VISCOELASTIC BEHAVIOR OF BENEFICIATED COAL-WATER SLURRIES AND THEIR ATOMIZATION CHARACTERISTICS.

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Abstract

Experimental data on the effects of CWS properties and air flow rate on mean drop size for simple pressure atomizers, were examined in our laboratory. A model equation which is derived based on the physical processes involved in air-pressure atomization is proposed. This equation demonstrates a good agreement with our experimental data.

Introduction

Atomization has been used very extensively in a wide variety of applications [1]. However, the physical mechanisms of fuel breakup into droplets continue to receive attention. Theoretical analyses based on wave theory have postulated growth along surfaces [2,3], but until recently there was little experimental evidence on generation and growth of waves [4]. The influence of fluid properties, viscosity, surface tension, and density have always been considered important factors in atomization [5]. Even though the effect of rheological properties on CWS have been examined [6,7], the influence of viscoelastic properties on CWS atomization has not been given much attention.

The objective of this program was to explore the relationship between rheological properties including viscoelasticity of CWS, and atomization quality in order to delineate the effect of these properties on atomization.

The CWS utilized in this work were derived from beneficiated coals. The beneficiated coals were either heavy media cleaned or froth flotation Cleaned. Also, CWS derived directly from the parent coal was utilized. The choice of these samples was to allow for variation in properties of the CWS. The variation in properties of the CWS used, make it important to determine the characteristic relationship between atomization and rheological properties.

There are several empirical relationships that have been established to account for the design of spray systems [8,9]. However, it would be of practical significance to have an understanding of how the rheological characteristics of the CWS affect atomization. Though viscosity and surface tension are considered to be relevant parameters affecting atomization, there is an indication in work done with polymeric solutions that the viscoelastic properties produced even by low polymer concentrations can significantly affect spray quality [10]. The addition of polymeric additives to stabilize CWS, can thus affect the spray quality.

This paper examines the rheological properties of beneficiated coals and the effect these properties have on their atomization characteristics. An assessment of the atomization data in relation to Air/Fuel ratio is also discussed.

Experimental

Three CWS samples beneficiated to different levels were examined for moderate and high shear rheology and viscoelastic character. The samples were derived from Heavy media cleaned coal, Froth Flotation clean coal and Uncleaned Parent coal. The heavy-media cleaning was done in a stirred vessel with a 1.35 specific gravity circulating magnetite slurry as the parting medium. The parent feed coal was pre-crushed to -1/2 inch and screened to remove the minus 14 mesh fines before separation.
The magnetite media was rinsed from the float coal with spray water on a vibrating screen. The float coal was subsequently ground to minus 48 mesh in a ball mill and filtered.

The parent coal was also ball-mill ground to minus 48 mesh for the froth flotation, and the flotation was accomplished in a series of seven 1 cubic foot mechanical aeration flotation machines using 0.34 pound diesel fuel and 0.51 pound methyl isobutyl carbinol (MIBC) per ton of feed coal as reagents.

The coal water slurries were prepared from the filter cakes. In each case, a portion of the filter cake was ground to minus 48 mesh in a stirred ball mill and blended to achieve a desired particle size distribution. Henkel A-23 -M naphthalene sulfonate was used to disperse the coal and reduce the viscosity of slurry, and Pfizer Flocon 4800C xantham gum was added to prevent formation of a hard packed sediment. Table 1 lists the physical characteristics of the slurries immediately after preparation and Table 2 lists the particle size distribution used in the formulation of the slurries.

Rheological Properties

The Rheological properties of the CWS and the simulated fluids with and without the xantham gum, were determined using a Haake RV-20 rheometer and HVA-6 capillary viscometer. The glycerine solutions without the xantham gum, were found to be Newtonian and the viscosities ranged from 384 mPas.s to 598 mPas.s, depending on the concentration. The flow behavior of the glycerine solutions containing the xantham gum exhibited a dilatant flow behavior [12]. Table 1 shows that there is no significant variation in the shear viscosity of the CWS utilized in this study.

In order to understand the CWS atomization behavior, it is necessary to understand the viscoelastic behavior of the CWS as well as the shear flow behavior. Viscoelastic properties of the CWS were measured using Haake-CV20. The linear viscoelasticity was measured by subjecting the sample through a small amplitude oscillatory test. For a system where the strain varies sinusoidally with time, t, the strain amplitude can be given by:

$$\gamma(t) = \gamma_{max} \mathrm{Sin}\,\omega t \qquad (1)$$

where γ_{max} is the maximum strain amplitude and ω is the angular frequency of oscillation [14]. The corresponding stress is given by

$$\tau(t) = \tau_{max} \mathrm{Sin}(\omega t + \delta) \qquad (2)$$

where δ is the phase shift between stress and strain.
The above equation, (2), can be re-written as:

$$\tau(t) = \gamma_{max}(G' \sin\omega t + G'' \cos \omega t) \qquad (3)$$

The storage modulus, G' and the loss modulus, G" are defined in terms of the phase angles as:

$G' = (\tau_{max} \cos\delta)/\tau_{max}$ (4)

$G'' = (\tau_{max} \sin\delta)/\tau_{max}$ (5)

The storage modulus G' represents the "stored' or elastic component of the stress and is in phase with the strain. The loss modulus, G", represents the viscous component and it is the out of phase component.

For a fluid that is purely viscous, G' is zero and the phase is 90° and for a purely elastic material where energy is stored but not dissipated, G"is zero and the phase is 0° [15]. Figure 2 shows the oscillatory flows obtained from these measurements.

The G" values for the cleaned coal CWS samples show that with increasing frequency, the viscous component remains fairly constant with increasing frequency of oscillation whereas the uncleaned coal CWS and the xantham gum solution acquire a sharply decreasing G" value characteristic at high oscillatory frequency rates. Figure 2 shows an initial increase in the G' for all the CWS samples and reaching a plateau at high oscillatory frequencies. This effect is more pronounced in the uncleaned CWS sample than the cleaned CWS samples. This indicates that shear deformation of the uncleaned CWS is accompanied by significant energy storage. Figure 1 compares the high shear flow behavior of the three slurries analyzed. Analysis of the flow data indicated that there is no significant differences in their shear flow behavior.

Atomization Studies

Atomization studies were performed at Adelphi University. The initial tests were performed to compare and optimize conditions necessary for the CWS atomization. A Malvern 2600 particle size analyzer and a Delavan Airo Nozzle were used to provide information about the spray characteristics, including drop size distribution, mean median size distribution and spray velocity. The source of atomizing air used was the house air system, which delivers air at pressures up to a maximum of 85 psig. The atomizing air passes through a filter and a flowmeter before it enters the atomizer.

Theoretical analysis of the physical process governing atomization was proposed by considering an energy balance across a control volume that extended from the nozzle exit plane to the line of spray measurement in a previous study [11]. The inlet conditions were calculated using a two-phase flow technique and the outlet conditions calculated by using conservation of momentum and assuming that the final velocities of the air and liquid are equal. The final expression is of the form:

$SMD/L = 1/3\ \rho_A/\rho_F\ We^{-1}(1+M_F/M_A) + 1/3\rho_A/\rho_F CK\gamma^n(1+M_F/M_A)$ (6)

The above equation demonstrates that there are two possible mechanisms for the breakup of the CWS. The first term is due to competition between surface tension forces and aerodynamic shearing force and the second term is due the competition between viscosity forces and surface tension force..

The experimental data suggests that the correlation equation obtained can best be represented by:

$$SMD/L=1/3\rho_A/\rho_F We^{-1}[(1+M_F/M_A)]^{0.5}+1/3\rho_A/\rho_F CK\gamma^n[(1+M_F/M_A)]^{-0.25} \quad (7)$$

The comparison of the measured and the calculated SMD for the glycerine-xantham gum solution and the CWS using equation 7, are illustrated in Figures 3 and 4. The calculated SMD values for the Delavan nozzle used in this experiment is found to agree very closely with the calculated values using the viscosity data at 10^5 s^{-1} (Figure 4). The SMD values calculated using viscosity data at both a shear rate of 100 s^{-1} and 10^5 s^{-1} for the glycerine-xantham gum solution is shown in Figure 5. There is a much better correlation of the experimental and calculated values when viscosity data at 10^5 s^{-1} is used compared to using viscosity data at 100 s^{-1} .

Variation of SMD as a Function of Viscosity

The variation of the Air/Fuel ratio from 0.12 to 0.45 seems to have a significant effect on the SMD. This influence seems to diminish as the Air/Fuel ratio is increased.

The SMD of glycerine-water mixtures at high Air/Fuel and low Air/Fuel data are plotted in Figures 6 and 7. The data show that at high Air/Fuel ratio, there is no significant change in the SMD as the viscosity is varied. However, at low Air/Fuel ratio the SMD shows a strong dependence on the viscosity. This is due to the fact that in the high air/Fuel regime, the relative velocity between the droplets and the air is very high and this produces high pressure forces on the droplets to the same extent. Considerable dispersion of the droplets was also observed at high A/F ratios. This effect is minimized in the low A/F regime.

Table 3 lists the experimental SMD values obtained for the different fuels atomized at high and low A/F ratios. The SMD values obtained for the CWS showed significant variations both in the high A/F and low A/F regimes with the uncleaned slurry having the highest SMD values. The shear viscosities at high shear rates showed no significant differences. The uncleaned coal slurries however, exhibited the highest viscoelastic behavior compared to the two beneficiated slurries (Figure 2). The higher SMD values obtained for the uncleaned slurry indicate difficulty in atomization of this slurry. This observation can be associated with the higher viscoelastic behavior of the uncleaned coal slurry. This is an indication that, in addition to shear flow, oscillating flow also plays a role in characterizing atomization, and that the higher the elastic component, the poorer the atomization quality.

References

1. Marshall W.R., "Atomization of Spray Drying" AICHE Chemical Engineering News, Monograph series, Vol. 2., (1954).

2. Reitz, R.D., and F.V. Bracco, "Mechanism of Atomization of a Liquid Jet, " Physics of Fluids, Vol. 25, #10, p 1730, (1982).
3. Giffer, E., and A. Muraszew, "The Atomization of Liquid Fuels," John Wiley, New York, (1953).
4. Tsai S.C., and Vu T., "Atomization of Coal Water Slurry Using Twin-fluid Jet Atomizer," Fuel, Vol. 65, 566-571, (1986).
5. Levebvre, A.H., "Airblast Atomizatin," Progress in Energy and Combustion Science, Vol 6, p. 223, (1980).
6. Tsai, S.C. and E.W. Knell, "Rheology and its Effects on Atomization of Coal Water Slurry" 1st Pittsburgh Coal Conference, Pittsburgh, (1984).
7. Yu, T.U., Kang, S.W., and J.M. Beer, "Fuel Type Effects on Coal-Water Slurry Atomization. AiAA-86-0298, AIAA 24th Aerospace Science Meeting, Reno, Nevada, (1986).
8. Lefebvre, A. H., Wang X.F., and C.A. Martin, "Spray Characteristics of Aerated-Liquid Pressure Atomizers", AIAA Journal Propulsion and Power, 4, 293, (1986).
9. Levebvre, A.H.. "Energy Considerations in Twin-Fluid Atomization," ASME 90-GT-3, (1990).
10. Goldin, M. et.al., "Breakup of a LaminarCapillary Jet of a Viscoelastic Fluid," Journal of Fluid Mechanics, 38, 689, (1986).
11. Ohene F., Quarterly Progrees Report, #7, U. S. Sept. Of Energy. (#
12. Phillippoff, W. "Vibrational Measurements with large Amplitudes, Trans. Soc. Rheol., 10 (1966) 317-334.
13. Macdonalds, I.F., B.D Marsh, and E. Ashare, "Rheological behavior for Large Amplitude Oscillatory Motion", Chem. Eng. Sci., 24 (1969) 1615-1625.
14. Ohene, F., D. Luther and U. Simon ," Fundamental Investigation of non-Newtonian Flow Behavior on Atomization," Prooceeding of the 18th International Conference on Coal Slurries and Technologies, Clearwater, Fl. (1993).

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TABLE 1.
Properties of Coal Water Slurry (CWS) Fuels Used for Atomization Studies

	Cleaning Procedure		
	None	Heavy Media	Froth Flotation
Slurry Composition, %			
Particular Coal	62.43	62.39	62.41
Dispersant (A-23-M)	2.51	2.54	2.53
(Flocon 4800C)	0.025	0.025	0.025
Total Solids	65.96	65.95	65.96
Water	34.04	34.05	34.04
Slurry Density, lb/gallon	9.75	9.75	9.75
Slurry pH	7.8	7.9	7.7
Dry solids Composition, %			
Volatile Matter	33.48	35.92	36.04
Ash	5.33	1.88	1.51
Fixed Carbon	59.39	62.20	62.45
Total Sulfur	1.80	1.19	1.21
Viscosity, Increasing Shear Rates, Centipoise			
100 s^{-1}	1,000	950	1,000
500 s^{-1}	995	900	1,015
1,000 s^{-1}	830	765	840
Viscosity, Decreasing Shear Rates After 3-Minute hold at 1,000 s^{-1}, Centipoise			
100 s^{-1}	500	400	580
500 s^{-1}	445	440	525
1,000 s^{-1}	435	430	490

Table 2.
Particle Size Distribution of Coal Samples

	Cleaning Procedure		
	None	Heavy Media	Froth Flotation
Particle Size Distribution, %			
Passing 300 µm	99.61	99.64	99.66
Passing 210 µm	97.93	97.83	98.16
Passing 150 µm	94.21	93.28	95.45
Passing 106 µm	89.05	88.28	91.01
Passing 75 µm	81.71	80.97	81.59
Passing 53 µm	74.67	75.72	75.54
Passing 45 µm	68.89	70.27	68.77
Passing 38 µm	66.51	66.71	68.48
Passing 30 µm	53.77	53.34	55.22
Passing 20 µm	43.49	42.30	42.09
Passing 15 µm	37.61	35.37	34.40
Passing 10 µm	29.78	27.60	27.24
Passing 8 µm	25.69	25.24	22.54
Passing 6 µm	21.26	20.06	19.69
Passing 4 µm	15.02	14.32	14.28
Passing 3 µm	11.63	11.21	11.14
Passing 2 µm	7.64	7.21	7.22
Passing 1 µm	2.35	2.25	2.20
Mass Mean Diameter (MMD), µm	42.9	44.9	42.3

Table 3
Atomization Data

SAMPLE	η_{me} (mPas)	A/F	γ dynes/cm	DENSITY g/ml	SMD µM
Gly-W	384	.387	63	1.23	19.6
	384	.127	63	1.23	105
	410	.392	65	1.26	22.8
	410	.174	65	1.26	131
	598	.412	66	1.26	20.6
	596	.198	66	1.26	159
	760	.425	66	1.28	21.6
	760	.243	66	1.28	189
	812	.223	67	1.28	201
	836	.411	67	1.29	23.5
	836	.392	67	1.29	26.3
	836	.189	67	1.29	231
Gly-Pol					
	55.7	.402	61	1.13	14.3
	55.7	.127	61	1.13	152
CWS-Flotation					
	.0875*	.427	67	1.17	24.5
	.0875*	.14	67	1.17	256
Uncleaned-CWS					
	.094*	.441	67	1.16	31.5
	.094*	.145	67	1.16	354
Heavy Media-CWS					
	.083*	.412	67	1.16	22.6
	.083*	.144	67	1.16	238

** VISCOSITY AT A SHEAR RATE OF 100,000/S.
Gly-Pol: Glycerine Polymer solution.
Gly-W: Glycerine-Water Mixture

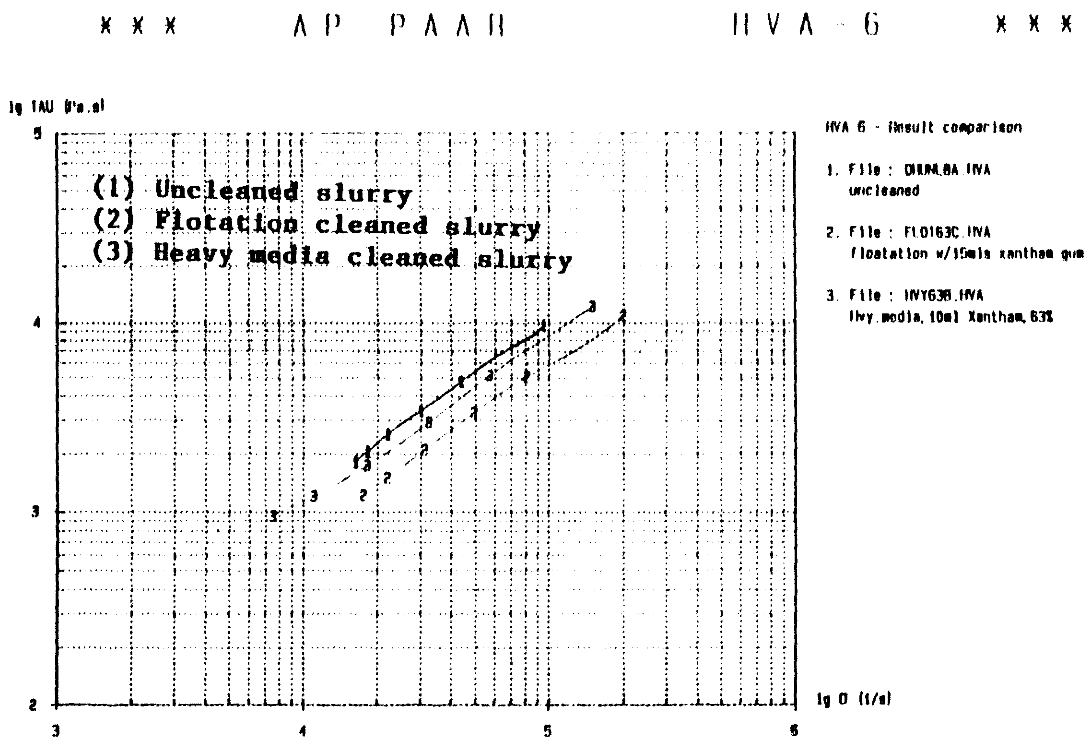

Figure 1. A comparison of High shear Flow Behavior of CWS.

