9.50
Comb.Air Temp. (°C)	237	253	253	254
Flue				
O2 (%)	5.02	5.51	4.93	4.90
CO (%)	0.003	0.002	0.005	0.004
CO2 (%)	12.25	11.65	13.60	13.80
NOx (%)	0.032	0.028	0.061	0.062
SO2 (%)	0.130	0.119	0.063	0.065
Temp. (°C)	1004	998	1052	1037
P' (gm/cu.m)	5.88	4.81	9.16	5.52
Solids Ash (%)	1.6	-	26.75	38.70
Cx (%)	98.77	-	95.91	97.64
Cx (from CO2;%)	100	98.36	97.54	98.79

All abbreviations, symbols and volume measurements as in table 1

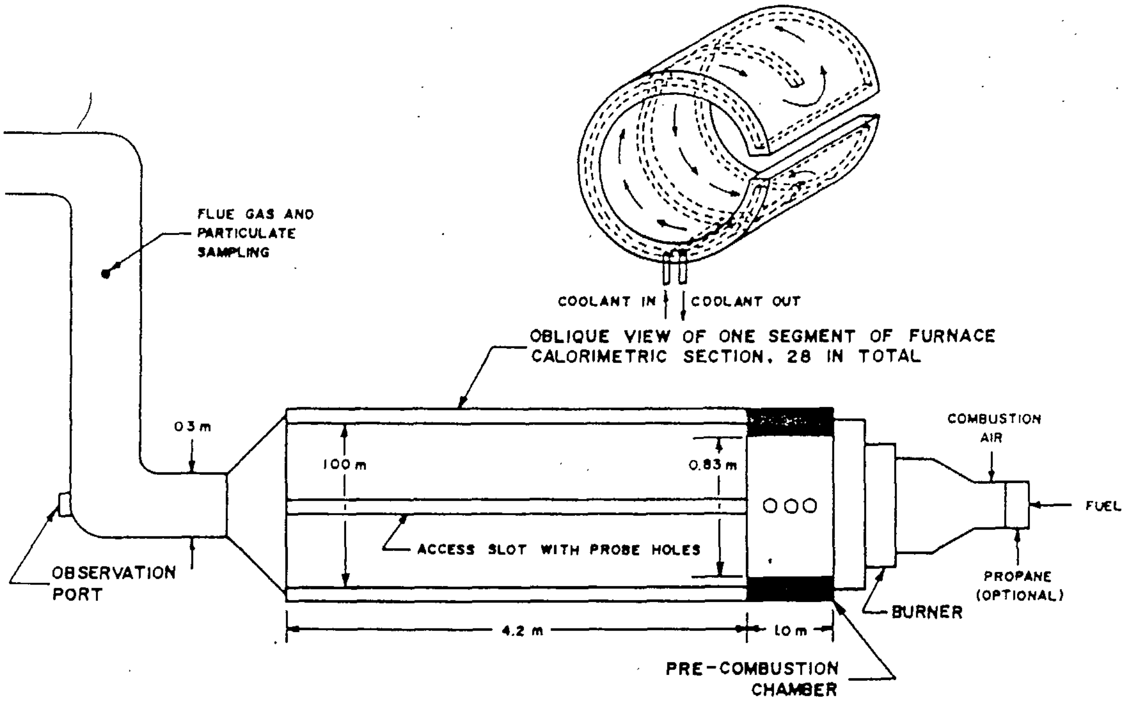
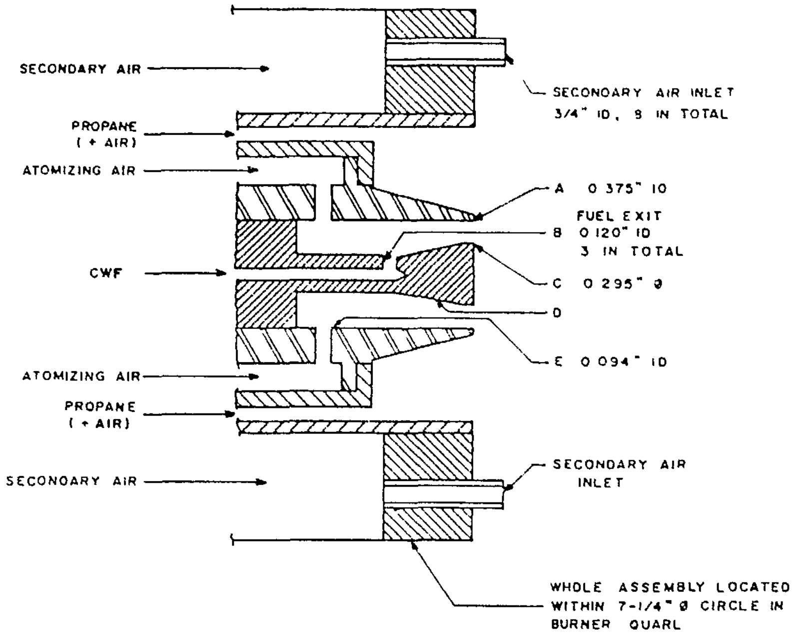


Figure 1. The CANMET Flame Tunnel Furnace



N.B. PREMIXED PROPANE SUPPORT FLAME FOR INITIAL IGNITION ONLY

SUMMARY OF NOZZLE WEAR

RUN	A	B	C	D	E
CWF 5% O_2	0.386"-0.394"	0.120"	0.292"	PARTICLE TRACKS WITH SURF WEAR	0.094"
CWF 3% O_2	0.383"-0.395"	0.127"-0.128"	0.293"	"	0.094"
CWF 1% O_2	0.386"-0.405"	0.128"-0.129"	0.293"	"	0.094"

