SEWAGE SLUDGE: A FASCINATING FEEDSTOCK FOR CLEAN ENERGY

M. Rashid Khan, M. McMahon, S. J. DeCanio
Texaco Research & Development, P.O.Box 509, Beacon, NY 12508

Sewage sludge is composed of organic and inorganic materials. The organic portion of the sludge is predominantly composed of C, H, N, and S. On a dry-basis, the heating value of sludge is greater than that of oil shale or tar sand. The volatile matter content of dry sludge can be higher than that of the high volatile bituminous coal. Available correlations in the literature, developed for coals, were applied to predict the experimentally determined heating values. In addition, the sludge compositional data (C, H, S, and ash) were used to develop a new correlation specifically for raw sewage sludge. Compared to the models tested, the new correlation developed in this study for sewage sludge provided a better fit between the measured and predicted values.

KEYWORDS: Sludge, heating value, composition, coal

INTRODUCTION AND BACKGROUND

Treatment plants receive tremendous quantities of waste-water containing dissolved and suspended solids from a variety of sources including domestic, industrial and urban-offs as well as from storm drainage. Consequently, a variety of organic and inorganic materials can be found in a waste-water treatment plant (1).

Traditionally, the solid residue or sludge, the principal product of primary and secondary treatments, has been ocean dumped or landfilled. However, current federal regulations restrict such traditional practices. The option to dispose of such materials by landfilling also suffers from psychological (e.g., "not-in-my-backyard" syndrome) and genuine environmental concerns (e.g., contamination of ground water or agricultural products and leaching). A recent survey of compositional characteristics of domestic sludges indicate that most sludges can be classified as "hazardous," and consequently not suitable for disposal by landfilling (2). Keeping these alternatives in mind, conversion of sewage sludge to clean fuels via gasification (which readily converts essentially all the organic constituents) to synthesis gas (CO and H_2) for power generation or as chemical feedstock, provides an excellent avenue to utilize this renewable resource (3).

The use of sewage sludge requires a better understanding of its physical and chemical properties. In particular, the ability to estimate its calorific value would indeed be of great importance keeping in mind that the measured heating values of sludge are generally not readily available and the reported data often suffer from a relatively large experimental variation (partly due to possible biological/chemical degradation of samples during various treatments). Correlations are important for justification and modeling of the conversion processes now being developed.

The correlations between the coal composition and heating value were reported as early as 1940. Over 20 different equations are reported in the literature which enable one to calculate the heating value of coal based on the ultimate/proximate analyses (4-9). However, essentially nothing could be found in the literature that could be readily applied to specifically estimate the heating value of sludge.

To examine the utility of existing correlations (developed for coal), the most widely used equations were tested for sewage sludge. Mott and Spooner (1940) claimed that their equation will yield heating values agreeing within 200 btu for the whole range of fuels, from peat to anthracite (4). We, however, were much less successful with this equation for dewatered sewage sludge.

Mason and Ghandi (1980) developed a correlation based on coal samples from the Pennsylvania State University coal data base (6). A comparison of the experimental results and the predicted values (based on Mason and Ghandi's equation) was made. Compared to the equation by Mott and Spooner, this equation (termed Data Base [DB] Equation) did a better job in estimating the heating value of sludge.

EXPERIMENTAL

In this study dewatered sewage sludge samples (originating in various treatment plants of the country) were dried in a lab vacuum oven under N_2. The dry samples were characterized by monitoring the following: ultimate analysis (C, H, S, N), ash content and high heating value. A selected set of samples were characterized in multiple laboratories which included the following: Huffmann Laboratories, Inc. (Golden, CO), Institute of Gas Technology (IGT, Chicago, IL), and Texaco Research & Development (Beacon, NY) to ensure that analyses in various laboratories provide comparable results. In general, the data obtained from various labs were within the variation allowed by the conventional ASTM guidelines for each analyses. All analyses for a given sample were completed relatively rapidly to minimize degradation of samples due to bacterial growth.

The data (30 observations in total) were analyzed by using the Statistical Analytical System (SAS) package developed by SAS Institute (10). The regression programs available in this package were applied to develop an empirical model.