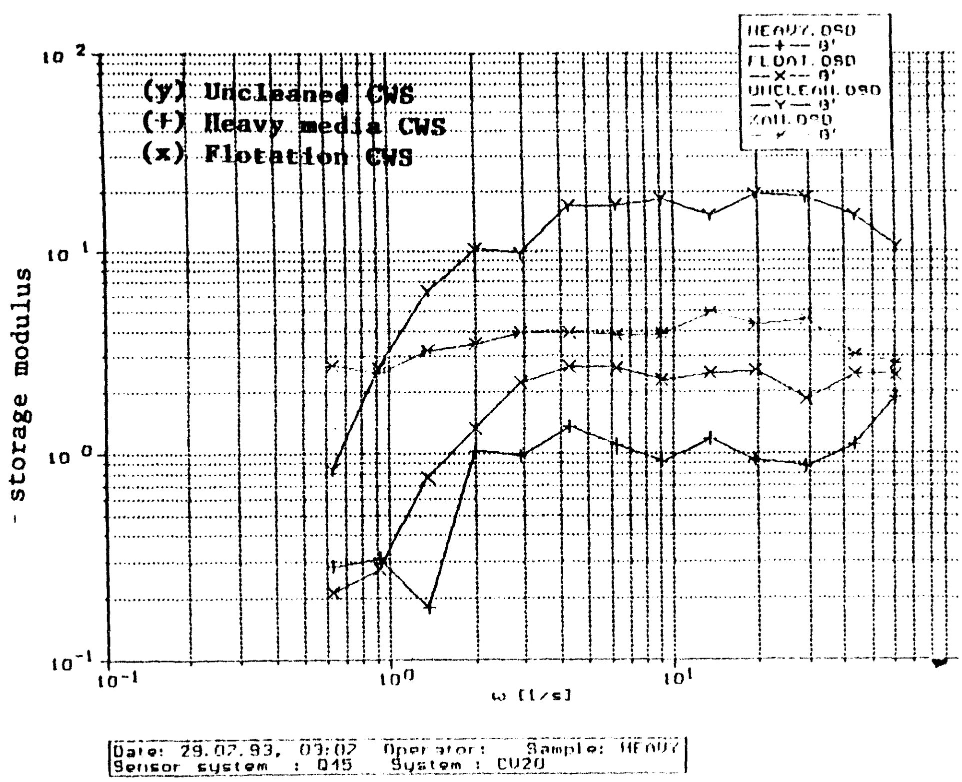

Figure 2. Oscillatory Flow Behavior of CWS

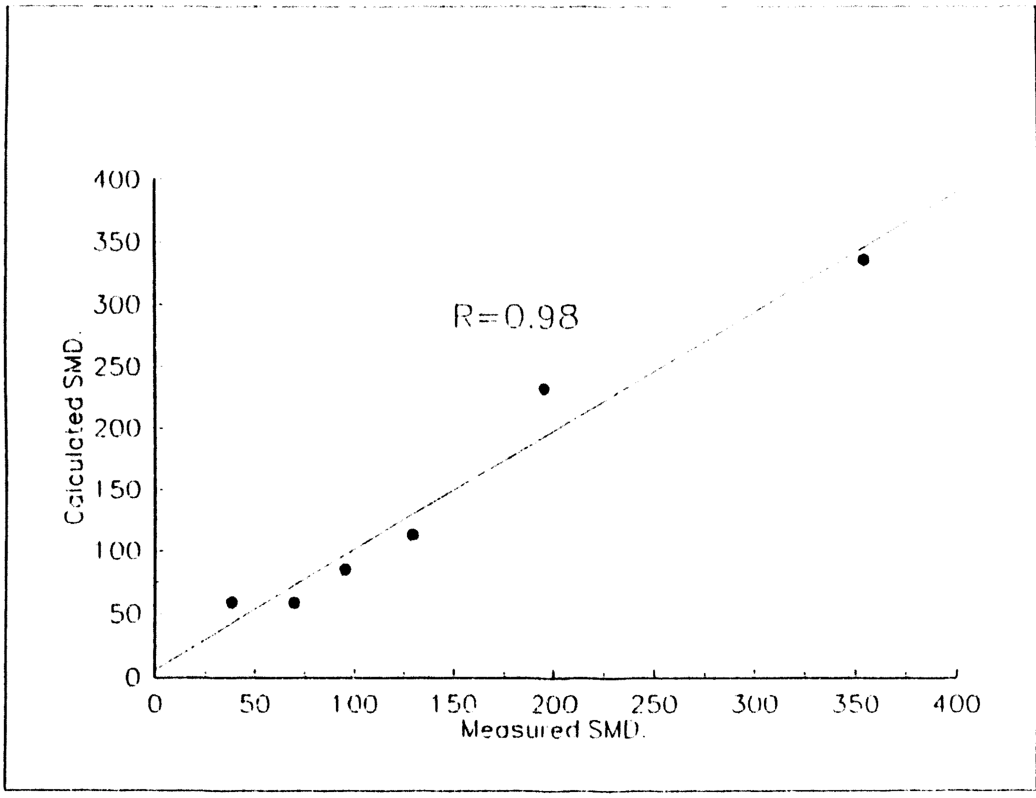

Figure 3. Calculated SMD vs Measured SMD For glycerol-water solution

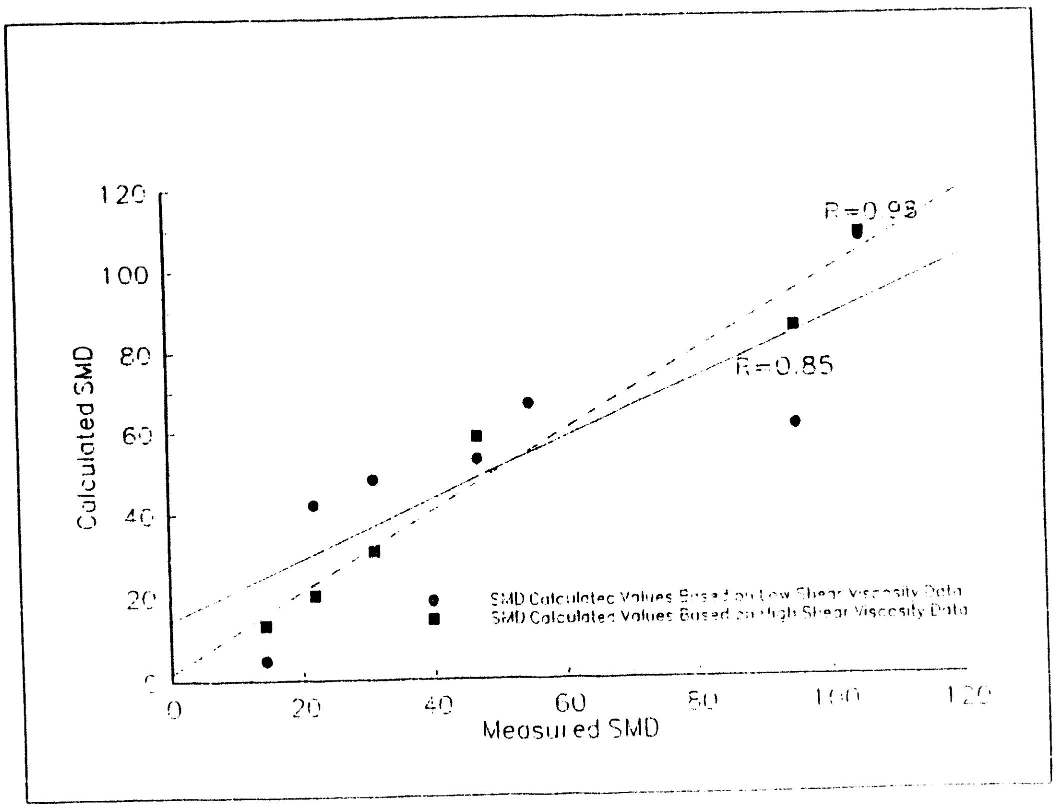

Figure 4. Calculated SMD vs Measured SMD For CWS.

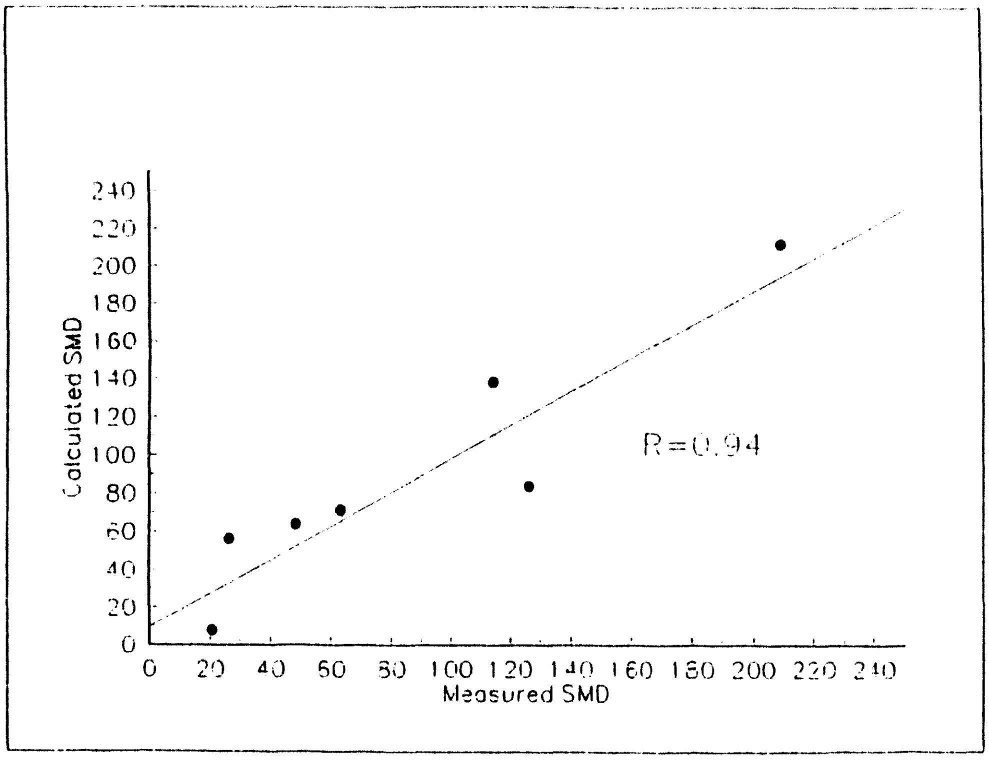

Figure 5. Calculated SMD vs Measured SMD For Glycerol-Xantham Gum solution

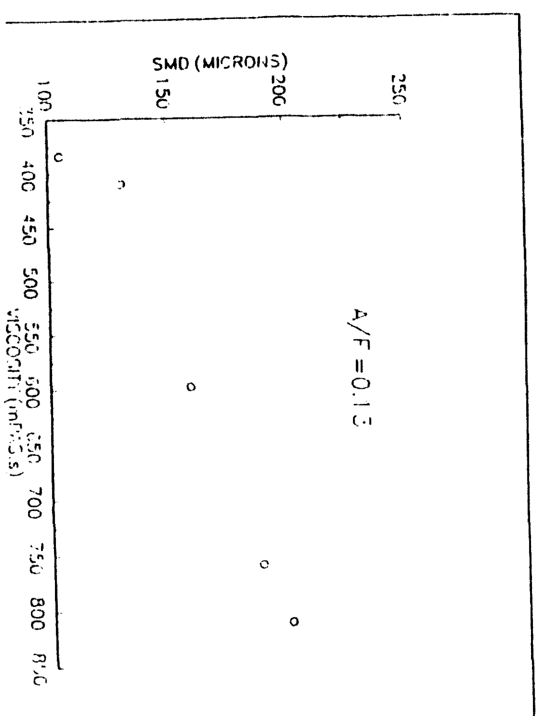

Figure 7. SMD Vs. Viscosity

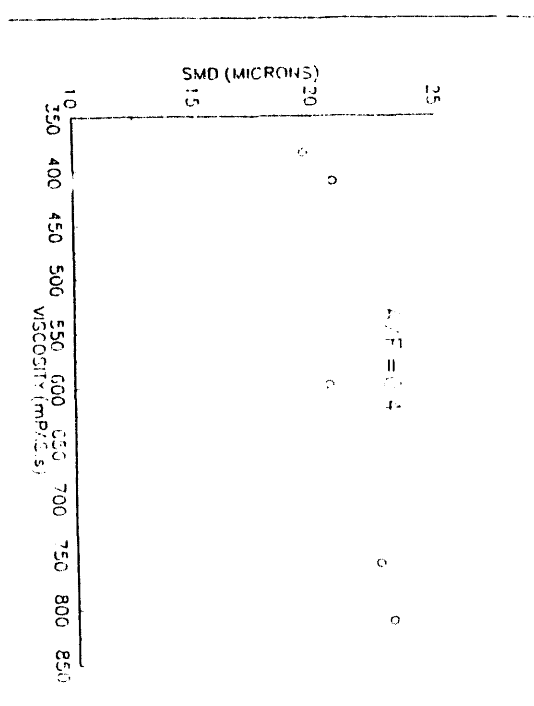

Figure 6. SMD Vs. Viscosity

The following manuscript was unavailable at the time of publication.

AN INNOVATIVE COAL-WATER SLURRY PROCESSING TECHNOLOGY

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DEVELOPMENT OF A PHENOMENOLOGICAL MODEL FOR COAL SLURRY ATOMIZATION

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BACKGROUND AND INTRODUCTION

Highly concentrated suspensions of coal particles in water or alternate fluids appear to have a wide range of applications for energy production. For enhanced implementation of coal slurry fuel technology, an understanding of coal slurry atomization as a function coal and slurry properties for specific mechanical configurations of nozzle atomizers should be developed.

FACTORS AFFECTING ATOMIZATION

Viscometric Properties

It has been demonstrated that it is possible to describe viscometric properties of dense coal slurries by treating them as mechanical continua following the rheological behavior of a power law fluid.

$$\tau = k \dot{\gamma}^{n} \qquad (1)$$

where

τ = shear stress (Pa)
k = consistency index
$\dot{\gamma}$ = shear rate (s-1)
n = power law index

The power law index (n) is a measure of the deviation from Newtonian behavior of the fluid, i.e. n=1 for a Newtonian fluid, n<1 for a pseudoplastic system, and n>1 for a dilatant system.

In some cases a stress must be overcome to obtain fluidity. This yield stress requires a modification of Eq. 1 where:

$$\tau - \tau_0 = k \dot{\gamma}^{n} \qquad (2)$$

The apparent viscosity of the system is obtained by evaluating $d\tau/d\gamma$ at a specific shear rate, $\dot{\gamma}$.

Coal water slurries are classified as suspension concentrates. Suspension concentrates are solid in liquid dispersions in which the mean particle size exceeds colloidal dimensions, i.e. greater than one micron. These coarse suspension concentrates differ from colloidal suspensions in that upon standing, particles will settle to the bottom of a container due to gravity, whereas colloidal suspensions are kept suspended by thermal agitation and Brownian motion.

For highly concentrated suspensions which are the main focus in the study of coal water fuels, phenomenological approaches have been developed. In the phenomenological approach, a relation between bulk properties, viscosity, η, and volume concentration, ϕ, is obtained.[1] The shear viscosity will be infinite at some value called the maximum packing, ϕ_m. At this volume density of particles, the suspension will not flow under the stresses typical in pumping and flow of the suspensions. Therefore,

$$\eta = F(\phi, \phi_m) \tag{3}$$

such that

$$\eta \rightarrow \infty \text{ as } \phi \rightarrow \phi_m$$

Adelphi University has researched these phenomenological models and utilized one based on the following principles:

- The viscosity at typical pumping shear rates of 100 s^{-1} depends only on ϕ and ϕ_m.
- The flow pattern in typical flow situations such as pipe flow consists of a concentrated dense core with a particle depleted outer core. This pattern has been observed in slurry flow.
- The functional relationship between η, ϕ, and ϕ_m should minimize viscous energy losses during flow.
- The maximum packing, ϕ_m, includes structural information such as the geometric placement of particles which maximizes ϕ_m by smaller particles filling voids present in the loose packing structure of larger particles.

Application of these principles leads to a unique relation of the form:

$$\eta = F(\phi/\phi_m) \tag{4}$$

where

$$\eta \rightarrow \infty \text{ as } \phi/\phi_m \rightarrow 1$$

and

$$\phi/\phi_m = \text{relative packing fraction}$$

Viscoelastic Properties

In systems such as coal water slurries which can have internal structure, viscoelastic properties can be exhibited. These properties could affect the stability and the slurry breakup into ligaments upon exiting a nozzle orifice as well as the subsequent breakup of ligaments. Assume a deformation γ given by $\gamma_0 e^{i\omega t}$ where γ_0 is the maximum shear strain. Then for $\omega T << 1$, the fuel behaves like a viscous fluid.

$$\tau = \eta \gamma = i\omega\eta \gamma \quad (5)$$

However, for large frequencies, $\omega T>>1$, the fluid behaves as a solid and the shear stress is given by the theory of elasticity

$$\tau = \mu \gamma \quad (6)$$

where μ is the elastic storage modulus. For intermediate frequencies, $\omega \sim 1/T$, the stresses given by the two expressions must be of the same order of magnitude, which implies that

$$\omega\eta \sim \eta/T \sim \mu \quad \text{or} \quad \eta \sim \mu T$$

From these arguments, it is possible to develop a simple model (Maxwell model)

$$\tau = \mu \gamma /1\text{-}i/ \omega T \quad (7)$$

for which $\omega \rightarrow 0$ yields $\tau = i\omega T\mu \gamma$ and for $\omega \rightarrow \infty$ yields $\tau = \mu \gamma$ where $\eta = T\mu$ is the fluid viscosity.

The complex shear modulus, G^*, can be defined by

$$\tau = G^* \gamma \quad (8)$$

where

$$G^* = \mu / 1\text{-}i/ \omega T = G' + iG'' \quad (9)$$

with

$$G'(\omega) = \mu \omega^2 T^2 / 1+\omega^2 T^2 \quad (10)$$

$$G''(\omega) = \mu \omega T/ 1+\omega^2 T^2 \quad (11)$$

Theoretical analysis has shown that viscoelastic affects can impact the the break-up of liquid jets. Viscometric measurements on the slurries that were atomized have been performed in order to determine the relationship between G' and G" and the atomization quality. The slurries with the higher elastic component atomized poorly as compared to those slurries with the lower elastic components. [2] This is not unexpected since the break-up of ligaments or segments of fluid are caused by the growth of wave-like instabilities on the surface which is a frequency dependent phenomena. Elastic effects would be expected to inhibit fragmentation.

Extensional Viscosity

The definition of extensional viscosity can be visualized in the simple case of the uniform extension of a cylinder of an incompressible Newtonian fluid along its axis. In a cylindrical coordinate system where z is oriented along the cylinder axis and the radial dimension ir r, we may write the following for the case of symmetry about the ϕ direction:

$$\sigma_{rr} = -p + 2\mu \frac{\delta v_r}{\delta r} \quad (12)$$

$$\sigma_{\phi\phi} = -p + 2\mu \frac{v_r}{r} \quad (13)$$

$$\sigma_{zz} = -p + 2\mu \frac{\delta v_z}{\delta z} \tag{14}$$

For the stress equation where p is the hydrostatic pressure, and σ_{rr} , $\sigma_{\phi\phi}$, and σ_{zz} are the extra stresses normal to planes perpendicular to the r, ϕ, and z axis, respectively. The equation of continuity for an incompressible fluid is given by

$$\frac{v_r}{r} + \frac{\delta v_r}{\delta r} + \frac{\delta v_z}{\delta z} = 0 \tag{15}$$

We now note that

$$\sigma_{rr} + \sigma_{\phi\phi} = -2p + 2\mu \left(\frac{v_r}{r} + \frac{\delta v_r}{\delta r}\right) = -2p - 2\mu \frac{\delta v_z}{\delta z} \tag{16}$$

but since for equilibrium, $\sigma_{rr} = \sigma_{\phi\phi} = 0$, we obtain

$$p = -\mu \frac{\delta v_z}{\delta z} \tag{17}$$

Combining equation (14) and equation (17) to eliminate p yields

$$\sigma_{zz} = 3\mu \frac{\delta v_z}{\delta z} = n_e \frac{\delta v_z}{\delta z} \tag{18}$$

where n_e is defined as the extensional viscosity, which is 3μ for a Newtonian fluid. There is evidence that the extensional viscosity can have an effect on atomization.[3,4]

GOALS AND OBJECTIVES OF PROPOSED PROGRAM

As has been demonstrated, the complexity of coal slurries has prohibited obtaining a reasonable understanding of coal slurry atomization. The complex rheological behavior of many types of coal slurries requires an extensive characterization for each type of coal, each type of coal particle size distribution, chemical additive composition, and coal concentration. The relationship of these properties to the atomization process is therefore unclear and the ability to make a prediction as to whether a specific slurry will atomize well or whether a specific coal is suitable for combustion applications does not exist unless extensive testing is performed for each slurry. The overall objective of this program is to develop a phenomenological model for coal slurry atomization which has the capability of distinguishing atomization properties for different coal slurries. In order to avoid complications due to mechanical factors, the model will be developed for one type of air blast atomizer configuration.

Subsidiary technical objectives include:

- Ascertain the effect of physio-chemical properties of coal slurries on atomization.
- Ascertain the statistical influence on coal slurry atomization.
- Predict the atomized drop size of a coal slurry from a few basic coal and slurry properties.

METHODOLOGY

Extension of the Existing Phenomenological Model to Coal Slurry Rheological Properties Relevant to Atomization

The basic properties of the model are:

$$\eta_r = F(\phi/\phi_p^c) \tag{19}$$

where F(x) is a rapidly increasing function of x which represents the effect of increasing coal concentration on slurry viscosity.

Prior to extending the model to viscoelastic and extensional properties, atomization tests will be performed on several coals. All atomization will be done on Adelphi's bench scale atomization facility with one type of internal mix air atomizing system. Droplet distribution will be analyzed throughout the spray as a function of air to fuel ratio using a Malvern particle size analyzer.

The model will then be extended to the viscoelastic properties as in the following manner. Since G" represents the viscous energy it can be directly related to the viscosity of the coal slurries through the equation

$$G'' = \eta\omega \tag{20}$$

The dependence of G" on coal properties, concentration, and particle size distribution is therefore determined through the modeling of η. This will be verified and modified as needed by measurement of G" using an oscillating viscometer. In order to model G' a stepwise approach will be taken.

The rate of agglomerate formation and breakup can be expected to be different under extensional flow than under shear flow. Before this can be evaluated, sufficient data will be taken on extensional flow for three types of fluids. One will be the model slurry of glass beads in calibration fluid to verify the proportionality of η_e and η for Newtonian fluids. The second type of fluid will be a mixture of water, corn syrup, and xanthan gum which has a significant extensional viscosity. The third set of studies will be on several coal slurries with differing agglomerate structures as determined from the viscometric analysis. The measurements will be done utilizing a converging flow extensional viscometer. This viscometer is based on an analysis of converging flow which allows the derivation of extensional data from measuring the pressure drop across a converging channel and yields data at extension rates comparable to shear rates used for the viscometric studies. This type of viscometer has recently given reproducible results for a variety of fluids and is suitable for coal slurries. This will allow the phenomenological model to be extended into the extensional region.

Predictive Model for Atomization

Having determined the most important physical parameters which influence atomization as discussed previously, the last phase of the program will be directed toward formulating a predictive model for atomization.

In order to obtain a predictive model for atomization it is necessary to obtain a functional relationship between a quantity indicative of atomization such as the SMD and the relevant physical parameters such as R_e, R_e', W_e, Z, N_W, and N_D. These in turn will be dependent on the rheological model through the function $\eta(\phi,\phi_m,\gamma)$, $G'(\phi,\phi_m,\omega)$, and $\eta_e(\phi,\phi_m,\gamma_{ex})$. The form of the functional relationship between SMD and the dimensionless numbers including air to fuel ratio will be determined by energy and momentum transfer considerations the correlation studies discussed previously. The predictive nature of the model will be verified by computing parameters in the model at relevant shear rates for three coal slurries and comparing data on SMD with model predictions. Besides coal type, both coal concentration and particle size distribution (which will change ϕ_m) will be varied. The goal will be to predict the SMD through a few basic coal properties through the relationship between η_r, G', and η_e and the rheological model. Predictions will be tested over a range of air to fuel ratios.