Figure 2. The Internally Mixed CWF Nozzle

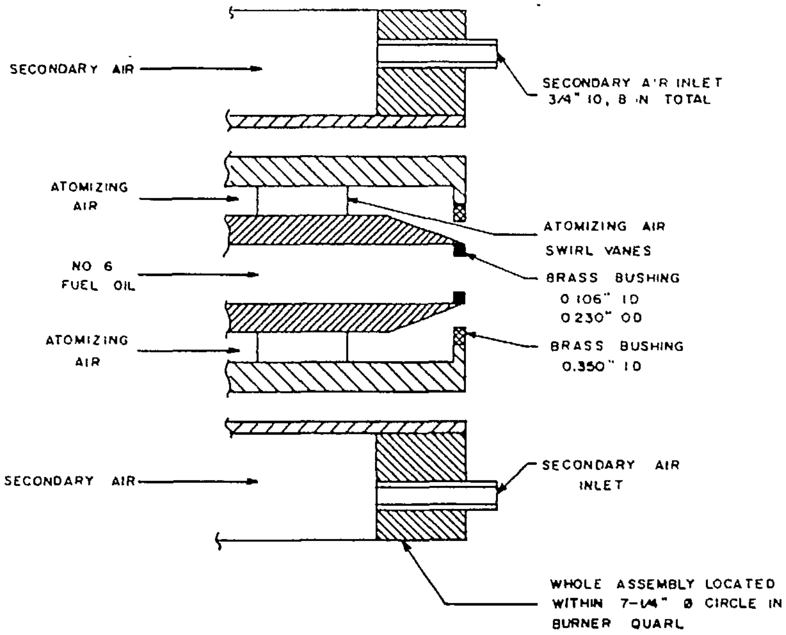


Figure 3. The Externally Mixed No.6 Oil Nozzle

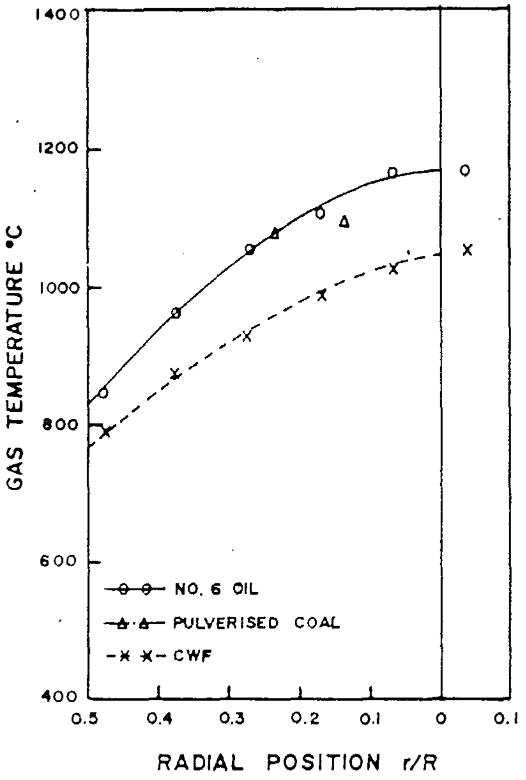


Fig.4 Radial Gas Temperatures; 1% Oxygen, 1.87m.

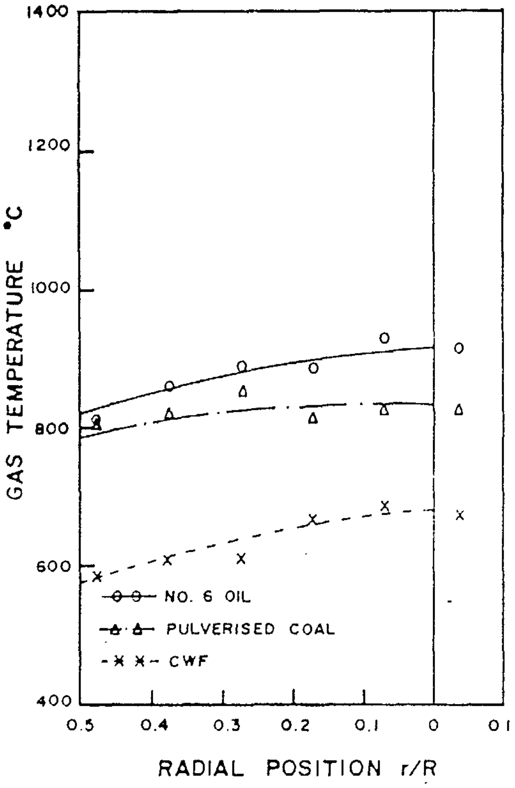


Fig.5 Radial Gas Temperatures; 1% Oxygen, 2.92m.