RESULTS AND DISCUSSION:

1. The Heating Value of Sewage Sludge Compared to the Various Fossil Fuels

The mean heating value (gross) of sludge (based on 30 observations) compared to various fossil fuels is shown in Figure 1. The heating value of oil shale (Green River formation of Mahogeny zone; Colorado; 33 gal/ton, described by Khan, 1987) was 3200 Btu/lb (10). The heating value of eastern Kentucky shale can be significantly lower than the western shale considered in this study. The heating value of the Asphalt Ridge basin tar sand (Khan, 1989) was less than 2000 Btu/lb (11). By contrast, the heating value of an average sewage sludge is considerably higher (6400 btu/lb). The heating value of an industrial biosludge observed in this study to be greater than 9000 btu/lb. However, no industrial sludges were included in the data base aimed at developing the new correlation.

Compared to essentially all fossil fuels (excluding petroleum based fuels), sewage sludge has a higher H/C (atomic) ratio (Figure 2). The mean H/C ratio of sewage sludge was 1.65 (based on 30 observations), considerably higher than that of the bituminous coals (Pitt#8) with H/C ratio of 0.89 or a sub-bituminous coal (H/C of 0.96 for Wyodak coal). The H/C of the sewage sludge is comparable to tar sand bitumen (with H/C of 1.5).

In addition to the elements described above, significant amounts of chlorine and various volatile metals can be present in sewage sludge. For example, the chlorine content of one sludge was as high as 0.6% (dry basis). Other volatile inorganics identified in the this sludge included the following: Beryllium (less than 0.02 ppm), Vanadium (less than 1 ppm), and Manganese (900 ppm). However, this study did not consider the role of chlorine or vaporizable metals on the heating value of sludge.

2. Variations in the Sewage Sludge Composition

The mean, standard deviation, minimum and maximum values for the compositional analyses are presented in Figures 3 and 4. The variations in the C, H, N and S content in different samples are shown in Figure 3. The sulfur content for various sludges ranged between 0.18 and 3.61 percent with a mean value of 1.71 (with a standard deviation of 1.05 about the mean). The oxygen content of sludge ranges between 3.5 and 27.8% with a mean of 16.5 (and a standard deviation of 6.3%).

The volatile matter content for the a given sludge ranged between 45 and 62% (dry basis). These values are significantly higher than the volatile matter content of a high volatile bituminous coal (with a volatile matter content of 35%, dry basis). The H/C (atomic) for the data set used ranges between 1.44 and 1.86 with a mean of 1.65 with a standard deviation of 0.106.

Figure 4 shows that the mean heating value of the sludge was 6409 with a standard deviation of 816 (based on 30 observations). The measured values for the sludge ranged between 5261 and 8811 Btu/lb. The heating value and the compositional characteristics of sludge are dependent on the nature of sludge as well as on the degree of digestion (or pretreatment) a sludge has undergone. The minimum ash content for the sludge was 18.9% while the maximum value for the sludge was 58.68% (the mean was 40.5%). The higher ash content generally reflects that the sludge has either been digested or heat-treated to convert a large portion of the organic constituents.

The sludge composition is dependent on the nature of pretreatment a given sludge has experienced. For example, the sludge conditioned by a wet oxidation process (intermediate pressure, 300-400 psi; oxidizing atmosphere; temperature of 250-375 F) has a significantly different analysis and a lower heating value compared to an untreated sludge (low C, H but higher oxygen content compared to the untreated materials).

The compositional differences between various sludges can be significant; these differences will be discussed elsewhere. It is interesting to note that the pyritic sulfur is the dominant sulfur type for several sludge. The presence of this large concentration of pyrite is not typical of domestic sludges but suggests the formation of pyritic sulfur from organic sulfur by bacterial action.

3. Comparison of Various Correlations

Attempts were made to estimate the heating value of sludge using correlations widely reported in the literature applicable for coal (and oil shale). In particular, the equation by Mott & Spooner and the Data Base equations were compared with the newly developed correlation.

The percent variation between the measured and the predicted values were calculated for each model by the following equation:

$$\% \text{ Variation} = 100 \times (\text{Predicted-Measured})/\text{Measured}$$

The variations (between the measured and predicted values) for the three models are summarized in Figure 5. The model developed in this study provides a mean variation of 0.019% between the predicted and the measured values. The maximum variation between the measured and predicted values was never greater than 2.83%, based on the new model. In contrast, the Data Base Equation provides a maximum variation of 10.2% while the equation by Mott & Spooner yielded a maximum difference of 14.8% between the measured and predicted values.