REFERENCES

1. J. Dooher, et al., "Physio-Chemical Properties of Coal Water Gasifier Feedstock," Presented at the Fourteenth International Conference on Coal and Slurry Technology, April 1989.

2. J. Dooher, et al., "Factors Affecting Atomization of CWF," Coal Slurry Fuels Preparation and Utilization, Orlando, FL, May 1986.

3. W. Rakitsky, "Rheological Properties of Coal Water Fuels Significant for Fine Spray Production During Combustion", Third Annual Pittsburgh Coal Conference, Pittsburgh, PA, September 1986.

4. J. Dooher, D. Wildman, "A Comparison of Rheological and Atomization Data For Coal Water Mixtures and Liquid Mixtures", Fourteenth International Conference on Coal and Slurry Technology, April 1989, Clearwater, FL.

The following manuscript was unavailable at the time of publication.

PREPARING COAL FOR INDUSTRIAL BOILER RETROFIT APPLICATIONS

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The following manuscript was unavailable at the time of publication.

MICROSTRUCTURAL PARAMETERS OF COAL ASH DEPOSITS

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HIGH PERFORMANCE MATERIALS IN COAL CONVERSION/UTILIZATION

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The University of Tennessee Space Institute

INTRODUCTION

This paper describes the research being conducted at the University of Tennessee Space Institute (UTSI) on high performance materials for use in corrosive coal fired environments. Particular attention has been given to the ceramic composite manufactured by Lanxide Corporation as a potential tubular component in a recuperative high-temperature air heater.

BACKGROUND

The UTSI interests in high performance materials are related to the proof-of-concept testing of the US DOE Coal Fired Flow Facility (CFFF) magnetohydrodynamic (MHD) installation at UTSI. The achievement of the potentially high efficiency possible though MHD power generation is contingent on the ability to preheat the MHD combustion air to the neighborhood of 1371°C (2500°F)[1]. The initial MHD planning called for the development of a cumbersome cluster of ***regenerative*** high-temperature air heaters (HTAH) to achieve this goal.

Researchers at UTSI were able to perform material evaluations concurrent to the long duration MHD test series to explore the feasibilty of a ***recuperative*** HTAH for the preheating of the MHD combustion air[2]. Such an air heater would be cheaper and much simpler than a ***regenerative*** HTAH. New advanced ceramics and ceramic composites were tested as candidate materials for components in a high-pressure ***recuperative*** HTAH. These tests identified a tubular ceramic composite which indicated that it is now feasible to use a ***recuperator*** to replace the more costly and complicated ***regenerator*** HTAH concept for the MHD requirement[3].

RESEARCH EFFORTS

MHD HTAH RECUPERATOR

From 1989 through 1993, UTSI performed an extensive long duration MHD test series in the US DOE Coal-Fired Flow Facility (CFFF). Concurrent to the MHD tests, a materials testing program was conducted involving over fifteen different types of ceramic and ceramic composites. These samples were subjected to the potassium seeded exhaust from the combustion of either Montana Rosebud or Illinois #6 coal. Some tests lasted up to 300 hours and the materials were exposed in several temperature zones within the CFFF flow train. Of the materials tested only the Lanxide DIMOX™ ceramic composite survived and as a result it was tested extensively.

One, two and three inch OD Lanxide tubes were tested in lengths up to six feet long. Several of the two and three inch OD tubes were closed at one end. Over 20 Lanxide tubes were used in this study; some were cut into smaller sections to increase the amount of data collected. The most significant of these tests provided a indication of the temperature threshold for the Lanxide material. One tube survived with minor effects at a coal exhaust temperature near 2038°C (3650°F) for 247 hours while during the same test a similar tube in only approximately a 55°C higher gas temperature was severely corroded/eroded after only 179 hours. (Normally the tube temperatures were around 500°C cooler than the gas temperatures due to radiation losses.)

In addition to the exposure tests, heat transfer enhancement studies were conducted which resulted in two thesis presented for Master's of Science degrees[4,5]. This research was conducted on both straight and bayonet style heat exchanger tube configurations. The preliminary results indicated that it is possible and highly advantageous to incorporate some type of heat transfer augmentation technique in any HTAH since the costs of these material requires every effort be made to reduce the amount of heat transfer surface area needed.

Several attempts were made to provide a high pressure air seal for the exposed Lanxide tubes. One technique which offers promise and will undergo further testing involves a graphite compression fitting.

This sealing scheme was tested at a 371°C (700°F) temperature with minimal leakage at 14 ATM. At ambient temperature, the leakage was measured at less than 10 cc per hour at the same pressure..

PROPRIETARY HTAH RESEARCH

The MHD HTAH materials research has led to additional proprietary work for a foreign firm. A preliminary design report was prepared by UTSI on the air heater portion of the system and the report was based on the use of the tubular Lanxide composite in a recuperative HTAH. UTSI and Lanxide have participated in the planning for this venture.

JOINT UNIVERSITY/INDUSTRY RESEARCH GRANT

In October of 1993, UTSI was awarded a three year grant entitled, "High Performance Materials in Coal Conversion Utilization". The grant is for a joint university/industry effort under the Department of Energy (DOE) University Coal Research Program. UTSI is the prime contractor and The University of Pennsylvania and Lanxide Corporation are subcontractors.

The objective of the grant is to test, analyze, and improve the heat and coal slag corrosion resistance of Lanxide's $SiC_{(p)}/Al_2O_3$ DIMOX™ ceramic composite tubular material. The material will be evaluated for its ability to withstand the pressures, temperatures and corrosion attack which will be encountered within a coal-fired high pressure HTAH. The evaluation will include strength testing at elevated temperatures. Joining techniques and protective coatings are also being investigated.

UTSI's cost share contribution to this grant consists of upgrading an existing testing machine for the mechanical testing of ceramics at elevated temperatures. Strength tests in the testing apparatus will be conducted by the compression of C-ring sections. A computer code has been developed which determines the stresses associated with this test configuration as well as the appropriate Weibull parameters.

Under Lanxide's cost share portion of the grant, Lanxide is to provide 21 each 183 cm (six foot), 5 cm (two inch) OD $SiC_{(p)}/Al_2O_3$ DIMOX™ composite ceramic tubes for testing by UTSI. (Six of these tubes will be used to determine if different manufacturing processes can be used to improve quality and reduce manufacturing costs.) Four of the tubes have already been exposed during an MHD test in 1993 as follows:

Lanxide Ceramic Composite Tubes- Delivery #1
.52 Hours in Potassium Seeded Montana Rosebud Coal Exhaust

Tube 1.	1399°C	(2550°F)	Reducing Zone
Tube 2.	1260°C	(2300°F)	Reducing Zone
Tube 3.	1093°C	(2000°F)	Reducing Zone
Tube 4.	1149°C	(2100°F)	Oxidizing Zone

Approximately 10 liters of slag produced from Illinois # 6 coal was provided by Southern Illinois Power for the laboratory tests on the next deliveries of tubes. The slag is being pulverized to 250 μm in preparation for the exposure tests. An ash analysis was performed on this slag by UTSI with the following normalized results:

Water	2.25 %
Ash	97.75
Elemental (assumed oxide)	
Al_2O_3	16.57%
CaO	10.37
Fe_2O_3	19.79
K_2O	1.48
MgO	2.62
Na_2O	0.37
SiO_2	47.76
TiO_2	0.85
SO_3	0.19
Total	100.00%

Two UTSI furnaces have been equipped with temperature controllers. One will be used to heat clean tubes and the other will be for exposing the tubes to pulverized coal slag during the heating process. The "exposed" tube furnace has been modified to accommodate a video camera and a compressed time video taping will document the slag deposits on the test tube. An automated slag dispersal system was added to the furnace so that a fresh layer of ground coal slag can be sprinkled on the tube every hour. (See figure 1).

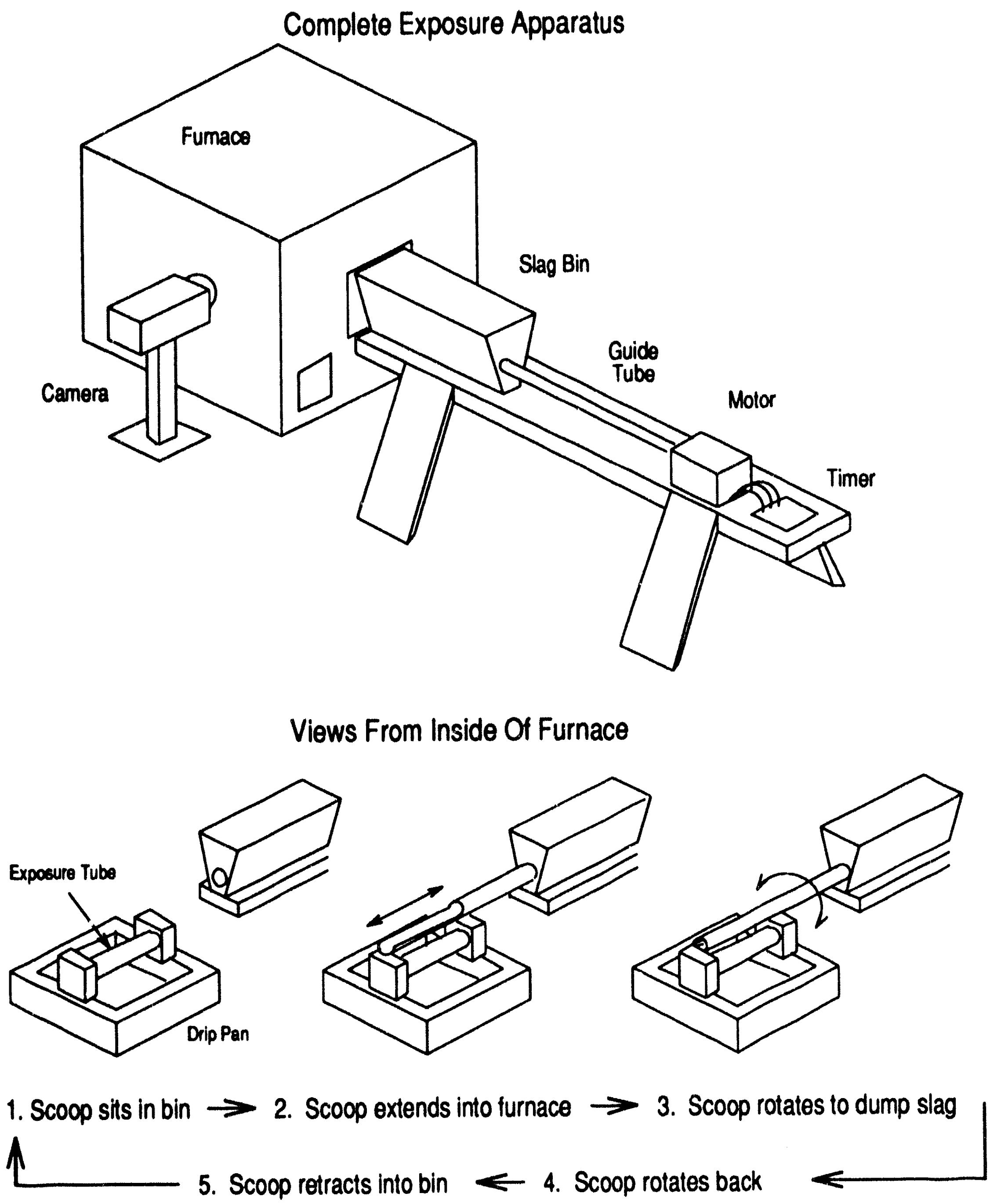


FIGURE 1.

Slag Dispersal System for Bench Scale Exposure Testing

The furnaces will be heated for 200 hours a 1100°C (2012°F), 1260°C (2498°F), or 1400°C (2696°F) for the test series matrix.

Research into the identification of suitable protective coatings based on thermodynamic considerations and the development of techniques for their application as well as joining ceramic materials has been initiated by UTSI. An aluminum coating will be applied to a Lanxide $SiC_{(p)}/Al_2O_3$ composite via physical vapor deposition which will then be heat treated to oxidize. A laser will then be used to surface treat the coating to enhance the bonding between the surface coating and the composite substrate. The effect of various wavelengths (CO_2= 10.6 μm, Nd-YAG= 1.06 μm and excimer= 248 nm) and modes (pulse or continuous) of operation on the bonding characteristics will be evaluated. The microstructure of the coating will be studied by SEM, EDS, and X-Ray mapping. The adherence of the coating will be evaluated and if warranted the sample will be exposed to heated slag and strength tested.

Preliminary attempts to develop a concept and establish a general procedure for laser joining of monolithic SiC ceramics and $SiC_{(f)}/SiC$ matrix and $C_{(f)}/SiC$ matrix ceramic composites have been conducted with reasonable success. The ceramic materials have been joined with a titanium-base interface reactant material. The joints thus created are believed to possess properties compatible to those of the base ceramic materials. The joining was conducted in air with high traverse speeds ranging from 1500 mm/min to 3500 mm/min using a pulse width modulated (PWM) CO_2 laser (10.6 μm) beam at suitable power levels (350-700 watts). Based on these initial trials, it appears that the laser joining techniques for ceramics holds great promise and can be developed further for a variety of ceramic materials.

The University of Pennsylvania is acquiring a code for the thermodynamic analysis of the UTSI tests to predict the corrosive effects of exposure to coal slag. The code is their cost share portion of their subcontract.

CONCLUSION

The experience that UTSI has acquired in several years of testing of the $SiC(p)/Al_2O_3$ ceramic composite manufactured by Lanxide Corporation has lead to proprietary HTAH work for a foreign firm and a three year grant from the US DOE. The results of this research by UTSI and others indicate that once the Lanxide material is more fully characterized, it may be possible to construct a high-pressure high-temperature recuperative air heater for use in an externally fired combined cycle and any other system that requires high temperature air from a corrosive high temperature energy source.

REFERENCES

1. Thompson, T. R., Boss,W.H., Chapman, J.N., "Application of High Temperature Air Heaters to Advanced Power Generation Cycles", DOE/ET/10815-178; UTSI, 1992.

2. Winkler, J. , Dahotre, N.B., Boss, W.H., "Evaluation of a Candidate Material for a Coal-Fired Magnetohydrodynamic (MHD) High Temperature Recuperative Air Heater", DOE/ET/10815-203; UTSI, 1992.

3. Boss, W. H., Babu, S., "An Investigation Into the Feasibility of a Radiant Recuperative Air Heater for a Magnetohydrodynamic/Steam Power Plant", DOE/ET/10815-139; UTSI, 1990.

4. Knollenberg, P.J., "Experimental Investigation of Convection Enhancement by Inlet Swirl in a Bayonet Heat Exchanger", MS Thesis; UTSI, 1992.

5. Dash, D., "Heat Transfer Studies in a Double Pipe Bayonet Tube Heat Exchanger", MS Thesis; UTSI, 1994.

DEVELOPMENT OF A ROTARY COMBUSTOR FOR REFIRING PULVERIZED COAL BOILERS. by Michael J. Virr (Spinheat Ltd)

The company has investigated the feasibility of using the ROTARY COMBUSTOR (RC) as a replacement for the conventional pulverized coal burners on utility and industrial boilers while burning coal to low emissions. The effort is focused on the design, manufacture and testing of a prototype burner to be tested and demonstrated at Detroit Stoker Company's test facility.

2.BACKGROUND AND TECHNICAL DESCRIPTION.

SPINHEATS's new ROTARY COMBUSTOR enables a utility not only to REPOWER but REFIRE an existing coal-fired furnace or boiler with a single, more efficient low pollution device that replaces the present burners and all the pulverized coal equipment and scrubbers, while keeping all the rest of the power plant intact.

Conventional coal boilers are equipped with pulverized coal dispersion burners which are inefficient insofar as they are power intensive, require expensive coal pulverization, necessitate the application of expensive scrubbers to reduce SOx emissions and produce flue gases with undesirably high NOx levels. Furthermore, NOx levels are typically reduced by replacing the burners with low-NOx units and injecting ammonia or urea, but the solutions are expensive and it is admitted that ammonia slip causes fumes to escape up the stack.

In an effort to overcome the the disadvantages of conventional coal burners and to provide a more environmentally acceptable means to produce energy from coal , SPINHEAT has investigated the use of rotating combustors as burners in coal fired boilers based on early work by Professor Douglas Elliott at Aston University and the author in the late seventies. The present invention (US patent #5,070,821) relates to a novel burner which is fitted to the standard boiler where coal is combusted efficiently to produce steam with considerably reduced SOx and NOx emissions.

2.1 TECHNICAL DESCRIPTION.

The Rotary Combustor is simply a rotary drum (see Fig.1 Schematic) into which coal and limestone are fed through a screw and thrown to the inside of the drum. The drum supports a porous distributor plate, and the particles are suspended in the stream of air that flows through the distributor. Because the coal and limestone are being thrown outward by centripetal force, the air can be blown at a much greater velocity before particles are lost which in turn gives a greater combustion intensity than the conventional combustor, which in turn allows the unit to be much smaller in size.

The RC is run at less than the full combustion air flow to the drum which, with a little water injection, causes a low BTU gas to be formed from the partial combustion of the coal. This gas flows, while still highly reducing, through the DeNOx firetube where its temperature is raised by injection of secondary air. The rise in temperature dissociates the NOx precursors into nitrogen and water vapor before the gas combustion is completed downstream in the main flame. The low BTU gas passes into the conventional boiler furnace where it is completely fired by tertiary air in the normal way. As the coal flame occurs in the furnace, in a similar fashion to the normal coal flame, the performance of the furnace is maintained, but with the sulfur absorbed by the limestone and the fuel-bound nitrogen already fixed.

The sulfur in the coal is absorbed in the traditional fluid bed manner by feeding limestone (calcium carbonate) with the coal through the inlet feed screw that calcines to the oxide in the suspended bed, which is controlled at the optimum temperature range of 1600-1650oF. The very reactive calcium oxide then reacts with the freed sulfur to form calcium sulfide in the reducing atmosphere of the bed. The particles of calcium sulfide, together with the coal ash, then spill over the weir at the end of bed, into the centrifuge part of the spinning drum, where they drop into the ash hopper. From where the spent particles are transferred into an oxidizing fluid bed of the normal type used on fluid bed boilers. In this manner, a high proportion of the sulfur will be removed from the coal before the resultant low BTU gas is even burned within the combustion chamber of the furnace. Experience in CFB's when working with similar particle sizes, higher velocities and a little longer residence times under a reducing atmosphere, has demonstrated that for the high sulfur coals, sulfur retention of 95-96% is possible. The air/gas residence time in the RC is shorter, but due to the higher reaction rates experienced in high gravity fluid beds, it is expected that similar sulfur retention will be achieved. It is one of the objectives of this project to demonstrate this.

The NOx emission is controlled by the arrangement of staged combustion between the rotary gasifier and the main combustion chamber. The fuel-bound nitrogen is the only nitrogen which will tend to form the NOx precursors at these temperatures(about 1600oF).

When gasifying, the nitrogen in the fuel will tend to form ammonia and a little HCN, ammonia in the range of 200-3000 ppmv. However in the firetube the temperature is raised to a high temperature at which the NH_3 will dissociate into nitrogen and water vapor. This has been advocated by Professor Jon Beer at MIT.

In this fashion the nitrogen is fixed before the final combustion and it is expected that the NOx (NO_2 and NO) emissions will certainly be below 100 ppmv and maybe below 25ppmv. This is a significant order of magnitude less than a regular pulverized coal burner, which normally generates NOx in the range of 350-450 ppmv.

In addition, because the final flame temperature experienced is in a typical combustion chamber of a pulverized coal furnace (above 2000oF), the formation of N_2O will be suppressed and be of the order of 10 ppmv or less. This is an order of magnitude less than that experienced from AFB's or CFB's, which typically generate about 100 ppmv.

The power consumption of a regular pulverized coal milling plant is greatly reduced as the RC will accept coal feed sized in the range of 1/4" x 0. The prototype will use coal of 1/8" x 0 due to the small size feed screw. This dispenses with the fine milling equipment, since only crushing is required. As the fine mills are large power consumers, a significant saving in parasitic power is achieved, increasing total saleable power by 2 to 2.5%.