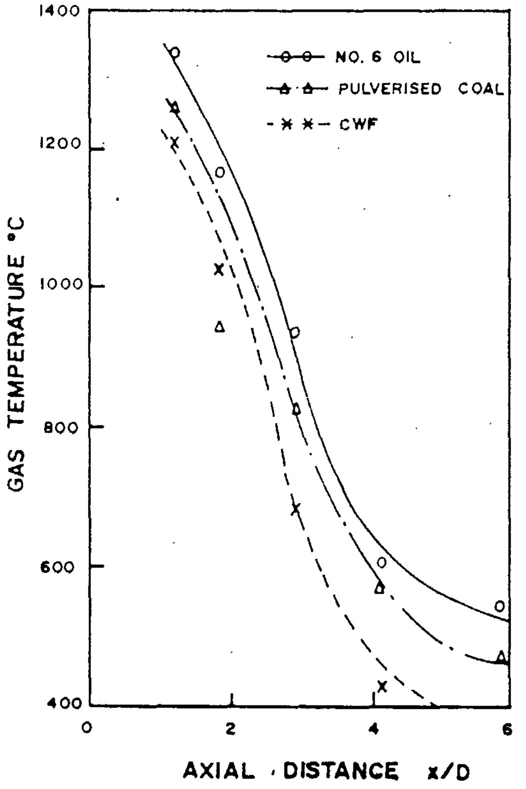


Fig.6 Centre Line Temperatures; 1% Oxygen

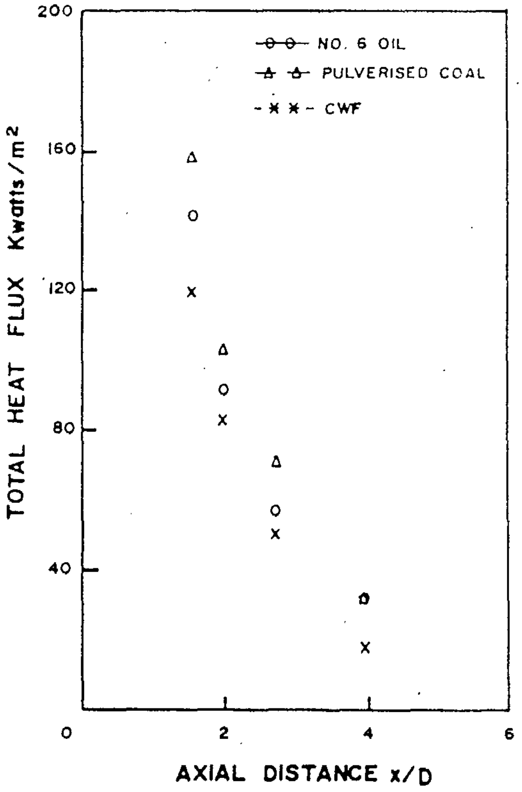


Fig.7 Total Heat Flux; 1% Oxygen

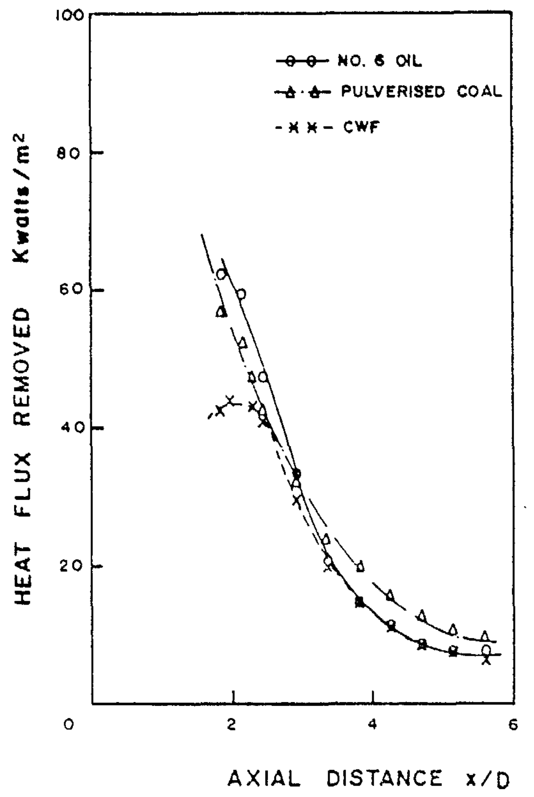


Fig.8 Cooling Load Heat Flux; 1% Oxygen

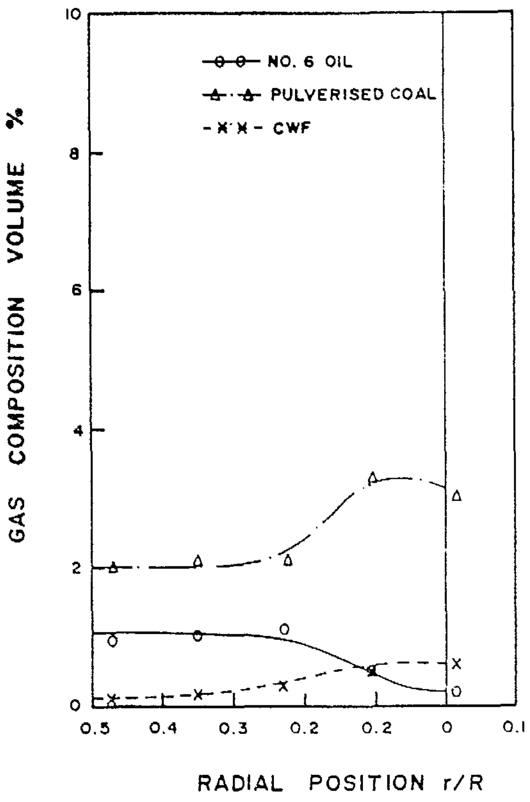


Fig.9 Oxygen Concentration; 1% Flue 02, 1.26m

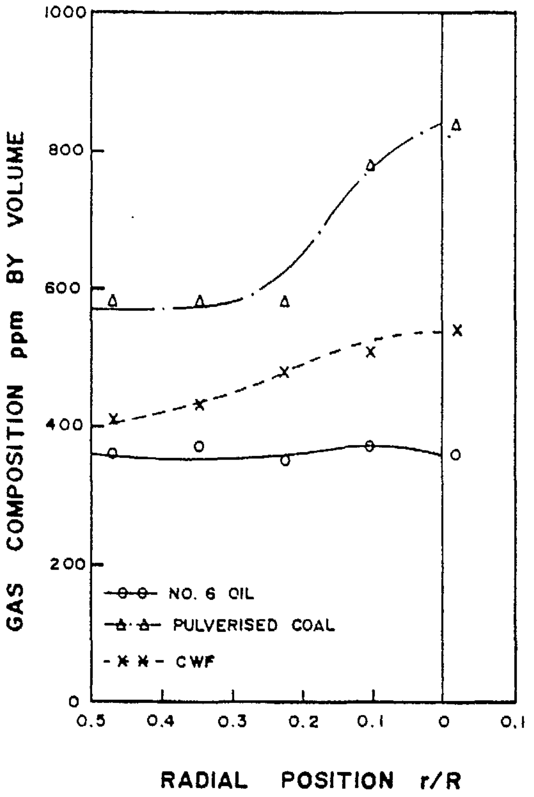


Fig.10 NOx Concentration; 1% Oxygen, 1.26m

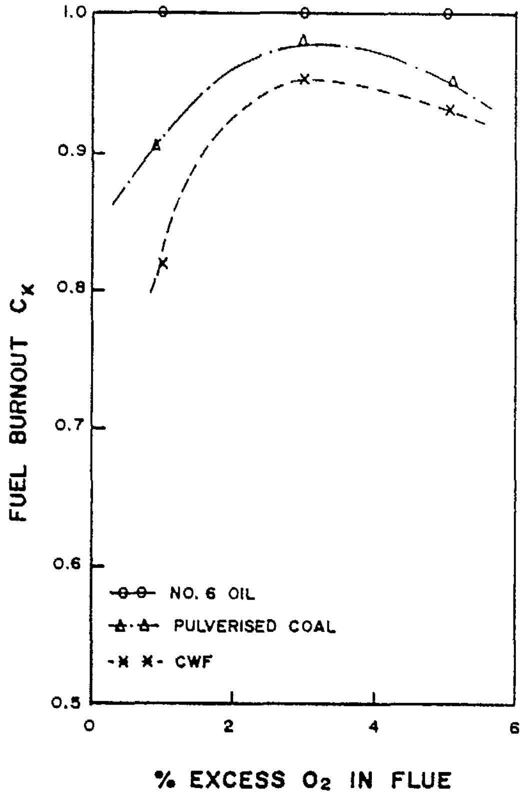


Fig.11 Fuel Burnout Efficiencies

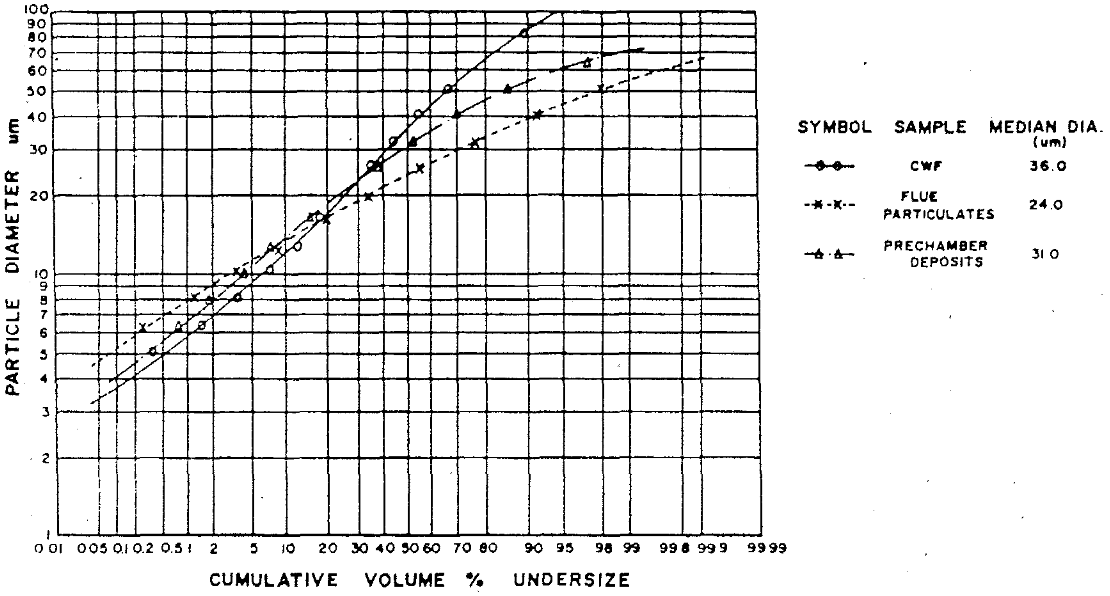


Figure.12 Size Distribution in CWF, Flue Particulates and Furnace Deposits; Run No.CW1