Figure 6 compares the measured and predicted heating values based on the Data Base Model. The disagreement between the predicted and measured values in Figure 6 is much larger than those shown in Figure 7 (based on the new correlation developed in this study).

4. Evaluation of the New Correlation

Figure 7 compares the measured and predicted heating values calculated based on the correlation developed in this study. The following equation describes this model:

$$Q\ (Btu/lb) = 241.89*C + 264.26*H + 236.2*S + 20.99*Ash - 4174.68$$

R^2 for the model is 0.99. The parameter measures the proportion of total variations explained by the regression. It is calculated by dividing the sum of squares due to regression by the total sum of squares. R^2 is related to correlation coefficient, r, by the following in simple linear regression: r = square root of R^2. In addition, r, has the same sign as the slope of the computed regression.

The F value for the model was 650.6. The F ratio is the ratio produced by dividing the mean square for the model by the mean square of error. It tests how well the model as a whole (after adjusting for the mean) accounts for the behavior of the independent variable.

The P value for the model was 0.0001. P defines the "observed level of significance." In statistical terms, the level of significance, alpha, of a test is defined as the probability of rejecting the null hypothesis (i.e., no linear relationship between the dependent and independent variables) given the null hypothesis is true. The P-value gives us the largest value of alpha that would lead to the acceptance of the null hypothesis. In other words, from statistical standpoint, the correlation developed is highly significant.

SUMMARY & CONCLUSIONS

The following conclusions are derived based on this study:

- o The heating value of dry municipal sewage sludge is considerably higher than tar sand or oil shale but lower than that of bituminous coal. The atomic H/C ratio of sewage sludge, however, is higher than that of bituminous coal, but comparable to the H/C ratio of oil shale. Some industrial biosludges can have heating value comparable to that of low rank coal.

- o The volatile matter content of sludge is higher than that of coal, oil shale or tar sand.

- o The compositional characteristics (C, H, N, S and ash) of sludge can vary widely among sewage sludge of different origin. Wet oxidation of sewage sludge significantly reduces its heating value as well as its C and H content.

- o The conventional equations developed for coal are not readily applicable for sewage sludge. The equation developed in this study serve reasonably well for estimating the heating value of sludge of various origin based on its analysis (C, H, S, and ash).

REFERENCES

1. V. T. Chow, R. Eliassen and R.K. Linsley, Editors, "Wastewater

Engineering: Treatment, Disposal & Reuse", McGraw-Hill, 1979.
2. Federal Register, "National Sewage Sludge Survey: Availability of Information and Data, and Anticipated Impacts on Proposed Regulations; Proposed Rule," Vol 55., No. 218, 40 CFR Part 503, Nov 9, 1990.
3. Willson, W. G. et. al, "Low-Rank Coal Water Slurries for Gasification," Final Report by UNDEERC, EPRI Report No. AP-4262, Nov., 1985.
4. Mott, R. A. and Spooner, C. E., "The Calorific Value of Carbon in Coal," Fuel 19, 226-31, 242-51 (1940).
5. Selvig, W. A. and Gibson, F. H., "Calorific Value of Coal," in Lowry, H. H. ed., Chemistry of Coal Utilization 1, 139, New York, 1945.
6. Mason, D. M. and Ghandi, K., Am. Chem. Soc. Div. Fuel Chem Preprints, 1980, 25(3), 235.
7. Boie, W., "Fuel Technology Calculations," Energietechnic 3, 309-16, 1953.
8. Grummel, E.S., and Davis, I. A., "A New Method of Calculating the Calorific Value of a Fuel From Its Ultimate Analysis," Fuel 12, 199-203, 1933.
9. Neavel, R. C., S. E. Smith, E. J. Hippo, and R. N. Miller, Fuel 65, 3, pp. 312-320, 1986.
10. Khan, M. R., K. S. Seshadri, and T. E. Kowalski, Energy & Fuels, 3, 412-420, 1989.
11. Khan, M. R., Energy & Fuels, 2, 834-842, 1988.
12. SAS User's Guide: Basic, Version 5 Edition; SAS Institute; Cary, NC, 1985.