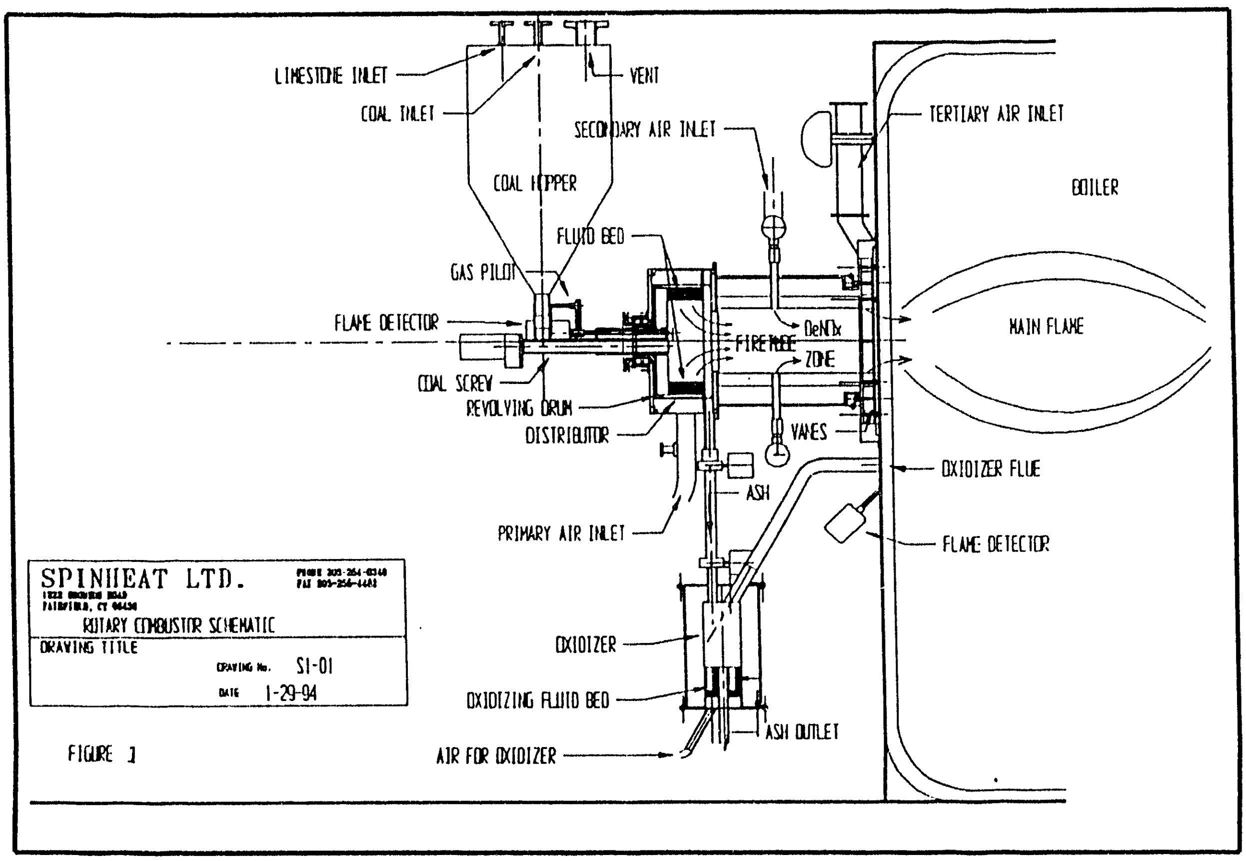
Also, because the final combustion flame is completed in a conventional furnace, the flame temperature may rise to its adiabatic limit if allowed by furnace design. Therefore, advanced steam or air cycles maybe utilized with the RC burners, enabling advanced cycles to be employed (in excess of 1100oF in the case of steam). Thus, high overall cycle efficiencies are possible. This is especially true because removing most of the ash at the burners reduces the chance of slagging on the final superheaters and resulting high temperature corrosion. In this way , RC burners may be employed on new, high efficiency, advanced cycle power plant in excess of 40% overall efficiency (HHV).

The patent for the "Rotary Fluid bed gasifier for boilers and furnaces" was published by the US Patent Office on December 10, 1991. Patent number 5,070,821.
Further protection is being sought for some of the practical advanced features of the RC.

3.1 DESIGN SPECIFICATIONS.

The rotary combustor firing rate was chosen to meet the test rig maximum (design) coal flow rate capacity of 500 lbs/hr. At this fuel flowrate the rotary combustor has a firing rate of 6.5mBTU/hr assuming the Allegheney coal with a heating value of 13,000BTU/lb. The rotary gasifier bed area was calculated by fixing the air flowrate to 40% of that required for stoichiometric combustion, the hot gas exciting the bed at 1600oF and a superficial bed actual velocity of 15 ft/sec.

Using the geometric parameters for the rotating bed a mathematical relationship was developed between the bed diameter to length (D/L) ratio and the distributor plate total flow area. This simple relationship enabled the bed diameter (D) to be calculated for various D/L ratios for various areas. This resulted in the selection of a Rotary Gasifier section of 18"diameter by 8"long as shown in Fig.1 below.



4.1 MATHEMATICAL MODELLING.

The mathematical modelling came in two parts; the first one for physically modelling the basic bed parameters in the rotating gasifer and the second the chemical modelling of the gases and temperatures in the gasifier,firetube DeNOX section and main flame using the CHEMEQ program.

4.2 PHYSICAL MODELLING.

The main purpose of this work is to select the physical size of the rotating fluidbed gasifier so that the bed particles do not elutriate until the coal is burnt up and the limestone reacted by either calcining or forming calcium sulfide. The fuel and limestone in the rotating bed breaks down into LASH (limestone and ash) in the range of 400-600 microns and the purpose of this exercise was to see that those particles would stay in the bed at the centripetal accelerations and gas velocities we were using. This was done by calculating the terminal velocities at the appropriate "g" force or acceleration that would be experienced at the radius of the fluid bed surface and again at a radius two inchs above that surface. A study of Fig.2 shows the size of particles that would be elutriated from the surface and two inchs above that for limestone and coal. It can be seen that particles above 390 microns for coal and 270 microns for limestone should be retained in the bed.

4.3 CHEMICAL MODELLING

The chemical modelling was carried out using the chemical equilibrium compositions program known as CHEMEQ which was originally developed by Gordon and Mc Bride at NASA for rocket jets.

The purpose of this modelling was as follows:

1. Calculate the chemical composition of gases in the three burner sections, namely immediately after the gasifier, after the secondary air injection and in the main burner flame. The purpose is to compare results with known air blown gasifiers and ensure a stable fuel gas would result.
2. Calculate the temperature at each stage to ensure good control in the gasifier, suitable temperatures in the firetube for NOx precursor dissociation and main flame stability.
3. Study the effects of limestone and steam and/or water injection.
4. Ensure the formation of calcium sulfide in the gasifier.

The main design condition gases of CO,CO2,H2O,N2,SO2 and H2 are shown in fig.3. This gas is very similar to other fluid bed gasifier gases which have a calorific value in the range of 130-150 BTU/ft3. These gases are known to be stable in normal burner registers. We confirmed that the sulfur all reports in the gasifier to CaS.

The theory of fuel NOx reduction in the burner in this burner is to drive the temperature up in the firetube by intoducing a little air while the fuel gas is still reducing in order to dissociate any NH3 or CHN which may have formed in the gasifier. This is well modelled by Loftus and Beer in the report on the development of an "Industrial Pulverized coal Low-Nox Burner" draft technical report on Phase I of the report performed under Contract No. DE-AC-92PC92152.
A detailed examination of the Chemeq data at the design condition shows that some 8-18ppm of NH3 and 9-14ppm of HCN will be generated in the gasifier respectively.
However by driving the temperature in the firetube up to 3130oF while still reducing causes a reduction of NH3 to 0.165ppm and HCN to .018ppm so this model confirms the theory.
Depending on the time experienced before mixing in the main flame this burner can expect a similar reduction. The main flame was modelled at an excess air rate of 25%. However, careful mixing of the air and fuel gas core must be acheived to avoid thermal NOx having fixed the fuel bound nitrogen.

5.1 COLD MODEL

A cold model was designed a little less than half scale with an 8" diameter rotationg bed (prototype size 18"dia.). In order to prove the general principal of the stationary equipment tube, two cantilevered bearings, seals and fuel feed screw the equipment tube. Seals and bearings were sized at 80% of full size (3.5"dia). By establishing a model so closely representing the prototype is was possible to to test the viability of the mechanical design with particular respect to bearings and seals. The resultant model (see photograph) was made with the bearing assembly, pulley drive and rotating fluid bed drive plate being machined from solid aluminium stock.

5.2 MODEL TESTS.

The model was set up with air supply from three "ShopVac" blowers for fluidization air. This enabled us to fluidize graded sand at velocities similar to those to be utilized in the hot prototype.

The bed was loaded with sand (425-650 microns) up to a static bed depth of 1" (resulting in about 1.25-1.5" fluidized) and the bed pressure drop measured at the equivalent accelerations of 6G,8G,10G,12G and 15G at velocites approaching 8ft/sec. This is shown on Fig.4.

These curves are interesting in that they show a pronounced hump before flattening into the characteristic flat end of the curve where the fluid bed is at a constant pressure drop with increased velocity. A similar shaped curve had been seen at Aston University. The explanation is that the bed fluidizes in layers. The inside portion, which is at a lower acceleration or "G" force first, fluidizes first. When the whole of the deep bed is fluidized then the flat part of the curve starts. These experiments proved that no significant bed elutriation occured at these velocities until a "G" force of 6 was experinced. This confirmed the data generated in the mathematical model and confirms that we should be able to retain bed LASH at accelerations of 8G or over.

6.0 ANTICIPATED BENEFITS

The capital costs of fitting a 500MW boiler with RC burners has been calculated with each burner costing about $550,000. This study shows that the capital cost of the RC burner installation will be the order of $110/KW installed.
This compares to some $200-250/KW for wet scrubbers and about $100-$125/KW for lowNOx burners.

The running cost of the RC burner is increased insofar as the limestone has to be supplied. This works out at 0.1 to 0.15 mills depending on the usage (Ca/S mole ratio) with the limestone costed at $50/ton.

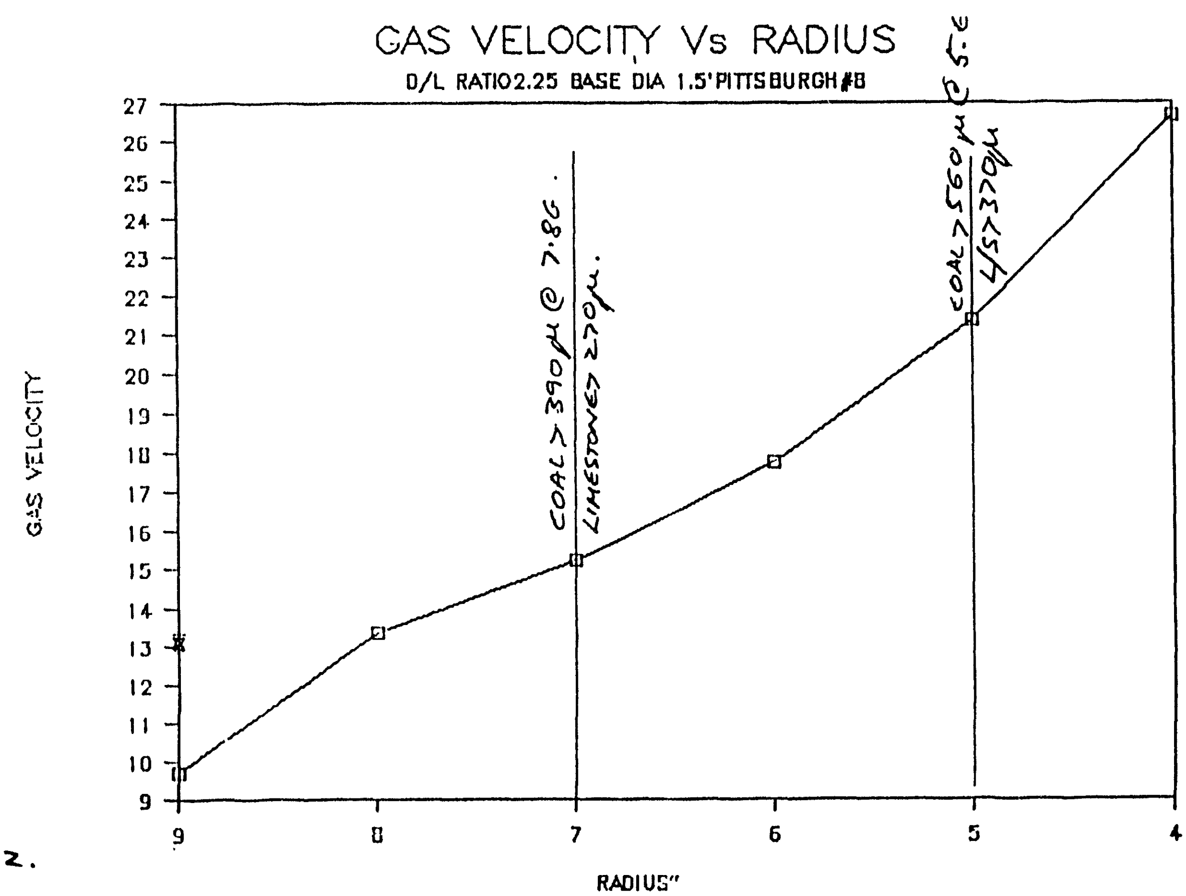


FIG 2.

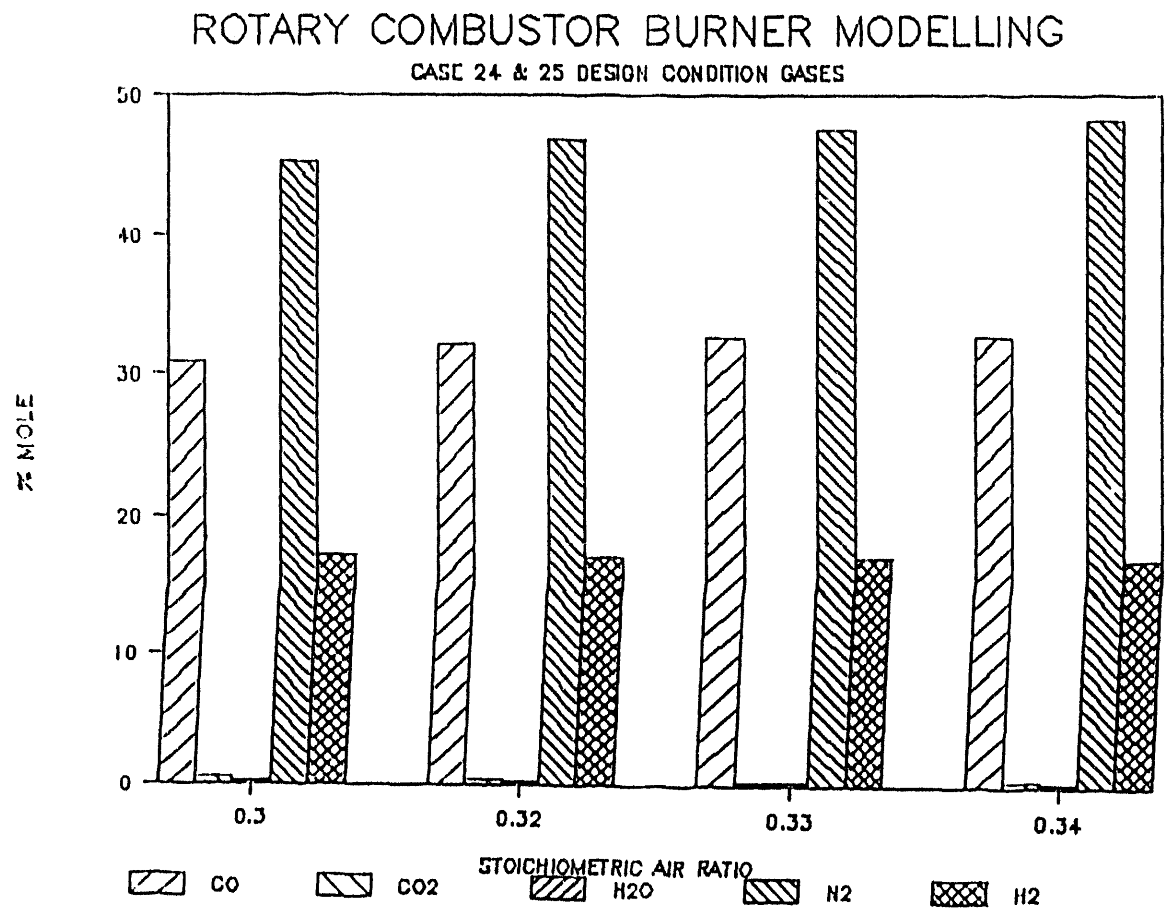

ROTARY COMBUSTOR BURNER MODELLING
CASE 24 & 25 DESIGN CONDITION GASES
% MOLE
50
40
30
20
10
0
0.3
0.32
0.33
0.34
STOICHIOMETRIC AIR RATIO
CO
CO2
H2O
N2
H2

FIG 3

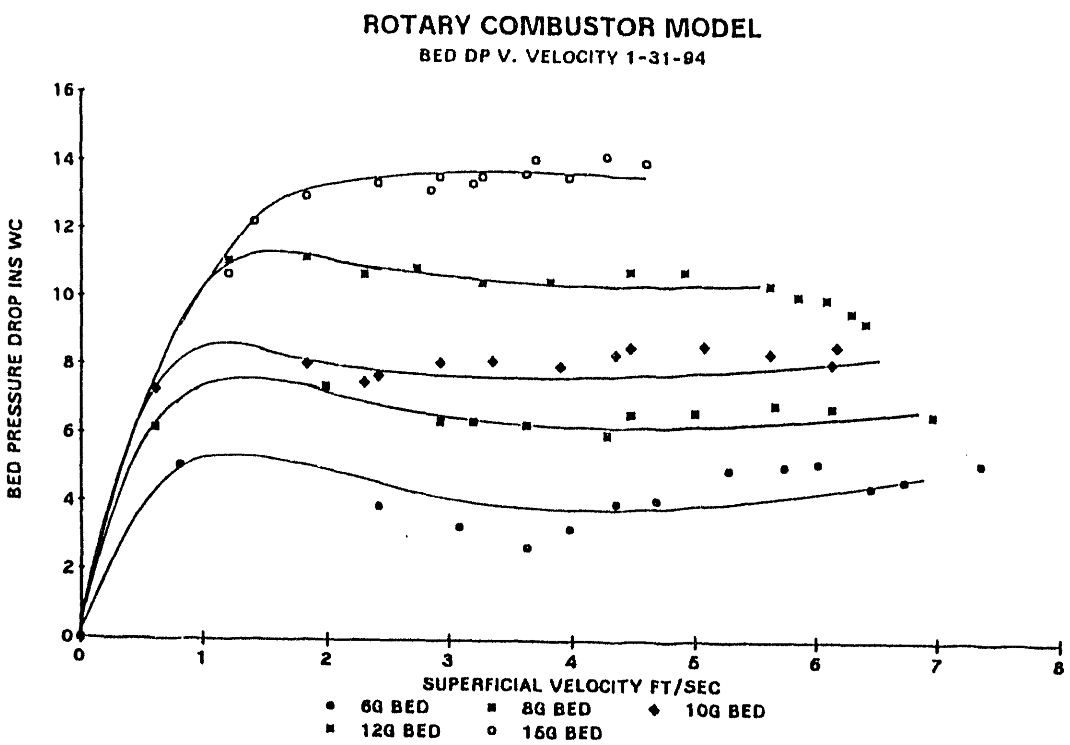

ROTARY COMBUSTOR MODEL
BED DP V. VELOCITY 1-31-94
BED PRESSURE DROP INS WC
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
SUPERFICIAL VELOCITY FT/SEC
6G BED
8G BED
10G BED
12G BED
15G BED

FIG 4

The following manuscript was unavailable at the time of publication.

COMMERCIAL AND INDUSTRIAL BOILER MODIFICATION PROGRAM

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Please contact author(s) for a copy of this paper.

PARTICULATE EMISSION ABATEMENT FOR KRAKOW BOILER HOUSES

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Introduction

Environmental clean-up and pollution control are considered foremost national priorities in Poland. More than four decades of centralized planning has produced serious contamination of air, water, and soil throughout the country and a resulting deterioration of public health. As a result, life expectancy is lower today than it was 20 years ago. Also, incidents of serious disease in adults and young children there have been on the rise. It is therefore, imperative that corrective action be taken.

The government of Poland has begun to implement strong environmental controls to reverse this condition. The target of these controls is the Polish coal industry, which currently comprises over 78% of primary energy production (65% hard coal and 13% lignite). The coal utilization, especially in low grade coals, is highly inefficient. For example, Poland uses almost three times as much energy as Western Europe per unit of gross domestic product (GDP). In many cases, coal combustors have no pollution controls. Moreover, most have relatively low stacks and release emissions relatively close to the ground, further aggravating the problem. The result is that concentrations of airborne dust have been found to be many times higher than the maximum safe level.

The City of Krakow, one of the world's great cultural centers, has a serious problem with airborne pollutants. These emissions are discharged from stacks burning coal, mainly unwashed. This paper discusses one of the projects initiated by the Department of Energy for environmental cleanup in Krakow. This particular project involves an efficient control technology for mitigation of particulate emissions. The technology is referred to as the *Core Separator*, and it has been under development by LSR Technologies, Inc. in the U.S.A.

Environmental Conditions in Krakow

The priceless monuments in the City of Krakow have experienced severe environmental damage in recent years. The damage is caused primarily by airborne pollutants emanating from the combustion of hard coal and coke in so called Low Emission Sources(LES). Fossil fuels are used heavily for heating purposes during the winter season. The 750,000 population in Krakow relies heavily on hard coal as the heating source. About 35% of the heating needs is provided by some 2,900 local boilers, often with low efficiency cyclones for particulate removal and no sulfur abatement technologies. These boilers consume yearly an estimated 370,000 tons of coal and coke. As a result, the combination of coal combustion and the city's location in a valley having a temperature inversion, quite often a heavy suspended smog is visible over Krakow.

A major portion of heating needs is provided by district heating supplied with heat from local power plants, Leg and Skawina. These plants have high stacks that dilute and distribute pollutants over large areas. The primary cause of low ambient air quality in Krakow is from suspended particles and SO_2 emissions. SO_2 pollution is generated to a large extent (some 47%) from the neighboring Upper Silesian Industrial Region, while the balance comes from Krakow industry and power sectors (some 18%) and Low Emission Sources (35%). The picture is, however, quite different with particulate matter. Low Emission Sources are almost entirely responsible for suspended particulate matter in the ambient air in Krakow.