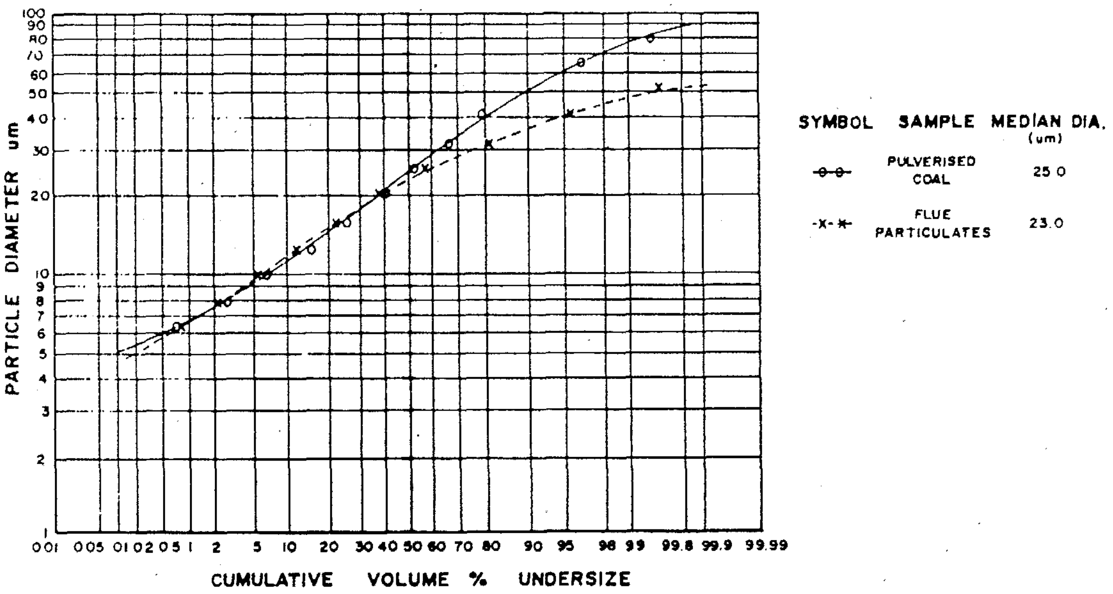


Figure.13 Size Distribution in Pulverised Coal and Flue Particulates; Run No.PC1

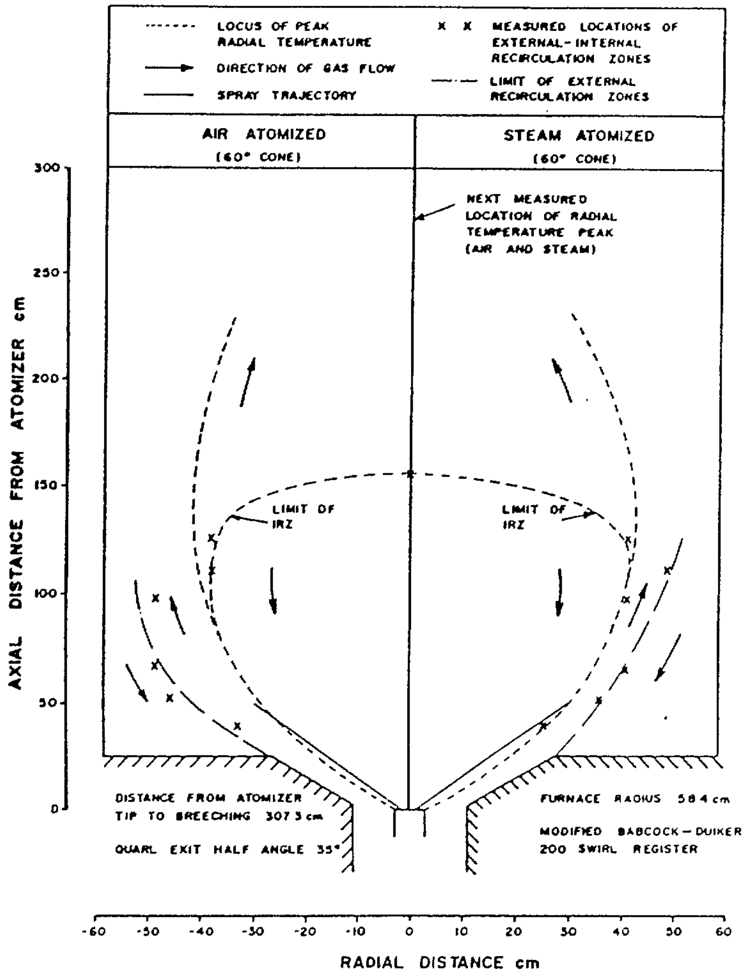


Fig.14 No.6 Oil Flow Boundaries; 1.8 MW(th)

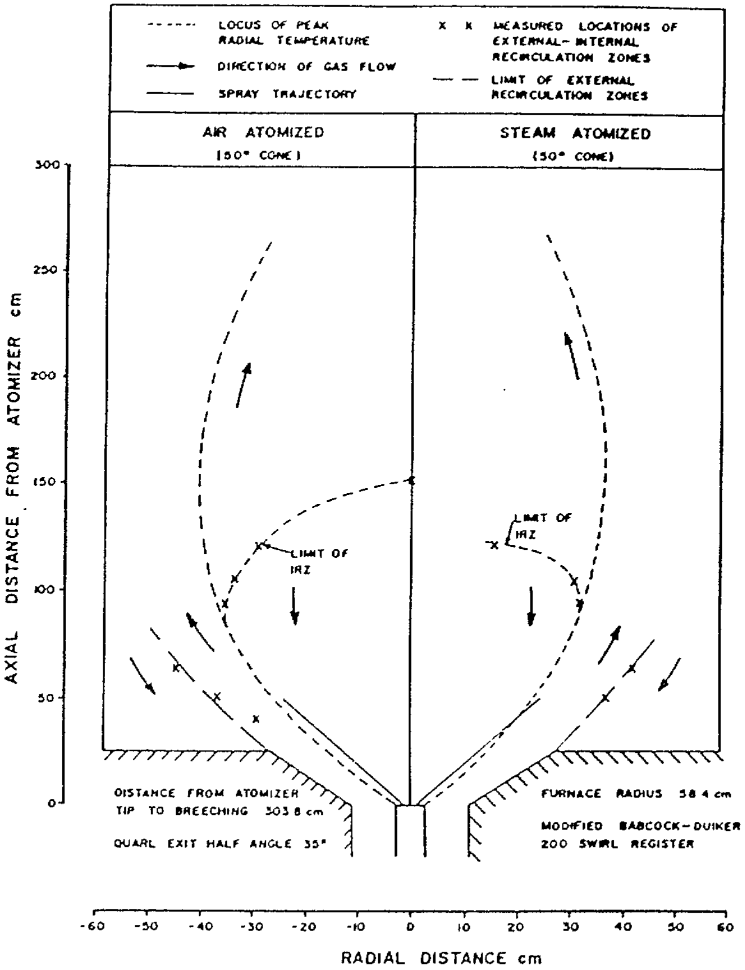


Fig.15 CWF Flow Boundaries; 1.8 MW(th)

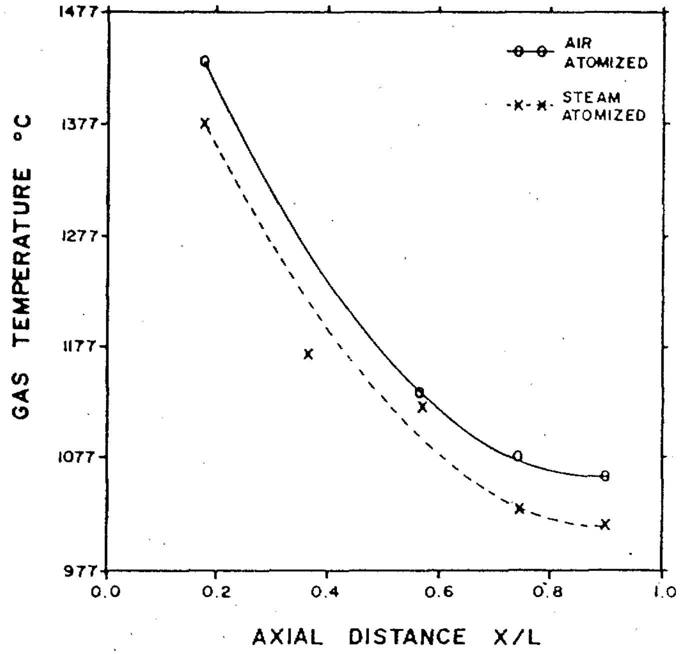


Fig.16 No.6 Oil Centre Line Temperatures; 1.8 MW(th)

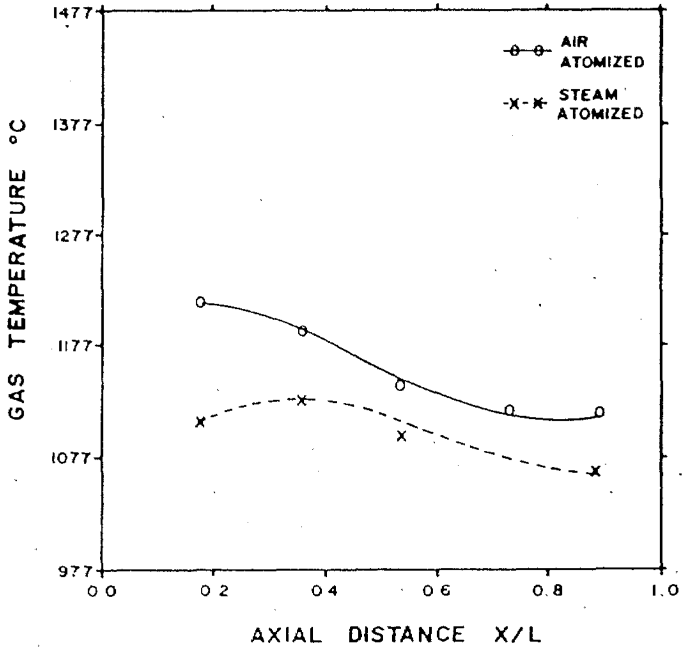


Fig.17 CWF Centre Line Temperatures; 1.8 MW(th)

NO. 105

EXPERIENCE WITH THE NRC BURNER ASSEMBLY

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Summary

The National Research Council of Canada (NRC) embarked on a Coal Liquid Mixture (CLM) burner tip development program in 1981. The goal was to develop an erosion resistant nozzle capable of atomizing efficiently the viscous, abrasive coal-oil mixtures of the time. Subsequent development led to an adjustable wear resistant atomizer integrated into a complete combustion assembly which has served as a useful experimental tool in several studies. Adjustment of the combustion assembly can be effected for today's wide range of coal liquid fuels and combustion environments. The versatility of this apparatus is illustrated here for several combustion applications ranging from heavy oil firing with erosive additives to a rigorous coal-water combustion study in a flame tunnel.

Introduction

The present NRC (National Research Council of Canada) combustion assembly encompasses an erosion resistant prefilming air blast atomizer supported on a gun capable of providing fuel heat exchange and atomizer adjustment. The design has proven to be versatile and adaptable to various combustion environment aerodynamics and fuel atomizing characteristics. The combustion assembly is shown schematically in Figure 1. A conical annular atomizer design is used, featuring pre-filming of the fuel stream at low velocity coupled with a high velocity air stream which shears the thin sheet of liquid at the atomizer lip. Such atomizers have proven to be useful in atomizing highly viscous liquids[1] and providing fine droplets for turbine combustion[2]. The surfaces near the nozzle discharge which are exposed to high velocity streams have been fitted with alumina wear surfaces to eliminate erosive wear[3,4].

As seen in Figure 1, heat exchange capability has been designed into the combustion assembly. Preheating can be used to reduce fuel viscosity, resulting in a smaller mean diameter of the atomized spray and thus improved combustion. On the other hand, some fuel manufacturers require that their fuel not exceed a certain maximum temperature. In this case, cooling of the gun and fuel can be used.

As also shown in Figure 1, the atomizer can be adjusted to yield an atomization mechanism which is suited to the fuel being used. Studies of air blast atomization have shown that liquid properties of viscosity, surface tension and density are of importance. By far the most important parameter influencing the mean drop size, however, is the air velocity[2]. Another important parameter also related to the atomizing fluid is the air/liquid mass ratio. In Figure 2, the mean diameter of water droplets as a function of the air/liquid mass ratio is shown for the NRC CLM atomizer at an air atomizing velocity of 134 m/sec. The data are seen to agree well with those of Rizkalla and Lefebvre[5] for the air/kerosine system. While droplet sizes of 20-30 µm are routinely possible, compatibility with the combustion aerodynamics must be preserved. A situation develops where the momentum of the atomizer discharge must be limited so as not to create flame instabilities. This means lowering the atomizing air velocity and thus compromising the degree of atomization.

The adjustable feature of the NRC atomizer allows an optimized atomization mechanism to be created by externally varying the geometry of the atomizer. Combining this feature with the heat exchange capability of the gun provides a versatile combustion assembly which can yield a spray of coal liquid fuel compatible with various combustion aerodynamics. Several recent combustion experiences with the NRC combustion assembly are described here to illustrate this versatility.