"Suspended particles" are those with a size less than 10 µm in diameter that do not fall to the ground from the force of gravity. These particles are in the respirable range, i.e., they have potential for accumulating in the lungs of humans causing respiratory disease. The quality of Krakow air is continuously measured by a network of Automatic Ambient Air Monitoring Stations. The instantaneous/real time concentrations of SO_2, CO, suspended dust, and NO_2 in the ambient air are monitored continuously. The 30-minute (D_{30}) and daily (D_{24}) average concentrations for each pollutant are plotted and tabulated. From this, the actual pollutant measurements can be compared with permissible values. According to Polish Law, Krakow is located in a "protected area." For designated protected areas, the permissible concentrations of the main air pollutants are given in Table 1.

Table 1 Allowable Concentrations- Pollutants in Ambient Air Protected Areas of Poland

Pollutant	30-Minute Concentration D_{30} µg/m^3	Daily Average Concentration D_{30} µg/m^3
SO_2	600	200
NO_2	500	150
CO	5000	1000
Suspended Particles	**250**	**120**
O_3	100	30

It is of particular interest to compare measurements of suspended particulate concentrations in both the winter and summer seasons. Figures 1 and 2 show measurements taken at one monitoring station in February 1993 and in July/August 1993. In these figures, it is immediately apparent that: (1) concentrations are significantly higher in winter during the heating season, and (2) concentrations in wintertime very often exceed the permissible values from Table 1. The same correlation can be observed in other air pollutants from coal combustion such as sulphur dioxide and carbon monoxide. The conclusion in each case is unmistakable, that LES used during the heating season are responsible for this situation.

Abatement Options for Dust Emissions

In order to improve ambient air quality in Krakow, the discharge of emissions during the heating season must be reduced. A few ways have been identified to limit particulate emissions from LES. Conversion of coal/coke boilers to natural gas and connection of some heated areas to the district heating network are a couple of examples. Also in this category are improvements in energy saving measures in buildings, which would reduce fuel consumption. In the long run though, it is unlikely that coal combustion in local boilerhouses in Krakow will be entirely eliminated.

The Ordinance of the Polish Ministry of Environmental Protection recently promulgated emission standards for combustion sources. The values have become more stringent for travelling grate boilers fired with hard coal, and much lower for coke and other firing systems. The deadline to comply with these limits was set for the beginning of 1998. In addition, the local voivod environmental standards will likely be even more stringent than that of the Polish Ministry. Existing pollution control equipment (mainly cyclones) is not likely to meet future regulations for dust mitigation in Krakow. Utilization of smokeless fuel or bag filters are possible options, but both are rather costly. The novel *Core Separator* technology developed by LSR Technologies can meet these regulations for either new or existing boilers. This technology is described in more detail in the following section.

Principle of Operation

The *Core Separator* is a new technology developed through research sponsored by the Department of Energy and Environmental Protection Agency. Some *Core Separator* units have been placed in commercial operation in the U.S. All of the units now in service are performing difficult separations, i.e., those involving dust particles with small aerodynamic diameters. Historically, mechanical separators have been ineffective in removing dust particles with diameters below 10 microns. In comparison, the *Core Separator* is able to remove a high percentage of particles even at 2-3 microns in diameter. This is roughly equivalent to the performance of a medium-efficiency electrostatic precipitator (ESP).

A simplified schematic of the *Core Separator* system is shown in Figure 3. The system includes two conventional components, a cyclone collector for extracting solids and a fan for flow recirculation. The *Core Separator* is actually a multitude of cylindrical units. Each unit has a single inlet for the stream to be treated and two outlets, one for the cleaned gas stream and the other containing a highly concentrated recirculation stream. The dust-laden recirculation stream is fed to the cyclone and then returns again by means of the fan. The processes of separation and

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collection are accomplished separately 'n different components. The *Core Separator* cleans the inlet stream and detains dust particles in the system. Since its efficiency is quite high, the dust particles cannot leave the system. They recirculate again and again until collected in the cyclone.

Two factors govern the performance of *Core Separator* systems: (1) a high separation efficiency of the *Core Separator*, and (2) an interaction between individual components. To achieve high separation efficiency, a proper recirculation flow is required. By varying recirculation flow in the *Core Separator*, the tangential and radial velocities can be controlled independently to maintain them in the proper range.

The *Core Separator* System can be arranged in a variety of configurations depending on process conditions, required performance, inlet dust concentration, abrasiveness of solids, etc. The *Core Separator* component actually predetermines the efficiency of the system even if the collector efficiency is low. The following formula can be used to calculate partial collection efficiency when the collector is situated downstream of the *Core Separator*,

$$E_{sys} = \frac{E_{cs} \times E_{cyc}}{1 - E_{cs}\left(1 - E_{cyc}\right)}$$

When the collector is situated upstream of the *Core Separator*,

$$E_{sys} = \frac{E_{cyc}}{1 - E_{cs}\left(1 - E_{cyc}\right)}$$

Here E_{CS}, E_{cyc} and E_{sys} relate to the *Core Separator*, collector and *Core Separator* system partial separation efficiencies, respectively.

The *Core Separator* has been under development since 1989. During its research, numerous laboratory and field prototypes were built and tested. In 1992, the Riley Stoker Corporation installed a *Core Separator* unit to remove flyash from their PC-fired Combustor Test Facility. Test results obtained by Riley showed the particulate removal efficiency to range between 95 and 98% over a series of several controlled tests. Several *Core Separator* units have also been sold on a commercial basis in the U.S. and abroad. These units range in size from 500 - 7,000 ACFM (850 - 11,900 NM^3/h), and each perform difficult separations, i.e., those removing dust particles with small aerodynamic diameters. The boiler houses in Krakow are of a comparable scale to the *Core Separator* units currently in operation. Thus, the major development concerns and technology unknowns include:

(1) Performance with Polish Coals
(2) Performance with Crushed Coal Feed Systems

During this project, six demonstration units will be placed in operation in the City of Krakow in 1994-1995. These units will demonstrate the performance of this technology with Polish coals and different boiler firing systems.

Emissions Reduction Potential and Impact on Heating Cost

The City of Krakow has about 1300 boiler houses providing heat for industrial, commercial, and residential use. The boiler houses contain about 2250 boilers, some with no emission controls at all. Many boilers are equipped with cyclone collectors, which remove about 80% of the total particulates. High efficiency collectors such as bagfilter units and electrostatic precipitators are practically non-existent due to their high cost and maintenance requirements.

The cost of emission reduction options requires a careful economic analysis. It is unlikely that any one option is best in all cases. In this section, attention will focus on ways to modernize boiler houses through the addition of particulate control equipment. The choices considered include:

- Addition of Cyclone Collectors
- Addition of Bagfilter Units
- Addition of *Core Separator* Systems

A cost analysis was performed based on data for particulate control equipment sold in the U.S. Table 3 provides a cost comparison of cyclones, pulse-jet bagfilters, reverse-air bagfilters, and the *Core Separator.* Cost data for the *Core Separator* was based on historical costs, whereas data for cyclones and bagfilters were based on recently completed studies by the Electric Power Research Institute (EPRI). The capacities shown in this table are typical of boiler capacities throughout the City of Krakow.

It is also interesting to compare the cost and respective benefit of each of these alternatives. As shown in Table 4, conventional cyclones provide the lowest cost per ton of pollutant removal. However, this criterion is not normally used in the U.S. or EC nations, since (1) cyclones cannot meet most regulatory standards, and (2) the incremental cost of higher efficiency increases sharply. For this reason, the penetration of the pollutant into the atmosphere is more meaningful. Such a comparison reveals that the *Core Separator* costs a little more than twice that of an equivalent sized cyclone, but allows only about 1/5 of the total penetration of solids to the atmosphere. It also has the ability to meet future emission standards in Poland, which may not be within reach of cyclones.

The *Core Separator* is well suited to particulate emissions from LES in Krakow due to the following attributes:

- Cost-effectiveness even at boiler capacities below 500 kw

- Efficiency in removing respirable (PM_{10}) particles

In addition to the 1300 boiler houses in the City of Krakow, the region has many other industries requiring fine particle control equipment.

Conclusion

The U.S. and Polish Bilateral Steering Committee with the assistance of DOE contractors have identified specific methods to improve air quality and reduce emissions throughout the city. These include:

- Extensions to the district heating system to eliminate many small uncontrolled boilers
- Conversion of hand-fired boilers to natural gas
- Elimination of home stoves in selected parts of the city
- Use of improved home stove designs
- Modernization of boiler houses to reduce emissions

This project addresses modernization of boiler houses through the application of new technology recently developed in the U.S. for particulate emissions. The technology is well-suited to the industrial size boilers located in Southern Poland and is capable of removing dust particles below 10 microns in diameter, the so called PM-10 emissions. Its performance is almost as good as ESPs and fabric filters, but without the attendant cost and maintenance. In small boiler applications such as those in Central Europe, it may be the Best Available Control Technology (BACT).

Acknowledgement

The authors would like to thank Mr. Douglas Gyorke for his guidance in preparing this paper and the Department of Energy for supporting this important project.

References

Informacja nr 2/93 i nr 7-8/93 o poziomie zanieczyszczenia powietrza w lutym i lipcu/sierpniu 1993 w Krakowie. Publication of Environmental Protection Office at Krakow Voivodship.

Ordinance of the Ministry of Environmental Protection Natural Resources and Forestry of 12th February 1990 on Protection of Air Against Pollution. Poland.

Krakow Development Office Publication by Janusz Bardel, Jan Bieda and others.Personal Communication with Janusz Bardel from Krakow Development Office, 1994.

Pierce, Barbara L. and Butcher, Thomas A., "Krakow Clean Fossil Fuels and Energy Efficiency Project," Ninth Annual Coal Preparation, Utilization, and Environmental Control Contractors Conference, U.S. Dept. of Energy, July 19-22, 1993.

Smolensky, L.A., Easom, B.H. and Wysk S.R., "A *Core Separator* System for Fine Particulate Removal," Eighth Annual Coal Preparation, Utilization, and Environmental Control Contractors Conference, U.S. Dept. of Energy, July 27-30, 1992.

Smolensky, L.A., Wysk, S.R. and Murison, A., "Novel Particulate Control for Industrial Gas Cleaning," Filtration and Separation, January/February 1993

Monthly Suspended Dust Concentrations

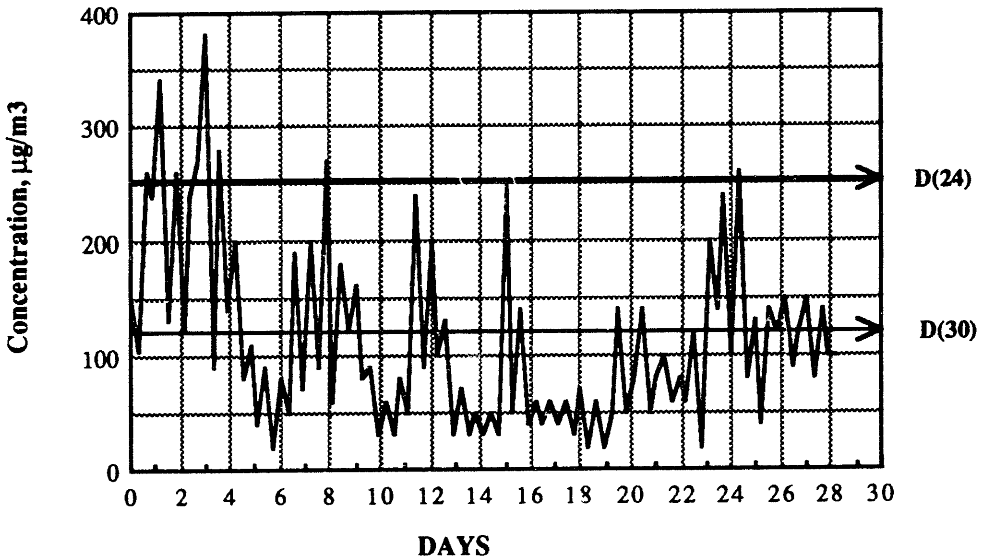

Fig.1 Transient Concentrations - Suspended Air, µg/m3
Krakow February 1993

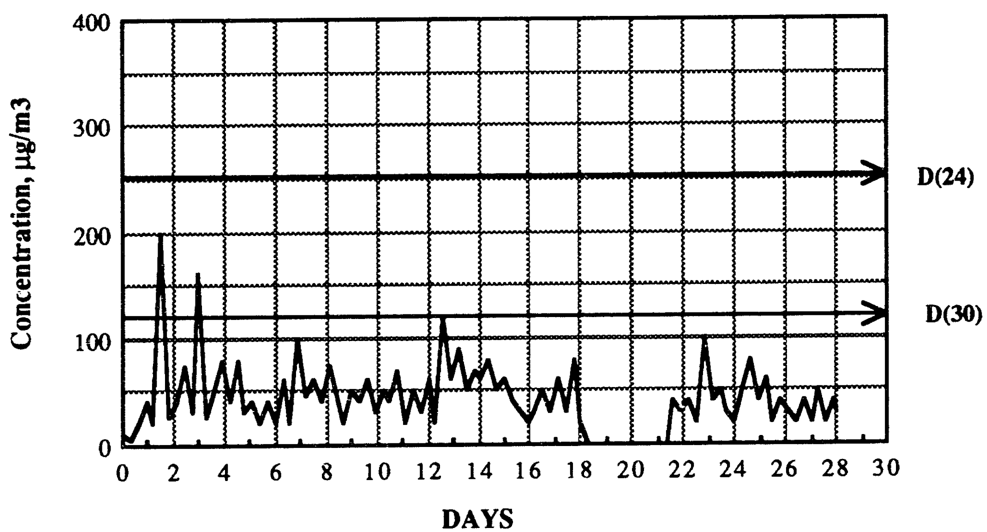

Fig.2 Transient Concentrations - Suspended Air, µg/m3
Krakow July/August 1993

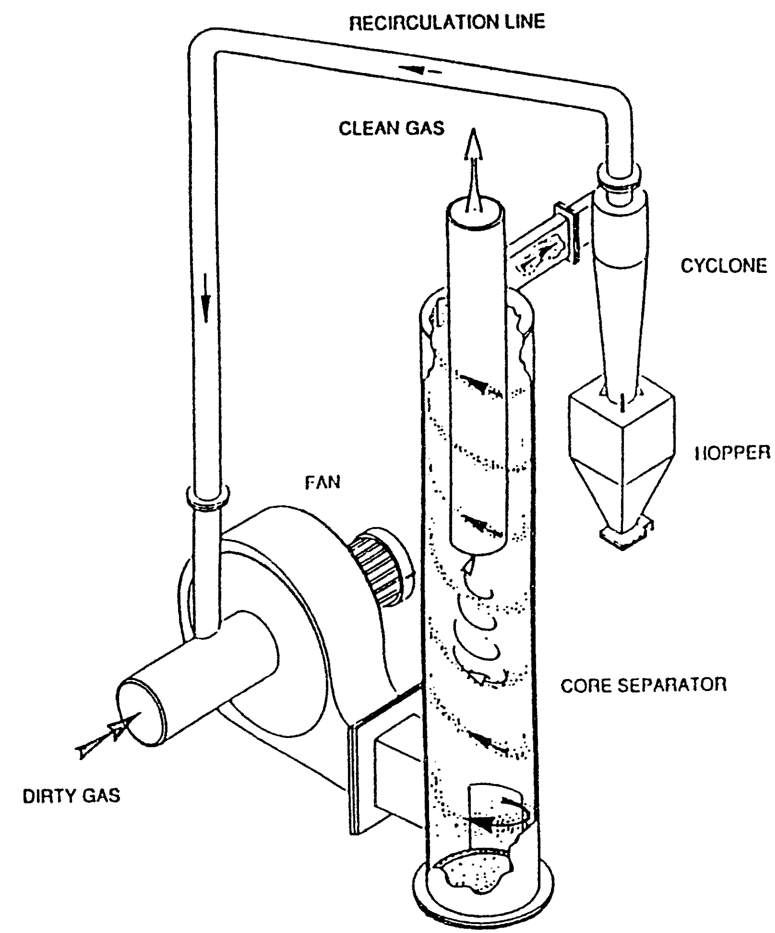

Fig. 3 Simplified Arrangement - Core Separator System

Table 2 Total Installed Cost - Particulate Control Devices

Size or Capacity		*Device Type*			
Gas Flow ACFM	Thermal Input KW	Cyclone $/ACFM ($/KW)	Pulse Jet Baghouse $/ACFM ($/KW)	Reverse Air Baghouse $/ACFM ($/KW)	Core Separator $/ACFM ($/KW)
1,000	342	1.68 (4.90)	24.68 (72.16)	38.20 (111.69)	4.20 (12.28)
2,500	856	1.53 (4.47)	19.88 (58.06)	30.77 (89.86)	4.01 (11.71)
5,000	1,710	1.43 (4.18)	16.88 (49.35)	26.13 (76.39)	3.87 (11.32)
10,000	3,420	1.34 (3.92)	14.33 (41.90)	22.18 (64.85)	3.74 (10.93)
15,000	5,130	1.29 (3.77)	13.02 (38.07)	20.15 (58.91)	3.67 (10.73)

Basis: (1) Boiler Heat Rate 12,500 BTU/KWH
(2) Baghouse Data "Sloat, D.G., et al 1991 EPRI Particulate Control Symposium
(3) Cyclone Data "Vatavuk, W.M., Chemical Engineering, May 1990
(4) Core Separator Data from Historic Costs

Table 3
Cost/Benefit Comparison - Particulate Control Equipment

	Cyclone	*Core Separator*	Baghouse
Overall Collection Efficiency, %	75 - 85	94 - 98	98.0 - 99.9
PM10 Collection Efficiency, % (particles < 10 μm)	20	94	99.5
Cost ($/acfm)	1.34	3.74	14.33
Cost ($/PPH solids removal)*	27.87	64.93	239.12
Cost ($/PPH PM10 solids removal)**	558.38	331.51	1200.14

* Based on 7 gr/acfm solids loading
** Based on 1.4 gr/acfm PM10 solids loading

EXTENSION OF THE CENTRAL DISTRICT HEATING SYSTEM

KRAKOW, POLAND
KRAKOW CLEAN FOSSIL FUELS AND ENERGY EFFICIENCY PROGRAM

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Summary

It is generally agreed that centralized district heating systems, when coupled with electricity generation (cogeneration), represent one of the most energy efficient approaches to providing space and process heat in urban areas. Centralization in turn affords the opportunity to cost-effectively limit emissions. Minimized primary fuel consumption and maximized pollution control makes expanding the use of district heat a very desirable approach toward urban air quality improvement.

The planned DOE-supported project addresses Pilot Project 1 of the Krakow Clean Fossil Fuels and Energy Efficient Program - extension of the central station district heating system into the Koniewa area, to eliminate local boiler houses. This Project Area is considered by most to be the most cost-effective area within the DOE/Krakow program. The project will be particularly effective because the large boilers to be eliminated are antiquated, with very low-quality particulate removal systems. Moreover, unlike other areas of the city, Koniewa is relatively open and easy to work in, and many of the institutions to be converted to district heat are centrally owned and/or operated, reducing administrative difficulties.

Our scope of work is to design and construct new portions of the heating system network, to enable the abandonment of existing local boilers. Prior to final design, we shall perform exhaustive engineering evaluations of alternative pipe types, burial techniques, and energy conservation and control features, such as variable speed pumping and controls. Our goal is to achieve, in a pilot project sense, a piece of heating system network expansion that is state-of-the-art in its energy efficiency and cost-effectiveness.

At the same time, the project team will carefully develop the economic and legal framework knowledge necessary for the development of a commercially-viable business entity in Krakow. This entity, which presumably will be started as a joint venture, will ultimately perform district heating system expansion and upgrade work elsewhere in Krakow and Poland. It will be formed of project team members, and others as applicable, and will offer engineering and contracting services throughout the region.

Background on Shooshanian Engineering

Shooshanian Engineering Associates, Inc., located in Boston, Massachusetts, is a mechanical and electrical engineering firm specializing in study, design, and construction services for the following systems for commercial, industrial, and institutional clients:

- Heating Systems
- Piping Systems
- Ventilating Systems
- Air Conditioning Systems
- Electrical Systems
- Telecommunications Wiring
- Security Systems
- Energy Conservation Systems
- Fire Protection Systems
- Sanitary Systems
- Refrigeration Systems

Founded in 1961, Shooshanian Engineering Associates is one of New England's largest mechanical and electrical engineering firms. Shooshanian employs a staff of 90 which includes professional engineers, designers, draftspersons, construction administrators, computer applications specialists, and energy conservation and management experts.

Shooshanian Engineering Associates has been involved in the international arena since the early 1970s, providing mechanical and electrical engineering consulting services to governments, corporations, and architects worldwide.

We are committed to the project for the following reasons:

- We are active in the international marketplace and have been pursuing work in central Europe for three years. We are pursuing other projects in Krakow also.
- We are committed, as a firm, to develop cost-effective applications of environmentally friendly technologies. Energy conservation is an area of significant concentration for us.

Other Team Members

Our partners, POLINVEST and MPEC, are ideally suited for this project. POLINVEST will perform financial and legal analysis, while MPEC, as owner of the system, will be intimately involved with the planning of its extension. POLINVEST and MPEC have a strong pre-existing business relationship. POLINVEST is a small but growing entrepreneurial enterprise and is very eager to develop this component of their business. MPEC would like to increase their market share in Krakow, and would thus like to continue its expansion.

The Project

Scope

Our planned project addresses Pilot Project No. 1 - Extend Central Station District Heating. In conjunction with our partners, MPEC and POLINVEST, Ltd., we will extend the existing district heating and piping network into the Koniewa district of Krakow. This scope also includes finding methods to increase the efficiency of heat distribution and methods to incorporate conservation measures in the district heating system. As a pilot project, this work will serve as the basis for future heating network expansions, both in Krakow and elsewhere in Poland and in central and eastern Europe. If successful, the project team will create a formal joint venture in Poland for the pursuit of this work.

Emissions reductions are achieved by eliminating local coal- and coke-fired boiler houses, providing the heat instead by far less polluting and more efficient cogeneration plants. Ample excess heat capacity exists in these cogeneration plants, and they are also equipped with pollution control equipment. Moreover, our work will include optimization of all components of the network expansion (pipe insulation, heat exchangers, variable flow, instrumentation and automation), to further reduce coal consumption and associated emissions. The objective is a major improvement in the air quality of Koniewa, needed to protect the health of its inhabitants and visitors. Once complete, the process can be repeated in other parts of the city, country, and region.

Local boilers will be demolished, removed, or abandoned in place. The largest of the boilers might be left on-line for peaking service, but this will be avoided. Existing independent hot water circuits will be connected to the network through new heat exchangers, to prevent network water from coming in contact with individual building piping and to improve overall control. A Polish contracting firm will do the construction work.

Our technical approach comprises very comprehensive analyses of the existing system and circumstances in Krakow. Shooshanian Engineering brings substantial experience with underground piping, hydronic systems and controls, and historical renovation work. POLINVEST is extremely well qualified in the evaluation of local legal and economic conditions, for the development of our partnership into a long-term viable commercial enterprise. MPEC, as a system owner/operator, brings the experience of decades of work with the system. Its highly qualified engineers will bring great knowledge and insight to the project.

The project is to be carried out in two phases. The first phase will consist of detailed technical and economic feasibility studies to determine optimum system design, and to identify the most appropriate investment strategy. At this time, it is anticipated that the conclusion of Phase I will involve the retirement of 4 large boilers with a combined capacity of 13.0 MW. The second phase will involve the retirement of 5 boilers with a combined power output of 5.5 MW. The feasibility studies may modify these plans, however, depending on the results.

The commercial entity anticipated as a result of this pilot project will be either a design firm (consulting) or a design/build firm (engineering and construction). It will be comprised of both American and Polish partners, and will be occupied primarily with the expansion and modernization of district heating systems in Poland and throughout central and eastern Europe. Revenues will be generated by charging for the labor and materials expended in each project. Funds will be supplied by a combination of the district heating companies, consumers (residential and commercial) brought onto the networks, and third party investors.

Detailed definition of the commercial approach will develop as the project progresses. Initially, costs will be shared by the project team and DOE. It is desired, however, that other investors eventually become involved. A detailed economic feasibility study will be carried out early in the project. The results of this study will form the basis of organizing third party investors, such as equipment suppliers, construction firms, or banks. In addition, MPEC will try to involve the owners of the boilers being liquidated in the financing of the project.

One of the crucial components of this pilot phase of the work is to develop the financial and legal framework necessary to cost-effectively expand the network. At present, by order of the President of Krakow, the owners of local coal-fired boilers must either install environmental regulatory equipment or eliminate the boilers by the year 1997. Hook-up to MPEC's system represents one of the possible solutions for these owners, and at this time it appears that the costs per individual participation in the network extension are comparable to those of installing pollution control equipment or converting to gas. However, most individual boiler owners do not have the financial means for any of the above.

The activities supported by DOE funds consist of the technical and economic study, design, and installation of a pilot state-of-the-art system extension project in the Koniewa district, for the purposes of reducing pollution and increasing the efficiency with which primary energy (coal) is consumed. When complete, the work will enable the project team to continue system extensions elsewhere in Krakow and throughout Poland and Europe. Construction techniques, energy efficient system features, implementation costs, and funding strategies will have been identified and optimized to ensure financially viable future ventures.

Rationale

From a technical standpoint, extending the network into Koniewa is fully feasible. In fact, Koniewa was chosen for this pilot project partly because of its relatively open and accessible terrain. It is also something of a recreational area, with a student housing campus and tennis courts. Further boosting feasibility is the fact that the existing network was designed with reserve capacity in this area, in anticipation of eventual expansion.

There are ten large coal-fired boilers in the Koniewa region, as well as a large number of buildings heated by unitary local coal furnaces. The boilers to be eliminated are generally old and without pollution control equipment, thereby greatly enhancing the potential for pollution reduction in the area. Future heat will be generated by efficient cogeneration plants that are fully equipped with pollution control equipment. The stated objective of the program - to reduce pollution in the Krakow area - will clearly be attained.

Based on the measurements taken and results presented during earlier phases of work associated with the Krakow Clean Fossil Fuels and Energy Efficiency Program, we estimate a total pollution reduction potential of roughly 130,000 pounds per year in the subject region associated only with the 18.5 MW of large boilers to be eliminated, with that amount again attributable to smaller residential stoves to be rendered obsolete. Our projection of total reductions in particulates, CO, NO_x, and organics connected with this proposed project therefore total 260,000 pounds per year.

Alternative approaches would include converting the existing boilers to gas or electric heat. The pollution reduction objective would be achieved in both cases, but neither would make as efficient use of primary fuel as the project proposed herein, so in the long run neither would be as cost-effective.

Heating network extension is by far the most effective and cost-efficient strategy for reducing pollution in Krakow. The cost per unit of pollution reduction is over an order of magnitude lower than that of the other options. This is because the main sources of low emissions - unitary coal-fired boilers and furnaces without pollution control - are eliminated, while the new sources of heat energy are very energy efficient and are equipped with substantial pollution control equipment. As part of our scope of work, we intend to calculate in detail what the reduction will be in Koniewa of each affected pollutant.

We anticipate, again on a preliminary basis, the following individual pollutant reductions:

Tons per Year	
Particulates	54
CO	39
NO_x	22
SO_2	14
Hydrocarbons	1
TOTAL	130

As for heating costs, in the future the heat will be generated by efficient cogeneration plants, having the net effect of reducing the coal required to heat the water. In theory, therefore, the cost of heat could go down or stay the same. However, the price of heat is already below what it should be based on the cost of producing it. The price must go up, regardless, and our analysis will include the determination of market-based heating price increases. By extending the district heating network, cleaner air and greater efficiency will be achieved at the lowest overall life cycle cost.

It is our full intent to maintain the highest standards of environmental protection, health, and safety throughout the course of this work, and we will do our utmost to comply with all applicable regulations.

Strategy

Our strategy in this project is multi-faceted, but it all centers around one key objective - to build a state-of-the-art network segment that is well-received by customers and highly cost-effective. To achieve this, we will begin with exhaustive analysis of technical and economic issues that will impact the final form of the work. Technical studies will include, but are not limited to, the following:

- Develop design criteria including distribution temperature, pressure, velocity, maximum allowable pressure drops, etc.

- Compare alternative pipe types, minimum wall thicknesses, insulation types, insulation thickness, covering type, burial method (tunnels, conduit, direct buried, above-ground), etc. Establish optimum piping system type for use in this project.

- Establish optimum expansion absorption strategies for this application, considering heat pre-stressing, expansion loops, and various mechanical compensator types (bellows, slip, ball joint, etc.).

- Develop criteria for maximum allowable pipe stress values and other stress limits for piping components (including pressure, temperature, ambient influences, dynamic effects, weight effects, thermal expansion and contraction loads).

- Develop criteria for placement of manholes, isolation valves, anchors, pipe and component supports, guides, drain points, air venting points, natural and mechanical expansion devices, etc., building on experience gained elsewhere in the system and on modern design practices.
- Determine feasibility and technical requirements for variable speed pumping applications in the new piping segment(s). Consider where secondary/tertiary loops would be appropriate and what would be required within pumping stations.

- Establish desired control parameters (e.g. flow, valve position, temperature, temperature differential, monitoring points, etc.). Determine if new controls will stand alone or be integrated into existing control system. Establish communications medium (radio, powerline carrier, twisted pair, fiber optic cable, etc.)

- Evaluate options for building interfaces, including metering strategies, heat exchanger types, valving schemes, electrical isolation flanges, and locations for each of the above.

- Provide test and operational data as available regarding emissions from existing boilers and power plants (e.g. Łeg, Skawina), so that Shooshanian can calculate and document changes in emissions resulting from this project on a boiler-by-boiler basis.

- Identify environmental impacts of construction activities, permitting needs, and safety requirements.

- Define soil environment for buried pipe systems including maximum soil loading, assessment of soil pH, electrical conductivity and chemical content.

- Determine appropriate cathodic protection schemes for underground piping system (pipe, fittings, anchors, electrical isolation flanges) to lengthen their useful lives in corrosive underground environments. Consider photovoltaics if lengthy grid extensions represent significant costs.

  The following schemes shall be examined at a minimum:

  a) Sacrificial anode systems

  b) Rectifier systems, both grid and photovoltaically powered.

- Perform ongoing economic analysis, developing cost-effectiveness criteria throughout. Establish projections for future returns on investment.

Economic studies will include, but are not limited to, the following:

- Cost of Delivering Heat

  Provide report detailing the full current and anticipated cost of delivering heat via MPEC's system. Cost items include:

  a) Fuel
  b) Electricity (pumping power)
  c) Depreciation
  d) Maintenance
  e) Labor
  f) Other (taxes, capital improvements, etc.)

- System Ownership Issues

  Provide report describing the lines of ownership of system components. Hot water is generated primarily from waste heat at Łęg, Skawina, Solway and Nova Huta power plants. Do the large heat exchangers and pumps belong to MPEC? Does MPEC buy the heat and/or participate in power plant coal purchases?

  Similarly, does MPEC own smaller boilers not directly connected to the central system, or participate in the fuel purchases and maintenance of these boilers? Does MPEC own piping and heat exchangers in end users' facilities? What ownership issues arise when MPEC hooks into a new building?

- Pricing Regulations

  As a public utility, MPEC is undoubtedly subject to public regulations pertaining to pricing. How does this process work? What is the procedure for MPEC to raise rates? Are billings done monthly? Who designs the rate structure, and how would a potential system of incentives (for hookup to the system) be decided upon?

- 1997 Environmental Regulations and Cost Implications

  Provide a complete description of the emissions reduction regulations, going into effect in 1997, that affect the boiler owners we will be dealing with. Describe what they must do to comply, what it will cost, what will happen if they do not comply, and how likely it is the regulations will be enforced.

- Boiler Ownership Issues

  Who owns the boilers that we are planning to eliminate in Koniewa? Is anyone making money through their operation? Who buys the fuel, and who does the operation and maintenance? Do the boilers have any salvage value, and if so, who would receive the proceeds if they were sold?

- Easement Issues

  As the piping system is expanded, will any special permit requirements or other legalities arise before excavation can take place for pipe burial?

- Public Bidding Requirements

  To ensure fair contractor pricing, DOE has strongly requested that all construction work be competitively bid. Are there regulations governing public bidding, as there are in the United States, such as advertising requirements, a period for public comment, prevailing wage laws, equal opportunity, etc? If so, we would like them summarized, along with their economic and procedural impact on the project.

- Long-Term Pricing Strategies

In order for MPEC to be economically viable as it expands while providing ongoing service, its rates must cover capital and operating costs. A long-term plan for how to establish and structure rates that ensure cost recovery is necessary not only for planning purposes, but also to attract potential investors.

Reasonable strategies are those that will meet no significant opposition from regulators, will be accepted by customers, will attract new customers to the system, and will generate profits. Structure can be either demand-oriented or consumption-oriented, depending on the nature of the operation, and on what is acceptable to customers and regulators. Consideration should also be given to interest rates, inflation, and equipment depreciation in the determination of long-term pricing strategies.

- Environmental Costs

Although this project will greatly reduce air pollution in Krakow, there may still be environment-related costs associated with it that should be considered in the economic analysis and planning. Examples include additional pollution control equipment at Łęg, boiler water treatment, disposal of additional boiler blowdown, disposal of additional cooling tower blowdown, etc., all made necessary by the added system load.

- Cash Flow Options

Expansion of the system, now and in the future, will require cash to pay for materials and installation labor (and possibly incentives as well). Without a large savings account, this needed cash may not always be available. Options for financing include local private lenders, public grants, and foreign grants and lenders. Discuss the applicability and desirability, along with likely repayment terms, of each reasonable option.

- Insurance Needs

Describe the insurance climate in Krakow, and the types and costs of insurance that MPEC needs to carry as they pertain to this project. This again is a cost that needs to be figured in the overall picture.

- Taxes

Is MPEC required to pay taxes on fuel purchases and/or its revenues? Are its customers (private residential, private commercial, public) required to pay taxes on purchased energy? If so, how much?

- Funding Sources

How can we inform potential investors, both domestic and foreign, of the opportunity that this project and future related projects have to offer? Shall we do a mailing, develop media advertising, or prepare listings for EBRD, World Bank, or related agency publications? How do we present the relevant information?

- Future Customers

Present day boiler owners and independent heat consumers are going to have to be convinced of the benefits and advantages of connecting to the district heating system. This is particularly true if purchased heat is more expensive (by the kilowatthour or kilocalorie, as it is likely to be) than self-generated heat.

It will be necessary to market the benefits of maintenance, space, cleanliness, and pollution reduction to the future system users. A user survey will be helpful, and a media campaign may be appropriate. Coordination with the Hart Industries project is essential.

The purpose of this study is to develop a marketing strategy of maximum effectiveness directed towards future customers.

- Investment Analysis

When individuals and organizations consider investing in the future Krakow heating system, they will compare the investment with others available to them in terms of likely return, potential return, liquidity, guarantees/insurance, and so forth. This study aims to develop and present a range of feasible scenarios for these investors to evaluate, in order to prepare for the eventual true offering.

- Structure of the Offering

  There are many ways that investors can provide financing. They can provide direct loans with fixed or variable interest rates, or they can purchase shares of stock, becoming owners and participating directly in the operation and return. The many structuring options need to be developed and evaluated, so that an approach can be decided upon that will be both very effective and in MPEC's best interest.

- Carrot Versus Stick Options

  Discussions with boiler owners have thus far centered around the issue of compliance with air pollution reduction regulations. More specifically, potential heat customers are informed that if they do not hook into the district heating system, they will have to implement costly modifications to their boiler plants in order to be in compliance with the law. This argument (the "stick" approach) has been used to try to convince boiler owners to participate financially in the expansion of the heating system. While the argument is sound, most boiler owners do not have the financial strength to come up with the necessary capital to proceed in either direction.

  Rather than a disincentive to do nothing, MPEC could offer an incentive to hook up ("carrot" approach). This incentive could take the form of up-front cash credit, reduced rates for an initial period of time, and/or conservation products and services (e.g. insulation, clock thermostats, etc.) that will help control consumption and thus reduce costs. Shooshanian will provide general information about various types of incentive programs that have been used in the United States. POLINVEST will provide input regarding which types of incentives would be applicable in Krakow, how they would be structured, how the approval process would work, and how the system would be publicized and implemented. We will also investigate any incentivization procedure(s) that has been considered that would apply uniquely to Krakow.

- Cash Flow

  The only way that any business can function is with a positive cash flow, or a negative cash flow that is limited to a relatively short period of time. In any analysis of incentive structures, any present-day disbursement of MPEC funds would have to be justified by expected future revenues and profits. The magnitude of any incentives would be a function of the expected return. The same would hold true for any third-party investors.

  This study will prepare a cash flow analysis for any reasonable options developed in the previous study.

- Existing Rates and Costs

  Boiler owners will be faced with a number of options in the years ahead. They can continue their present operation, maintaining and modifying equipment as needed to keep it operational and legal. They can convert to oil, gas or electricity, which presumably would drive up fuel costs but reduce maintenance and emissions. Finally, they can join the MPEC system.

  A key factor in the decision-making process is the relative costs, and effective negotiations by MPEC and POLINVEST will require a complete understanding of the financial aspects of each option.

  This phase of work asks that POLINVEST study and report upon existing energy pricing structures for different customer types (e.g. residential, commercial, industrial). In other words, what does it currently costs to heat an apartment building with coal, gas, electricity and MPEC heat? How easy is it to switch over to gas or to electricity, and who pays? Are there other incentives?

  This is essentially a study of the competition, necessary to strengthen, as much as possible, our own negotiating position.

- Future Rates

  Forecasting has never been an exact science, but it is necessary nonetheless to make educated decisions. In the case of negotiations, forecasts can be used to strengthen a position.

  This study asks POLINVEST to research trends in energy costs in Poland, and develop a position for MPEC, particularly regarding the nature and magnitude of future rates.

An argument could be made that increased cogeneration as well as economies of scale could make MPEC heat less expensive in the long run than self-generated heat. We will investigate the validity of this argument.

Projected Outcome

The outcome of this work will have three components:

- Heating network expansion
- Pollution reduction
- Joint venture

Network Expansion - the new, state-of-the-art network segments will conserve energy by making greater use of power plant waste heat, and by eliminating old, inefficient local boilers. It will also deliver heat to the new customers in a highly efficient manner, minimizing pumping costs, friction loss, and heat loss. Instrumentation, controls, and metering will be state-of-the-art also, allowing MPEC to deliver only as much heat as is needed, and allowing customers to pay for only as much heat as is used.

The new customers will enlarge MPEC's customer base, allowing them to spread fixed costs over a larger number of individual users. It will also increase MPEC's revenues, and ultimately its profits.

Pollution Reduction - Several factors conspire to render this project particularly attractive from the standpoint of pollution abatement.

a) The existing power generation equipment is outfitted with high exhaust stacks and pollution control equipment, while the boilers to be retired have neither. This leads to lower, less densely concentrated levels of pollution.

b) Waste heat is currently created at the generating station during periods of imbalanced demand for electricity and heat, while remote boilers are simultaneously being operated to deliver heat to buildings not connected to the network. Tying them into the district hot water system will eliminate many of these "unbalanced capacity" pollutants at the generating station.

c) Although yet to be verified, the power plant boiler system almost certainly enjoys higher combustion efficiency than the remote stations. Even taking into account distribution losses, central heating is likely to be the more efficient consumer of source energy.

d) The retirement of local boiler plants will also eliminate the need for coal delivery to these sites, leading to reduced traffic and, admittedly relatively small, automotive emissions in the Koniewa district.

Joint Venture - The successful development of this joint venture will require careful strategic planning, detailed financial and operational analysis, and ongoing management commitment.

At a minimum, we will provide technical, economic, and legal consulting services to district heating utilities in Poland who are contemplating expanding their network and/or making it more efficient. At a maximum, we will also provide labor, materials, and funding to achieve the same, and expand to areas outside of Poland. The business would be a private, for-profit joint venture with minority U.S. ownership.

We are sending teams of engineers to Krakow regularly to gather information and data for our studies and pre-design activities. We are very excited about the work, and are doing our utmost to ensure a successful outcome.

The following manuscript was unavailable at the time of publication.

INSTALLATION OF A STOKER COAL PREPARATION PLANT IN KRAKOW

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Please contact author(s) for a copy of this paper.

The following manuscript was unavailable at the time of publication.

EMISSIONS REDUCTION THROUGH DISTRICT HEATING IMPROVEMENTS

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THE KRAKÓW LOW EMISSIONS COAL BRIQUETTE PROJECT

David F. Natschke and Dr. Wojciech Jozewicz

Acurex Environmental Corporation

INTRODUCTION

Kraków, the third largest city in Poland, is severely polluted because of a vigorous expansion program during the 1950s, transboundary pollution from the upper Silesia region, and a heavy reliance on coal for heat. In large part, Kraków is heated by district heating systems, small boiler houses, and residential stoves. Surveys conducted by the U.S. Department of Energy (DOE) have found that there are 100,000 residential stoves burning approximately 132,000 tons of coal each year. Though small individually, residential stoves are significant contributors to Kraków's pollution. DOE estimates that 68 percent of emitted hydrocarbons are produced by residential stoves.

Residential stoves and small boiler houses are particularly difficult to control because of the following:

- Standard post-combustion controls are not cost-effective for small installations
- Installations of < 0.2 MW (i.e., all residential stoves) are exempt from Poland's pollution standards, fees, and penalties
- Pollution reduction through combustion condition modification may not be permitted by building codes

The Acurex briquette addresses residential stove pollution by providing an alternative solid fuel that reduces particulate, organic, and sulfur dioxide emissions yet may be used without any capital equipment changes by the consumer. In the coming two years, this project will develop a formulation using Polish raw materials; test this briquette in residential stoves, small boiler houses, and large scale units; and modernize an existing plant to produce these briquettes.

BACKGROUND

The Acurex briquette is based on a physical admixture of washed coal fines and a proprietary, non-combustible binder. This binder is unique in that it has an active role in reducing emissions during combustion. During burning, the binder provides a solid matrix that physically separates the combustion process from the coal gasification process.