Flame Tunnel Study

A series of tests has been completed[6] using the NRC combustion assembly in the Centre for Energy Studies (CES) combustion test facility at the Technical University of Nova Scotia. In-flame measurements provided direct comparisons between heavy fuel oil and a 70% solids coal-water slurry manufactured by the Cape Breton Development Corporation under license from AB Carbogel at firing rates of 6.1 MBtu/hr. The test program saw

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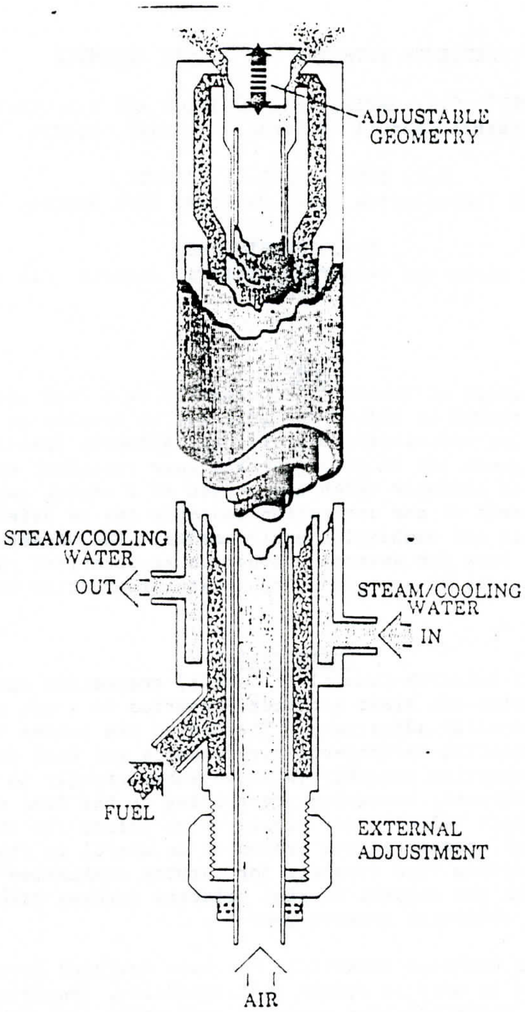

Figure 1: NRC CLM combustion assembly.

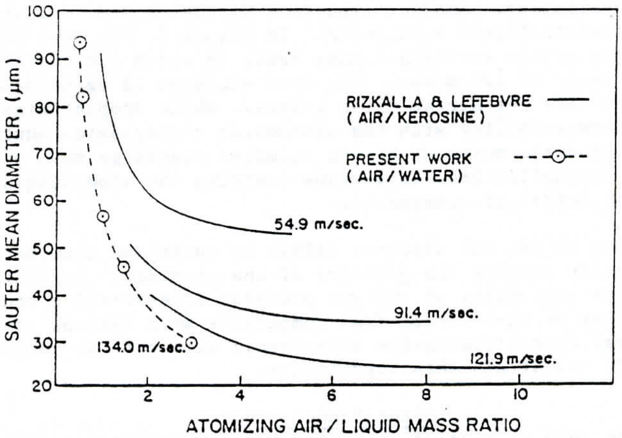

Figure 2 : Effect of air/liquid mass ratio on mean drop size.

both air and steam used as atomizing fluids at 3% and 5% excess oxygen levels in the flue gas. The test conditions are summarized in Table 1.

Table 1: Test matrix used in flame tunnel at CES/TUNS.

Test No.	Fuel Type	Flow lb/min.	Atomizing Fluid			Air Fuel Mass Ratio	Excess O_2 %	Carbon Burnout (% from CO_2)
			Type	Flow ft³/min.	Press psig			
1	HFO	5.50	Air	31.4	105	0.42	5	100
2	HFO	5.50	Steam	2.25 (lb/min.)	105	0.41	5	98.36
3	CW	9.65	Air	43.6	110	0.34	3	94.67
4	CW	9.65	Air	42.4	109	0.33	5	97.54
5	CW	9.65	Steam	2.25 (lb/min.)	101	0.23	5	98.79

The flame tunnel is of a balanced draft configuration. A steam heat exchanger/propane air heater combination can deliver combustion air at a temperature of up to 550°F. A full range of combustion air swirl is provided with a modified Babcock/Duiker 200 swirl register. The combustion chamber is a 9.8 ft. long by 4 ft. diameter cylinder. Refractory linings are installed on the front and rear walls and on the bottom of the furnace with 45% coverage of the internal surface area. Unlined water-jacketed walls elsewhere simulated a furnace load. Visual observation and in-flame probing are accomplished through access ports located along each side of the tunnel and in the breeching section. Combustion products exit the tunnel through a 1.3 ft. diameter water-jacketed refractory-lined breeching section. These hot gases are then diluted with ambient air before being drawn through an induced draft fan and exhausted to a brick stack.

A modified Babcock/Duiker 200 swirl generator was used to develop a tangential velocity component in the combustion air flow. When the air flow is swirled in this manner, radial and axial pressure gradients are produced on discharge of the flow into the furnace. These strong pressure gradients bring about a flow reversal of hot gases along the axis of the flame forming a large torroidal vortex. This vortex stabilizes the flame at the atomizer exit and promotes rapid heating, devolatilization and ignition of the fuel droplets in the fuel spray passing through the hot recirculation gases (Figure 3).

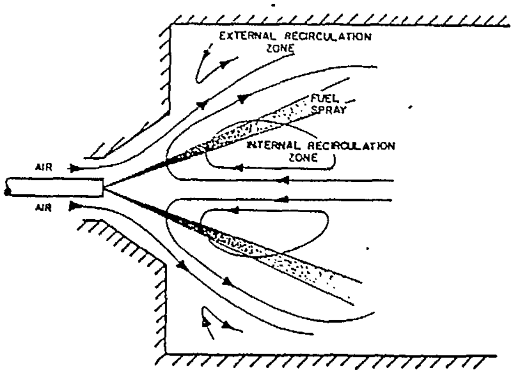

Figure 3 : Flame stabilization by internal recirculation zone in a swirling annular jet.

The size and strength of the recirculation flow has been shown[7] to be a function of burner geometry and input flow conditions. Studies have shown a divergent burner throat with a half angle of 35° to be optimum. A similar optimization process conducted at CES led to the installation of a trumpet-shaped divergent burner throat with a 35° half angle.

Swirled combustion develops three basic flow types as a function of burner geometry and swirl intensity[7]. Low swirl or type A develops with the air flow separating from the burner throat resulting in a fluctuating flame front downstream of the burner. Medium or high swirl (type B) develops an air flow attached to a divergent throat wall. The desired flow pattern of a large torroidal vortex develops providing a stable intense highly recirculated flame. Type C flames are generally formed by wide short divergent burner throats at moderate swirl levels where the flame is attached to the burner face and front wall of the combustion chamber.