Figure 1 summarizes results to date. A study was performed by Acurex Environmental (Lutes et al.) in which a chunk coal was burned as received and as briquetted with our binder. Filter samples were collected and after weighing for particulate determination, they were extracted with dichloromethane. These extracts were analyzed gravimetrically (GRAV) and by GC/FID for total chromatographable organics (TCO) and benzo(a)pyrene (BAP). Reactive gases—oxygen, carbon dioxide, carbon monoxide, and nitric oxide—were also analyzed with continuous emission monitors as per U.S. Environmental Protection Agency (EPA) methods. Sulfur dioxide was also attempted; however, because of instrumental problems, the data failed to meet quality assurance standards. Nitrous oxide was analyzed by an automated, on-line GC/ECD technique.

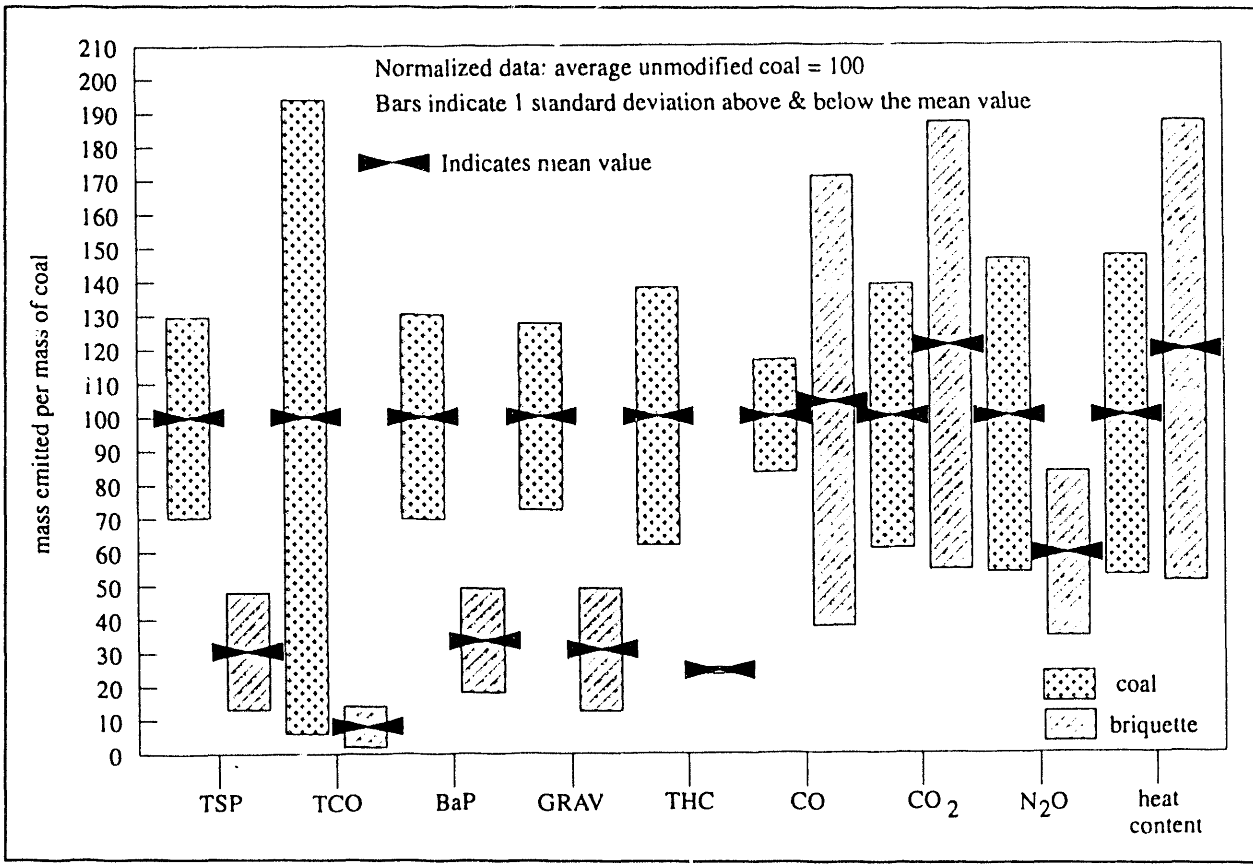

Figure 1. Comparison of coal and briquette with reproducibility data.

In this figure, THC stands for total hydrocarbons, TSP stands for total solid particulate. TCO is defined as the sum of organic material with boiling points between 98 and 300 degrees centigrade whereas GRAV is defined as those compounds greater than 300 degrees centigrade. These data have been calculated back to the original coal content to remove the binder's dilution effect and have been normalized to the chunk coal's average data. Each bar represents one standard deviation about the mean for replicate burns. Nitric oxide data are not presented because there was little change from baseline values for either fuels. The heating content is a calculated value based on fuel weight loss and flue gas temperature, humidity, and volume.

It should be noted that particulate and all organic pollutant markers are significantly reduced (approximately 70 percent) without loss of heating value. Although carbon monoxide, carbon dioxide, and heating value are not statistically differentiable, when viewed in concert, they are consistent with a more efficient combustion model. Unlike many other materials used as binders, ours is non-combustible. The binder forms a solid matrix that does not flake off or break away during combustion. Thus, particulate emissions are reduced by physical occlusion of the ash within the binder. Although the mechanism of organic reduction is not clear, we believe that the coal gases must diffuse through the hot matrix to reach the combustion zone. This diffusion process would result in a relatively long residence time during which cracking to simpler molecules may occur. If true, smaller molecules entering combustion implies more efficient combustion and smaller molecular products.

Table 1 presents an estimate of the Acurex briquette's impact on the pollution in Kraków. This is based on DOE's spreadsheet model of Kraków coal use. The first column presents DOE's estimates for winter of 1992. Since then, cheap, high sulfur coal has entered the residential market; the second column is our estimate of the impact this has made. The table is referenced to this column. Notably, this single change has increased residential sulfur dioxide by nearly 500 tons per year. The last three columns represent an increasing presence of the Acurex briquette on the residential market. At 50 percent market penetration, we estimate that about a fourth of the hydrocarbons, a tenth of the particulate, and a twelfth of the sulfur dioxide will be removed from Kraków's atmosphere.

TABLE 1. COMPARISON OF ACUREX BRIQUETTE TO PREVIOUS YEARS

	Winter 1992	Winter 1993	15% market	25% market	50% market
Consumer annual costs	$55,715,318	$60,907,923	$61,023,743	$61,100,956	$61,293,989
Difference	($5,192,606)	$0	$115,820	$193,033	$386,066
Consumer SO_2, tons	7842	8326	8125	7991	7655
SO_2 removed, tons	484	0	201	335	671
$ per ton SO_2 removed	($10,719)	--	$575	$575	$575
Consumer particulate, tons	10952	10952	10641	10433	9914
Particulate removed, tons	0	0	312	519	1039
$ per ton particulate removed	--	--	$372	$372	$372
Consumer hydrocarbons, tons	134.1	134.1	124.7	118.5	102.9
Hydrocarbons removed, tons	0	0	9	16	31
$ per ton hydrocarbons removed	--	--	$12,373	$12,373	$12,373

Winter 1993 used as baseline for comparisons; 60 % of market High Sulfur (1.23 %) coal

CURRENT PROJECT

The current project, Cooperative Agreement No. DE-FC22-94PC94116, is an agreement between Acurex Environmental Corporation and DOE to establish a briquetting company in Poland that will supply low-emitting coal briquettes to the Kraków market. Acurex Environmental will produce the Acurex briquette, utilizing washed coal fines for sulfur dioxide reduction, and target the LES market. This agreement, signed in March 1994, is a part of DOE's Kraków Clean Fossil Fuels and Energy Efficiency Program. Acurex Environmental has put together an American/Polish project team, shown Figure 2, that addresses the project's requirements. Planmar consulting Inc. of Durham, North Carolina will be responsible for market investigation and business development. Przedsiebiorstwo Energetyki Cieplnej (PEC) is the senior Polish partner and a district heat supplier. Through them, we have established agreements with KWK Jankowice, a coal mine and briquetting plant; Akademia Gorniczo-Hutnicza (AMM), briquetting and combustion laboratories and INCO Veritas, a small industrial boiler house.

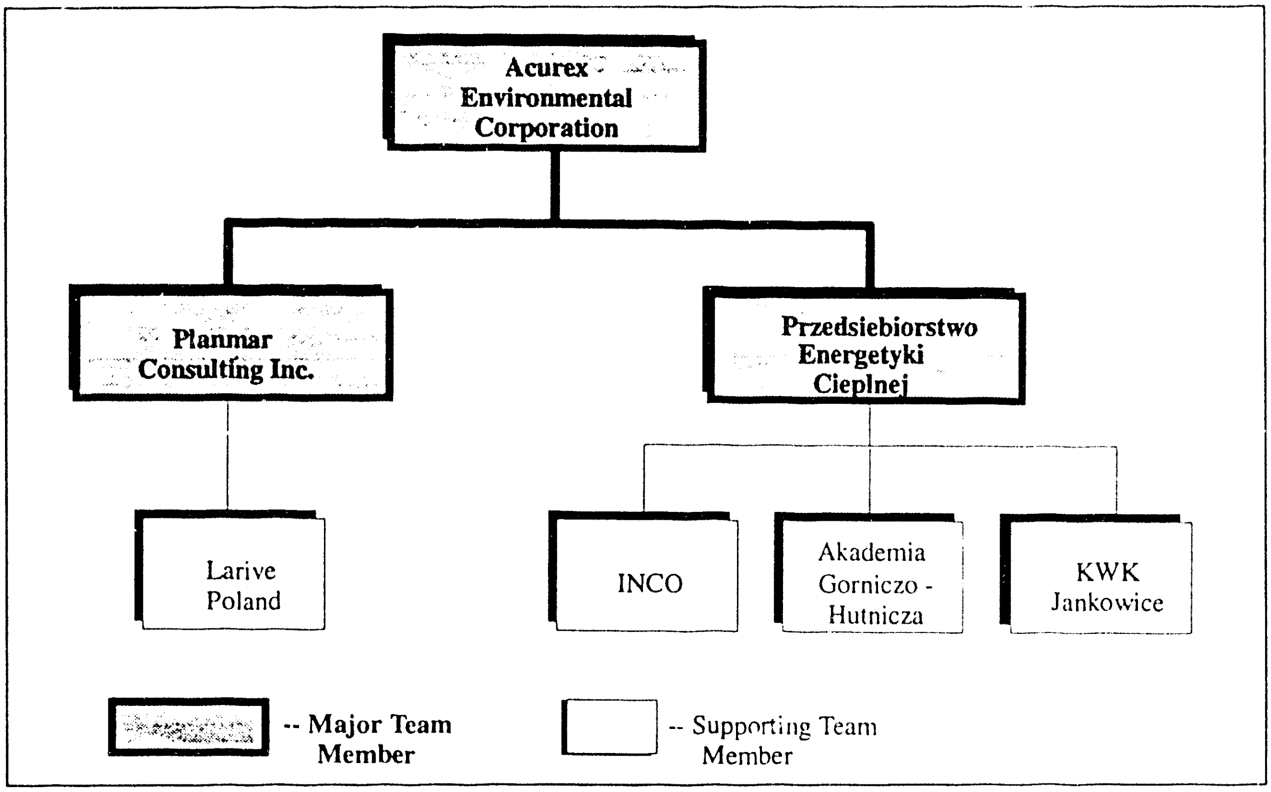

Figure 2. Project organization.

Figures 3 and 4 present the timelines for the two phases of the project. Phase I will include the proof-of-concept and developmental tasks. Phase II will establish the joint venture company and prepare the briquetting plant for full production. Each phase is expected to last one year. At the end of Phase II, DOE support will cease and full commercial production, sales, and distribution will commence.

Phase I—Technical

Phase I work will consist of proof-of-concept, formulation development, and combustion testing tasks. Proof-of-concept and formulation development tasks will be performed at the AMM. Combustion testing will be performed at AMM, INCO Veritas, and PEC.

Proof of concept will be a short-term task in which direct comparison combustion tests will be performed between the Acurex briquette and the chunk coal from which the briquette will be prepared. Wujek coal will be used because it was well-characterized during DOE's previous Kraków projects. The briquettes will be prepared as a single formulation similar to

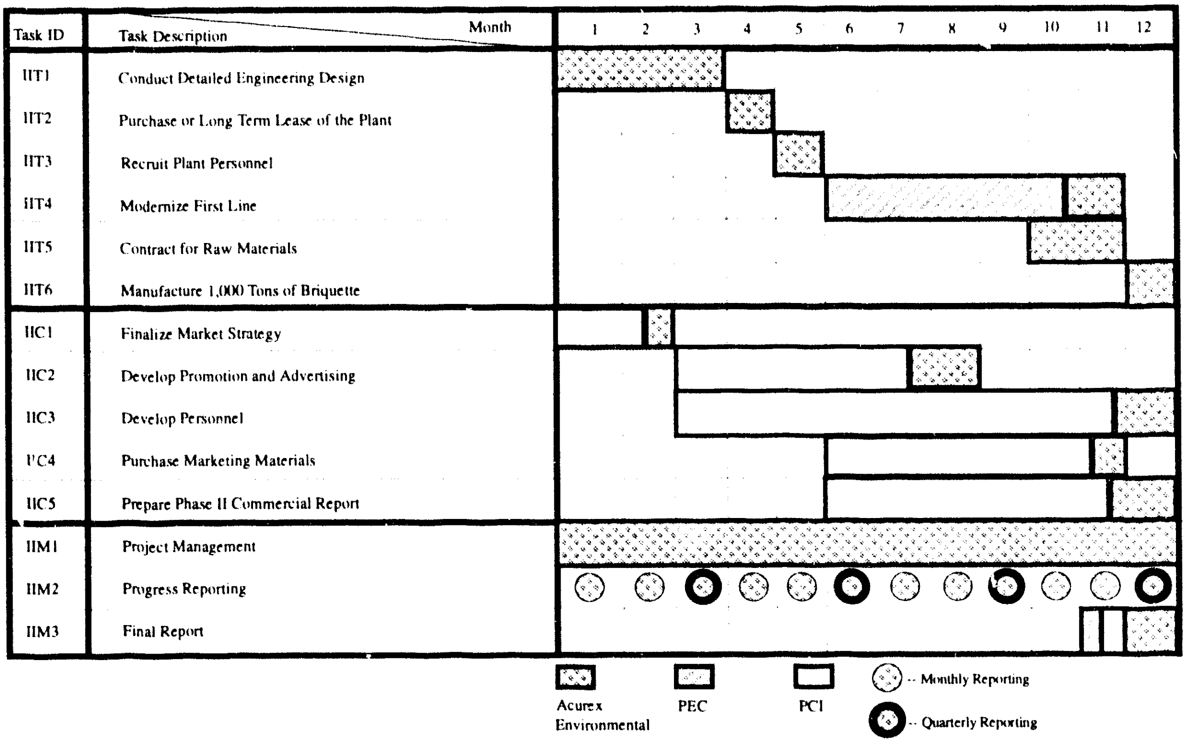

Figure 3. Phase I timeline.

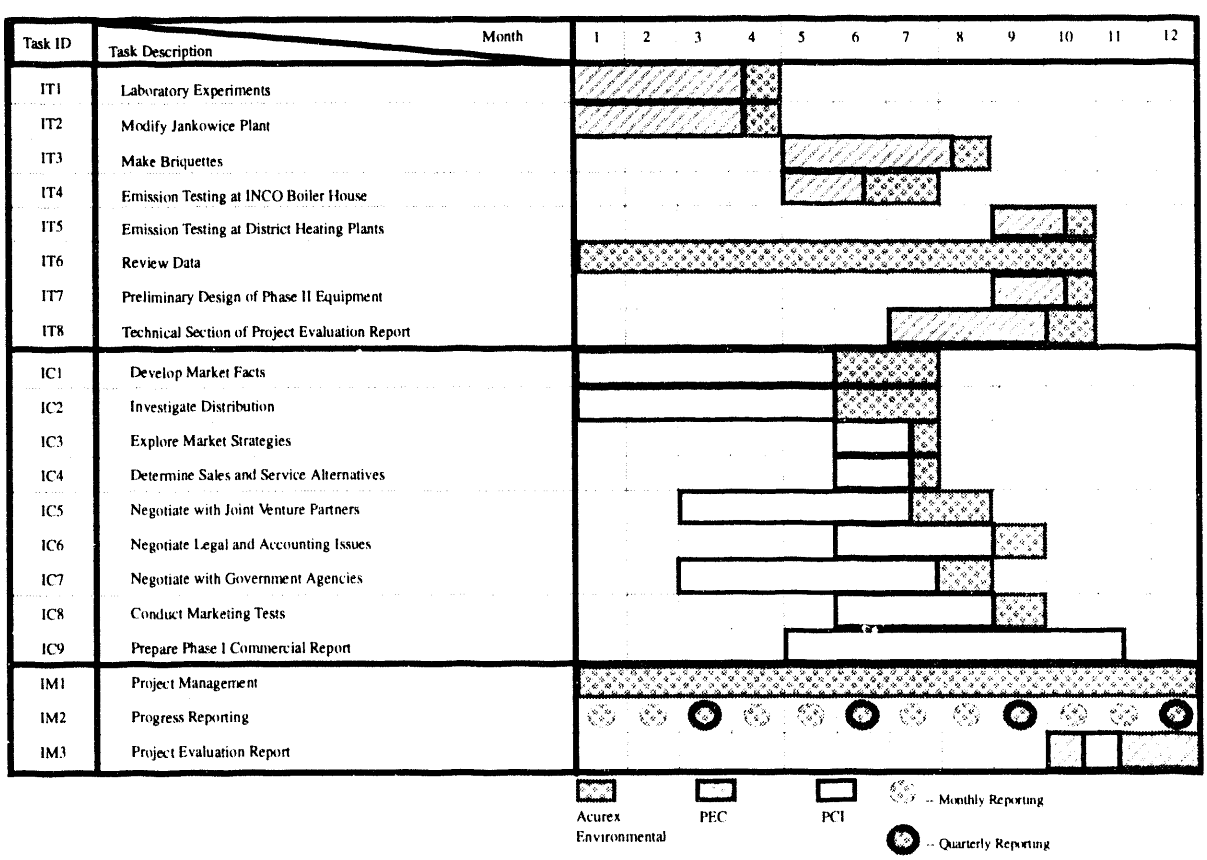

Figure 4. Phase II timeline.

that used during the Lutes et al. work. Both fuels will be burned under similar conditions in the fully instrumented tile stove located in AMM's Combustion Laboratory. This laboratory is equipped to perform EPA Method 5G testing. Reactive gases will be monitored continuously and filter samples will be collected. Filter samples will be used to determine TSP and extractable organic material (EOM). EOM is the sum of GRAV and TCO determinations performed on a dichloromethane extract.

Extensive formulation development is planned to ensure that a satisfactory formulation is available for later tasks. This work will be performed at AMM's Briquetting Laboratory. The test plan includes the use of five Polish sources of coal fines, two sources of binder, five coal:binder ratios, and four levels of briquetting pressure. Physical and ignitability tests will be used to cull unsatisfactory formulations prior to combustion tests.

Selected formulations will be tested in AMM's Combustion Laboratory. Testing will be similar to the previously described proof-of-concept tests. However, an XAD-2 cartridge will be added post-filter for semivolatile organic collection. The XAD-2 will be extracted and characterized for TCO, polycyclic aromatic hydrocarbons (PAHs), GRAV, and EOM. Combustion residues will be examined for unburned carbon (UBC) and tested for leachability. Extracted filters will examined by X-ray fluorescence (XRF), if possible, to characterize heavy metal emissions. After testing in the residential stove is complete, it will be repeated using a Polish cast iron residential stove.

Although this project is targeting the residential stove market, it has been recognized that this product is applicable to small, hand-fed boiler houses and may be applicable to larger facilities. Therefore, testing will also be performed at INCO Veritas and at PEC's Chrzanow facility. The briquetting plant at Jankowice will be used for the larger briquette quantities needed to satisfy these larger scale testing tasks.

The plant at KWK Jankowice is a large, multi-line facility capable of producing as much as 1,000,000 tons of briquettes per year. Currently shut down, this plant will require extensive changes to switch from its previous formulation to ours. These major capital improvements are not planned for Phase I. Instead, a single line will be isolated and brought on-line for batchwise, manual operation. During Phase I, approximately 2,400 tons of a single formulation will be produced here. Pilot-scale coal washing will be investigated.

Combustion testing will be performed at INCO Veritas and PEC Chrzanow. INCO Veritas, a small boiler house in Kraków, has four Eca IV hand fed boilers and produces 334 KW of process steam. Coke is currently used here although it has used coal previously. Currently, there is no overfire air, pollution control equipment, flue gas monitoring, or automated combustion control. PEC Chrzanow is a district heating facility with several boiler houses. Testing will be performed here on four boiler houses ranging in size from 2.5 to 25 MW.

Testing will be performed at two load levels and two excess air levels. The original fuels will also be tested for comparison with the briquettes. EPA Modified Method 5, including XAD-2 cartridge post-filter, will be used for this sampling. Reactive gases will be continuously monitored. Filters, XAD-2 cartridges, and combustion residues will be sent to AMM where they will be analyzed in a similar fashion to residential stove samples.