Various in-flame measurements were made in the CES/TUNS tunnel to characterize the combustion and heat transfer of each flame configuration in this test. Table 2 provides a summary of the equipment used for these measurements. Only a brief summary of the Hubbard probe and oxy-acetylene flame maps and the carbon burnout determinations as they relate to the atomizer performance will be provided here. A detailed presentation of these same test results will be made available[8].

Table 1 shows that an atomizing fluid/fuel ratio of 0.41-0.42 was used for the HFO fires while the CW flame was optimized at a ratio of 0.33-0.34 for air or 0.23 for steam. The spray angle was also varied in optimizing the fires with 60° and 50° spray angles being used for the HFO and CW fires respectively. The result was a stable type B highly swirled flame in all cases as shown in Figures 4 through 8. Large recirculation zones yielded intense bright stabilized flames for both HFO and CW firing.

Table 2: In-flame measurements (tunnel at CES/TUNS).

Apparatus	Measurement made
Land type SV4 water-cooled suction pyrometer.	Flame temperature Furnace exit gas temperature
IFRF Hubbard Probe	Flow boundaries for HFO
Oxy-acetylene probe	Flow boundaries for coal-water flame
IFRF type A gas/soot probe	Gas and solids sampling of CW flame
IFRF type B gas/soot probe	Gas and solids sampling of CW & HFO flame
Land type A 2π ellipsoidal radiometer measuring head	Total radiation
Land total heat flux meter	Total heat flux at furnace walls.

Carbon burnout values for the five tests are also shown in Table 1. The oil fires showed burnout values of the order of 99%. CW fires yielded burnout values in the 98% range. These high values of carbon burnout are indicative of a well atomized spray.

The results of these combustion tests demonstrate the versatility of the NRC combustion assembly where it provided an optimized swirled turbulent diffusion flame for both HFO and CW firing. Similar short intense fires with large recirculation zones were attained for both fuels with the longer residence time required for coal combustion reflected in the lower carbon burnout numbers for the CW flames. No difficulties were encountered when steam was used as the atomization fluid. The CW portion of this test work represents an estimated 200 hours of combustion work where no wear was detected on the NRC atomizer indicating the viability of the ceramic wear parts.

Coal-Water Firing of a Pellet Induration Machine

During the period of Dec. 11 - Dec. 13, 1984, the National Research Council participated in a CW mixture burn test in an Iron Ore Company of Canada iron ore pellet induration machine[9]. Two 70% solids by weight CW mixtures manufactured by Nycol and the Cape Breton Development Corporation were tested using the NRC coal liquid mixture combustion assembly. The CW fuel replaced HFO firing in one of 28 oil burners.

The NRC atomizer was of standard design without external adjustment containing ceramic wear-resistant components and rated at 12 MBtu/hr. of coal water mixture (assuming ~10,000 Btu/lb.). This design, through substitution of components, can be adjusted to handle various fuels. The atomizer has successfully burned No. 2 and No. 6 oils, coal-oil-water mixtures, and several coal-water mixtures. However, due to time constraints a fixed geometry with a 50° spray angle was used throughout this test.

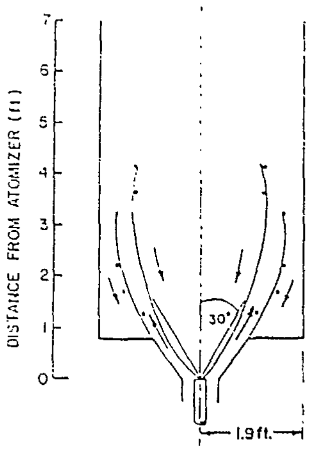

Figure 4 : Flow boundary for air atomized HFO flame at 5% excess oxygen.

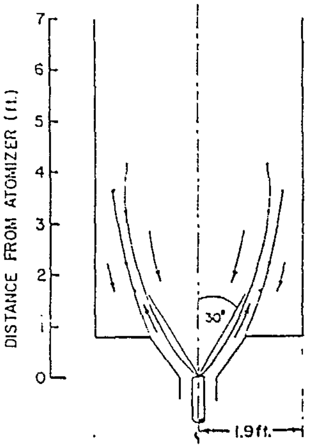

Figure 5 : Flow boundary for steam atomized HFO flame at 5% excess oxygen.

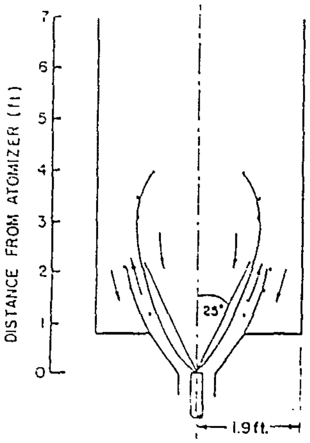

Figure 6 : Flow boundary for air atomized CW flame at 3% excess oxygen.

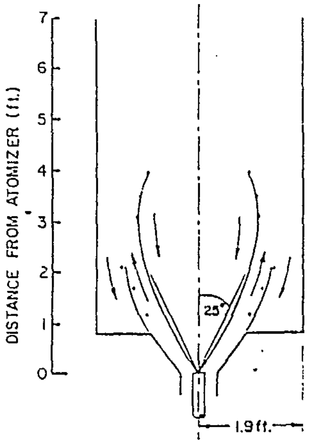

Figure 7 : Flow boundary for air atomized CW flame at 5% excess oxygen.

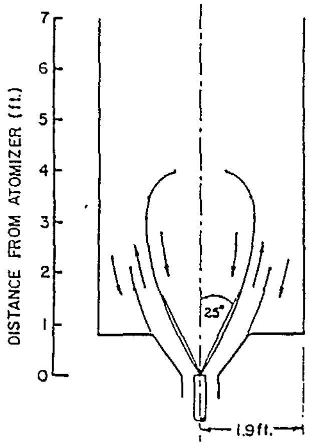

Figure 8 : Flow boundary for steam atomized CW flame at 5% excess oxygen.

The induration machine burner block is shown schematically in Figure 9. The NRC combustion assembly was placed concentrically in the center of the venturi throat such that the gun was 1½" inside the burner block refractory. Combustion air was fed to the burner at 1600°F via downcomers. The downcomers entered the burner block from above and the combustion air is forced around the burner block and then into the induration machine. No attempt to swirl or otherwise control the combustion air via baffles or dampers was made. A portion of the combustion air was drawn into the back of the burner block via the aspiration port and then down along the gun. The resultant flame was contained within the ~4 ft. diameter refractory throat which extended 2-3 ft. axially from the leading face of the burner block. Each combustion zone of the induration machine contained a multitude of such burner blocks spaced equally on each side of the machine separated by the ten foot width of the pellet bed. The zone containing the test burner was located in the high temperature portion of the induration machine. A typical operating temperature, as measured by a thermocouple mounted low in the wall, is 2370°F.

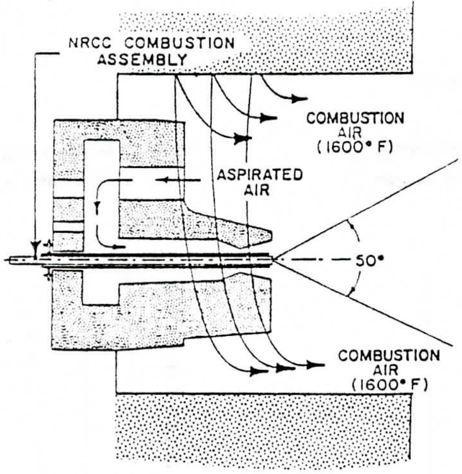

Figure 9 : Induration machine burner block.

The test summary is shown in Table 3. Indicated are the firing rates, fuel pressures, atomizing air pressures, air/fuel mass ratios and an estimated flame temperature as measured by a hand held optical pyrometer.

Table 3: Induration machine coal-water test.

Fuel	Firing Rate (MBtu/hr.)	Fuel Pressure (psig)	Air Pressure (psig)	Air/Fuel Mass Ratio	Flame Temperature* (°F)
Heavy Fuel Oil	5.9		82	0.35	3150
Nycol	2.5	20	82	0.43	2370
CBDC	5.8	33	83	0.20	2215
CBDC	8.8	44	82	0.12	2500
CBDC	10.4	50	82	0.10	2600

* Measured by optical pyrometer.

To demonstrate the atomizer's versatility and provide a qualitative evaluation of the combustion aerodynamics, an HFO flame at a firing rate of 5.9 MBtu/hr. was established. The resulting flame was compact and pencil-like with stable ignition anchored at the atomizer and positioned in an upper quadrant of the burner throat. This observation substantiated the belief that the low swirl combustion air was poorly distributed. However the air/fuel ratio of 0.35 provided enough spray momentum flux to generate a turbulent stable fire with an appearance somewhere between type A and type B.

The Nycol fire at a rate of 2 MBtu/hr. was established during a scheduled maintenance shutdown and was to demonstrate atomizer turndown necessary for this operational mode. Ignition was anchored at the nozzle with a resultant stable flame envelope. Viewing the flame from the opposite side of the machine, a clean bright fire with few sparklers was seen with the flame envelope again held in the same upper quadrant of the burner, as was the case with the oil flame. A recirculation pattern developed which saw a portion of the flame being drawn into the burner through the aspirated air port. This phenomenon was observed from the burner block front where flame could be seen being drawn back around the gun. This was attributed to the atomizer discharge dominating the aerodynamics of the combustion zone.

The CBDC fires were all accomplished with the induration machine in a production mode. Three firing rates of 5.8, 8.8 and 10.4 MBtu/hr. were established with air/fuel mass ratios of 0.20, 0.12 and 0.10 respectively. The flames were all highly turbulent and held by the refractory throat. Ignition appeared stable and established near the atomizer. As the firing rate increased the flame tips began to converge; the 10.4 MBtu/hr. flame began to form a type B recirculation pattern with a recorded flame temperature of 2600°F.

While this short test developed flames suitable to demonstrate the viability of CW substitution in such an application, it is apparent that optimized combustion conditions require further development. The incorporation of a swirl register would develop combustion aerodynamics which could be optimized to yield the turbulent recirculated type B flame obtained in the flame tunnel study.

Coal-Oil-Water Combustion Trial

In December 1983, a 25,000 gallon coal-oil-water (COW) combustion trial was completed at the Canadian Salt Company Ltd. in Pugwash, Nova Scotia. The combustion test unit was a Foster Wheeler type AG-136 water tube, return pass boiler. Prior to the burn the burner/windbox assembly was modified with a Babcock/Duiker swirl generator similar to that discussed earlier in the flame tunnel study.

The fuel used in this study was prepared by Scotia Liquicoal in their Dartmouth, Nova Scotia plant and transported 100 miles to Pugwash via highway tankers. A stable homogenous mixture was delivered with a nominal composition of:

55% coal
30% oil
15% water

The average ambient temperature in Pugwash during the test was 35°F. No difficulty was experienced in fuel transfer from the tankers.

The same NRC combustion assembly used in the induration machine study was used throughout this testwork. An 80° spray angle was found to be optimum in achieving a bright stable highly recirculated type B flame. Excess oxygen levels were maintained in the 3-5 percent range at an average firing rate of 27 MBtu/hr.

The 100 hour test provided an opportunity to evaluate the present NRC atomizer's resistance to erosive wear. Figure 10 illustrates the result of the erosion test. Erosive wear is expressed as the percentage increase in the product of nozzle discharge coefficient and discharge orifice area (CdA_0) as determined by a previously presented test method[3]. The 8.1% increase in CdA_0 is seen to compare well with the results for a prototype also fitted with alumina wear parts[3].

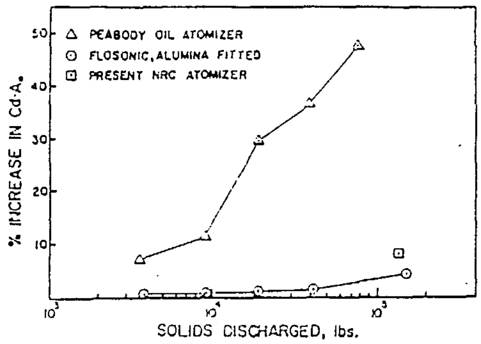

Figure 10 : Effect of erosion on atomizer discharge.

Other Trials

In a 40,000 lb/hr. package boiler application, the NRC combustion assembly was installed to burn bunker oil containing abrasive additives. Such additives are commonly used by utilities to prevent boiler tube corrosion by high concentration of vanadium in the fuel. They place heavy demands on atomizers due to their erosive nature which causes steadily deteriorating combustion due to poor atomization. The testing to date has been preliminary in nature and is being used to specify the burner/atomizer configuration required for an optimized longer term demonstration.

A larger scale version of the combustion assembly rated at 40 MBtu/hr. of coal-water fuel was used for preliminary testing in a utility boiler at the New Brunswick Electric Power Commission Chatham facility. The boiler was a four burner front-wall fired configuration. The combustion assembly was of the externally adjustable type and was fitted with a 70° spray angle. A fire was ignited and sustained using a coal-water fuel supplied by the Cape Breton Development Corporation (CBDC) using both air and steam as the atomizing media. The results of this short test work have led to the establishment of a future performance trial scheduled for April 1985.

This performance trial will see the combustion of 400-500 tons of CBDC-prepared coal water fuel under controlled utility conditions. A fully instrumented fuel and atomizing fluid delivery manifold will accompany the NRC combustion assembly providing accurate metering of both fluids to the atomizer. Nozzle wear will be evaluated throughout the test as well as flame temperatures, boiler efficiencies, flame radiation and oxygen measurements and ash analyses. The results of this test work will be reviewed in preparation for a coal water fuel demonstration trial, scheduled for an oil fired utility boiler in Charlottetown, Prince Edward Island.

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