Phase I—Commercial

Phase I commercial efforts will include market investigation and testing efforts. Accurate data will be obtained as to the market size and distribution throughout the city, current and projected prices for competing products, raw material prices and their seasonal fluctuation, and current distribution channels. Market surveys will be made to determine consumer receptivity to such a product, possible pricing structures, the effect of alternative packagings on consumer acceptance, and proposed marketing and advertising approaches. Some of the briquettes produced at Jankowice will be used for market testing. Four hundred residential sites will be selected to use the product and will answer questions about their willingness to buy this product. Potential distributors will be evaluated. Strategies to convince them to carry our briquette will be developed. Potential business risks will be identified and considered as part of the overall business plan. The applicable national and local regulations that would apply to this new company and its business will be identified. Negotiations with governmental agencies will occur. This phase will conclude with the completion of a realistic business plan that may be used to seek investment capital.

Phase II—Technical

Phase II will begin with an engineering review of the briquetting plant to plan for its modernization and conversion to Acurex briquette production. Actual conversion will begin once this is complete and the plant has been purchased on a long-term lease contracted. Plant personnel will be hired and trained. Raw material contracts will be negotiated. This work will conclude with a 1,000-ton production run to prove the plant is in a fully operational mode and to generate production cost data.

Phase II—Commercial

This work will include all preparations for launching a new product. Based on the results of Phase I, the final market strategy will be selected. Promotion and advertising campaigns will be planned. Promotional and advertising materials will be designed and produced. Marketing and sales personnel will be hired and trained.

REFERENCES

Lutes, C., Ryan, J., Harris, D., Chapman, R., "Full-scale Laboratory Simulation Facility to Test Particulate and Organic Emissions from a Third World Residential Combustion Process, III, Evaluation of a Potential Technique for the Control of Emissions from the Indoor, Open Hearth Combustion of Coal," Presented at the 85th Annual Meeting of the Air & Waste Management Association, 92-141.03, 1992.

Conference on Alternatives for Pollution Control from Coal-Fired Sources.
Plzen, Czech Republic; April, 1994

MICRONIZED COAL FIRING APPLIED TO PLANTS IN THE CZECH REPUBLIC AND KRAKOW, POLAND

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TCS, Inc. Oakland, Maryland

ABSTRACT

A TCS Micronized Coal-Fired System offers The Czech Republic and Poland a unique opportunity to retrofit its existing industrial, utility and district heating plants and achieve increased combustion efficiencies coupled with reduced air emissions.

Micronized coal is coal ground to a micron-size "talcum powder" consistency; which, because of its extremely fine particle size, has unique characteristics affecting combustion efficiency, reduction of sulfur dioxide and nitrogen oxide air emissions and the potential for producing by-product markets for its resulting ash.

There are numerous and unique micronized coal market applications in The Czech Republic and Poland, including:

* Retrofits to existing coal-fired stoker units, to achieve reduced air emissions and increase boiler efficiency.
* Ability to burn brown coal and brown coal dust with reduced sulfur dioxide emissions.
* Ability to burn black coal on boilers originally designed to burn brown coal.
* Ability to co-fire multiple fuels with micronized coal (e.g., gas, oil, waste oil, wood waste, etc.).
* Application to industrial process heat applications (e.g., kilns, air preheaters, etc.).

This paper describes principals of a TCS micronized coal fired system and, its advantages and applications as they exist for utilization in the Czech Republic and Poland. For orientation, a description is given for three TCS projects, including:

(1). Rochelle, Illinois: Electric utility project that is currently operating.
(2). Krakow, Poland: Heating plant located at the Polish Military Base near Krakow, which is currently being evaluated as part of a cooperative agreement with the U.S. Department of Energy's "Krakow Clean Fossil Fuels and Energy Efficiency Program".
(3). Dvur Kralove, Czech Republic: District heating-cogeneration plant being financed by The Czech Ministry of Industry.

The paper will describe fundamental advantages of micronized coal firing as they relate to the technical, financial and regulatory criteria evaluated by Rochelle in its decision to implement its project. The paper will also outline important emission control retrofit considerations of the Rochelle project which should be considered by other utility and industrial boiler owners in the Czech Republic. Emphasis will be placed on lessons learned at Rochelle that could be considered for decisionmaking criteria in The Czech Republic and Poland, including fuel utilization such as: (a). brown coal, (b). brown coal dust, (c). black coal, and (d). co-firing with natural gas, oil, and waste oils.

UNIQUE ADVANTAGES OF MICRONIZED COAL FIRING

Micronized coal is defined as coal ground to micron size "talcum powder" consistency yielding a size distribution with an average particle diameter of about 17 to 20 microns, or about one-half the diameter of a human hair. Because of its extremely fine particle size, micronized coal has unique characteristics affecting combustion efficiency, air emission criteria and potential by-product markets for ash, including: 1). flame and heat release characteristics similar to oil, 2). reduced sulfur dioxide air emissions, resulting from co-micronization of coal with limestone, 3). lower nitrogen oxide air emissions, and 4). superior by-product market potential in the cement and asphalt manufacturing industry, as compared to other coal combustion processes.

HIGH EFFICIENCY COMBUSTION CHARACTERISTICS SIMILAR TO OIL

Coal reactivity, although a function of coal rank, volatile content, hydrogen, oxygen and pyrolysis plasticity, is also a function of total surface area of the fuel to be fired. For the same unit weight of coal, micronized coal has about three times the surface area of conventional pulverized coal and about 5.5 times as many particles.

This size differential for micronized coal results in numerous combustion advantages, when compared to a conventional pulverized coal-fired flame, including:

(1). Ignites at a lower temperature, and completes combustion sooner.
(2). Amount of surrounding air required for combustion is decreased (i.e., lower excess air); thus, increasing combustion efficiency.
(3). Produces a shorter and more intense flame; thus, better than doubling combustion intensity (e.g., flame length is reduced about 60 percent).
(4). Volatiles are released at a more uniform rate over the combustion temperature range.
(5). Radiation heat flux and overall amount of heat absorbed by furnace load is considerably higher.
(6). Slag and ash deposition rate on convective tube passes is significantly reduced.

Essentially, these results indicate that micronized coal has similar combustion characteristics and flame size as compared to oil. Because of these unique combustion characteristics, micronized coal can and has been successfully and commercially fired in packaged gas/oil boilers, in addition to conventional coal fired units.

SULFUR DIOXIDE AIR EMISSION REDUCTION

TCS holds the only U.S. Patent involving the process of burning co-micronized limestone and coal. Co-micronized coal and limestone results in significant sulfur dioxide air emission reductions during combustion caused synergistically by:

(1). Lower flame temperatures which are close to the optimum sulfur-calcium reaction temperature spectrum.
(2). Intimate mixing and contact between coal and limestone particles.
(3). Accelerated calcination and sulfation reactions resulting from the small particle size distribution of coal and limestone.

Limestones are like "fingerprints", there are no two exactly alike. Composition of limestones vary considerable, depending on their geologic formation and chemical and physical characteristics. These variances affect the ability of a limestone to act as a effective sulfur sorbent.

Calcium is the primary chemical component in limestones which reacts with the coal's sulfur during combustion. However, the percent chemical content of calcium in a limestone does not necessarily mean that it is a good sorbent. Other primary factors that appear to affect a sorbent's performance ability include: particle size, grain structure, porosity, and magnesium content. For example, tests sponsored by TCS and numerous other organizations, show that samples of two different limestones, both having the same calcium content, can produce vastly different results as sulfur sorbents; wherein, one might be excellent while the other terrible.

Reasons why these variations in sorbent efficacy exist is not clearly understood by the research community, at least to the point that a clearly understood physical or chemical test indicator can predict a limestone's performance efficiency. The only sure way to determine how a limestone will perform as a sulfur sorbent is to conduct a test burn.

Generally, sulfur capture results realized by a TCS system co-micronizing limestone and coal, having acceptable calcium-sulfur molar ratios, range from about 40 to 70 percent capture, depending on the limestone performance characteristics.

NITROGEN OXIDE EMISSION REDUCTION

In addition to lower sulfur dioxide emissions with a TCS system, it is also possible to realize lower nitrogen oxide air emissions due to several reasons, including:

(1). Generally lower flame temperature due to small particle sizing.
(2). Lower excess air.

(3). Staged combustion achieved through proprietary TCS Low-NOx burner.

(4). When co-micronizing coal and limestone, the limestone acts as a flame temperature retardant; thus, contributing to a lowered nitrogen oxide emission, in addition to sulfur reduction.

Although the aforementioned factors assist in reducing nitrogen oxide emissions, without testing, it is impossible to precisely predict NOx emission rates in a new or retrofit application, since they are affected by many project specific criteria, including: nitrogen content in coal, combustion air temperature, furnace chamber size and configuration, and other factors.

Based on micronized coal firing tests conducted by TCS and other independent organizations, nitrogen oxide emission rates appear to range between 0.3 lb/MMbtu (370 mg/Nm^3) and 0.5 lb/MMBtu (620 mg/Nm^3).

MICRONIZED COAL ASH BY-PRODUCT MARKET POTENTIAL

It appears that micronized coal ash is a highly attractive recyclable material with by-product market value as a cement feedstock that is superior to conventional pulverized coal flyash. Micronized coal ash has all the advantageous chemical and physical properties of conventional flyash while improving on two very important factors: particle fineness and low carbon content. It is a cementitious and pozzolanic material (i.e., hardens in the presence of calcium and water - a requirement for cement feedstock); likewise, its particle size distribution is about half that of conventional fly ash. Fine particles increase the compressive strength of concrete structures and asphalt pavement. Thus, micronized coal should be usable for super-strength concrete; thus, commanding a premium by-product price.

TCS MICRONIZED COAL COMBUSTION SYSTEM

TAS COAL (TM) was established as a business organization in 1980. In 1988, TCS, Inc. acquired the worldwide patent rights to the technology an in the same year formulated a joint-marketing relationship with Babcock & Wilcox directed toward the U.S. industrial and utility boiler market.

* Since 1980, about one-hundred (100) TCS micronized coal mills have been successfully marketed, manufactured and installed in the United States, Canada, Europe, South America, and Israel. Commercially installed applications include industrial boiler retrofits, industrial process heaters, kilns and other applications.

The TCS micronization mill is a proprietary patented single-pass attritic mill in which regular coal is introduced into the top of a vertical cylindrical vessel equipped with rotating discs and impact blocks, which progressively reduces coal particle sizing down to micron consistency; whereupon, it is entrained in an exiting air flow and conveyed directly t a burner (Figure 1).

The TCS Low NOx burner is a proprietary multi-channel burner capable of a highly controlled staged combustion air flow which forms a "cool" flame envelope and regulates flame size and shape. Limestone acts as a flame temperature retardant; therefore, concurrent with micron particle sizing, when coal and limestone are co-micronized, a relatively "cool" flame results that promotes SOx capture and reinforces a significant staged combustion profile to reduce NOx formation.

ROCHELLE MUNICIPAL PLANT PROJECT

Rochelle's Utility Plant has been operating since the early-1960's and was originally designed to burn coal on stoker-grate units. The facility was converted to natural gas-only firing in the late-1980's as an interim measure until engineering, financing and permitting could be completed for a retrofit system to again burn coal.

During mid-1991, the City contracted with TCS to began installing micronized coal mills and Low-NOx burners, coal and limestone storage handling, baghouses, and required ancillary equipment to:

1). Reduce operating costs.
2). Achieve improved combustion efficiency.
3). Demonstrate 50 percent reduction of sulfur dioxide gas emissions by co-micronizing high sulfur Illinois coal with various Illinois limestones. Likewise, an SOx reduction option exists by co-firing coal and gas.
4). Reduce nitrogen dioxide gas emissions by use of low-NOx burners utilizing staged combustion and the relative "cool" flame temperature of micronized coal.
5). Achieve higher degree of load following control, as compared to original stoker system.
6). Assess the potential by-product market value of micronized coal ash in the cement and asphalt manufacturing industry.

Figure 2 presents a conceptual plan of the project.

The $17.5 million construction, plus two year demonstration program, will be funded through a combination of financing sources, including: a). City of Rochelle bonding and contributions, b). State of Illinois Clean Coal grant, and c). contributions from Peabody Coal Company and TCS, Inc.

Factors which the City of Rochelle considered in its decisionmaking process were multi-faceted and primarily included: 1). desire to preserve coal permit, 2). incorporate dual fuel capability, 3). eliminate stoker firing and its attendant high maintenance costs, 4). improve boiler efficiency, and 5). generate sulfur dioxide credits which potentially could provide benefits to the City by "opting in" for SOx allowances in response to the Clean Air Act Amendments of 1990.

The Rochelle Project is currently in a start-up and testing mode.

KRAKOW CLEAN FOSSIL FUELS AND ENERGY EFFICIENCY PROGRAM

The project proposes to retrofit the Balice Boilerhouse with a TCS Coal Micronization System and Amerex baghouses to achieve higher combustion efficiencies and lower air emissions, including SO2, NOx, CO and particulate matter. The Balice Boilerhouse is located adjacent to the Krakow Airport and provides heating steam for the Polish Military Unit No. 1616, which is based in the vicinity of the airport.

Project participants include:

* Polish Military Unit No. 1616; Krakow, Poland
* OPAM; Katowice, Poland
* U.S. Department of Energy
* TCS, Inc., Oakland, Maryland; USA
* Amerex, Inc.; Woodstock, Georgia; USA

The Balice Boilerhouse currently burns a Polish Fine Coal Type 31.2 coal (e.g., 21-22 MJ/kg, 15% ash, 0.6-0.8% S, 25% M.C.) on four (4) travelling grate boilers, which include three (3) SWC-900 and (1) SWC-600 Polish manufactured boilers.

Generally, the equipment necessary for the retrofit include: modification to existing coal handling system, TCS micronized coal mills, TCS Low-NOx burners, Amerex baghouse(s), new limestone storage silo and handling system, new ash storage silo and handling system, new I.D. fans, either new or modified F.D. fans, and other minor ancillary equipment and modifications.

The objective of the project will be to retrofit the existing Balice boilers to: (a). increase boiler efficiency due to the aforementioned advantages of micronized coal combustion, (b). achieve up to 50 percent SOx reduction, or more, through the co-micronization of coal and limestone, (c). reduce particulate emissions through the utilization of Amerex baghouses, (d). reduce NOx emissions through the use of TCS Low-NOx burners, and (e). reduce carbon monoxide (CO) through more complete combustion which is achievable with micronized coal.

Phase I engineering evaluation began in mid-March 1994, and will include:

* Identification, assessment and combustion testing of Polish coal(s) and limestone(s).
* Engineering assessment and design of retrofit options to existing and possibly new boilers.
* Environmental and health safety considerations.
* Cost and operating considerations.

It is anticipated that a preliminary report will be available by September 1994 to meet the Polish Military's fiscal year budgetary schedule. Final report will be available in late-1994.

DISTRICT HEATING-COGENERATION PLANT - DVUR KRALOVE, CZECH REPUBLIC

The district heating plant in Dvur Kralove provides electricity and heat to the City. The plant, owned by CEZ (Czech Power Company), burns a locally available brown coal and currently experiences excessive sulfur dioxide air emissions. As an attempted sulfur emission reduction program, Dvur Kralove personnel test-burned a higher energy content-low sulfur black coal available from Ostrava, Czech Republic.

Results of the Ostrava coal test burns were not satisfactory due to unacceptable combustion performance resulting from a mismatched grate size and configuration which was originally designed for lower energy-content brown coals. The project will entail the retrofit of a TCS micronized coal fired system to the existing boiler to allow multiple-fuel capability, including: (a). black coal from Ostrava, (b). co-micronized brown coal and limestone, (c). brown coal dust from existing processing plants, (d). possibly other fuels.

The project is being financed by the Czech Ministry of Industry in cooperation with CEZ. Project participants include:

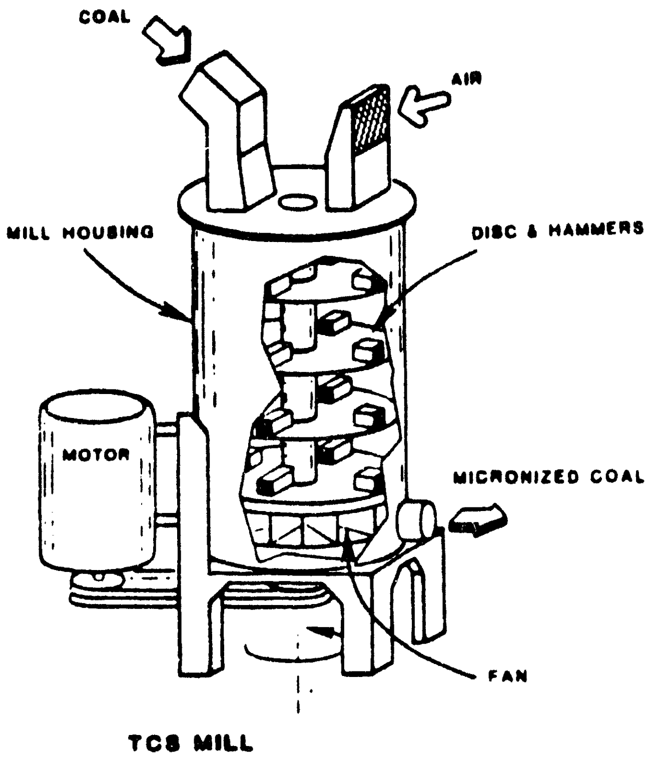
* Czech Ministry of Industry
* Dvur Kralove District Heating Plant (CEZ).
* ENVEN, Ltd.; Milevsko, Czech Republic.
* TCS, Inc.; Oakland, Maryland; USA.

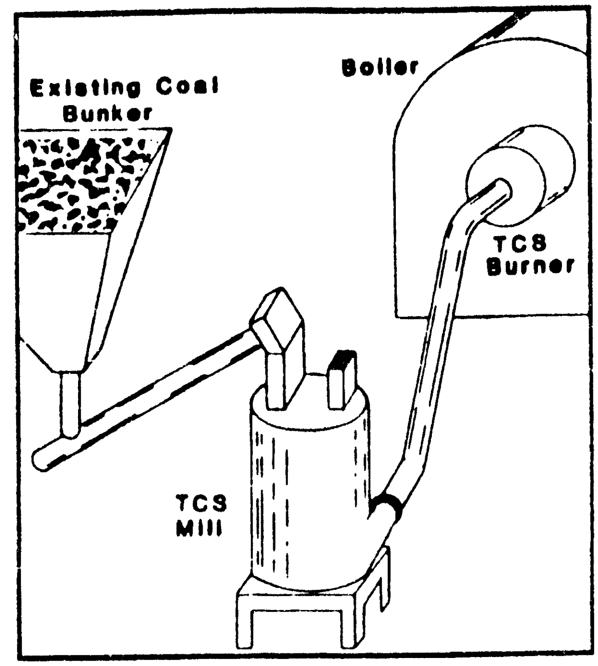
SUMMARY

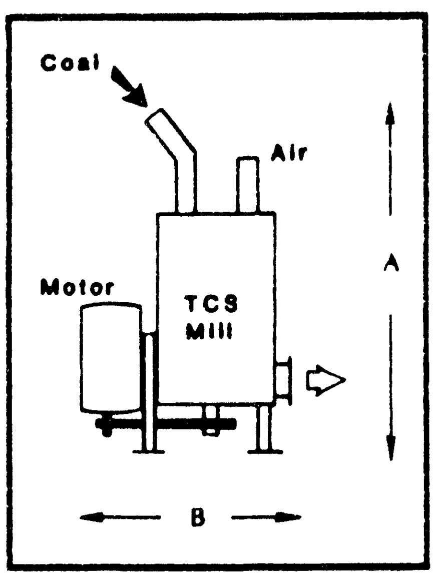
Micronized coal has combustion characteristics similar to oil, burns more efficiently than other coal options, can be co-micronized with limestone to reduce sulfur dioxide emissions, can reduce nitrogen oxide formation due to an inherently "cooler" flame and staged combustion. Since 1980, close to one-hundred TCS micronized coal mills have been commercially installed in the United States and overseas in conjunction with utility and industrial boiler retrofits, industrial process heaters, kilns and other applications.

There are numerous and unique TCS micronized coal market applications in The Czech Republic and Poland, including:

* Retrofits to existing coal-fired stoker units, to achieve reduced air emissions and increase boiler efficiency.
* Ability to burn brown coal and brown coal dust with reduced sulfur dioxide emissions.
* Ability to burn black coal on boilers originally designed to burn brown coal.
* Ability to co-fire multiple fuels with micronized coal (e.g., gas, oil, waste oil, wood waste, etc.).
* Application to industrial process heat applications (e.g., kilns, air preheaters, etc.).







MILL SIZE	A	B	MOTOR HP.	RATING (MMBtu/hr)
24"	7'-6"	4'-3"	30	5 to 15
26"	7'-6"	4'-5"	40	15 to 35
28"	7'-9"	4'-8"	75	35 to 50
32"	7'-9"	5'-4"	125	50 to 80
38"	9'-8"	5'-11"	200	80 to 100
42"	10'-9"	6'-9"	300	100 to 150

Figure 1: TCS MICRONIZED COAL SYSTEM

Figure 2: ROCHELLE MUNICIPAL UTILITIES
TCS Micronized Coal Retrofit Conceptual Plan
Boiler Building