Figure 1

Comparison of Heating Values
of Various Feedstocks (Dry-basis)

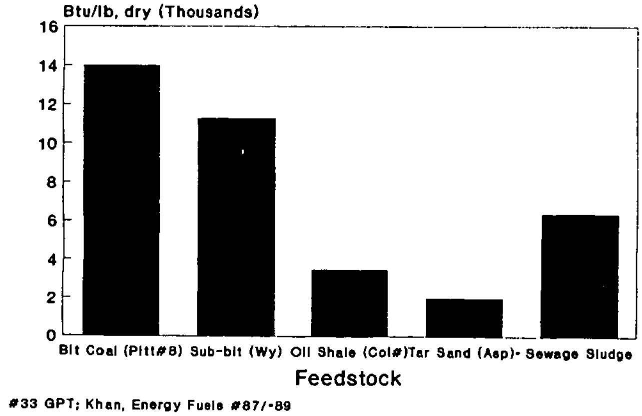


Figure 2

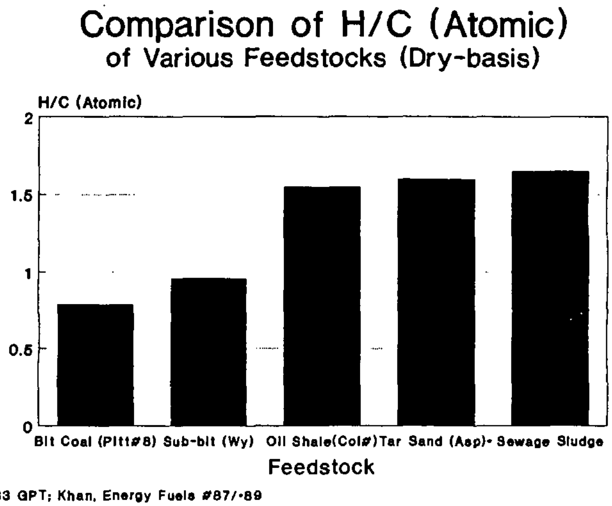


Figure 3

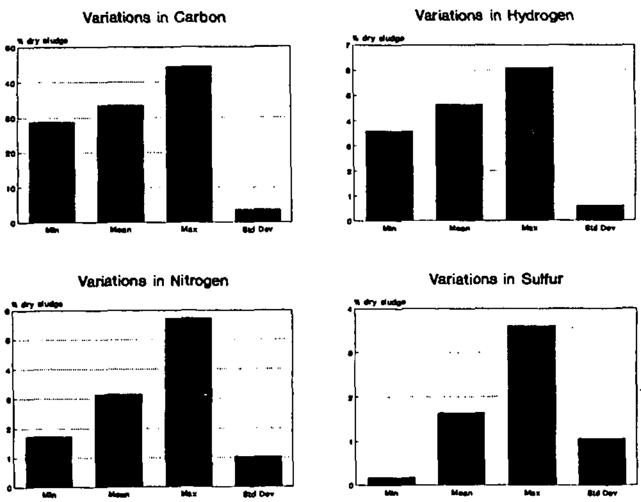


Figure 4

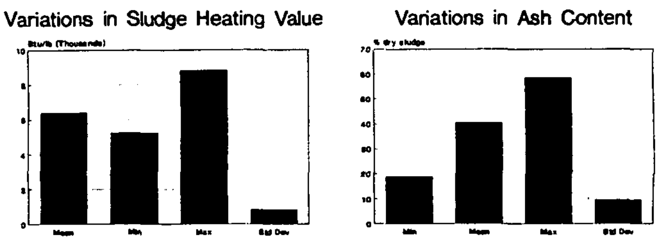


Figure 5

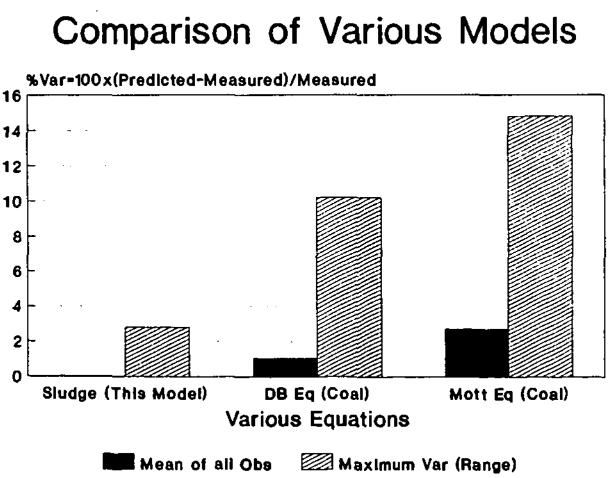
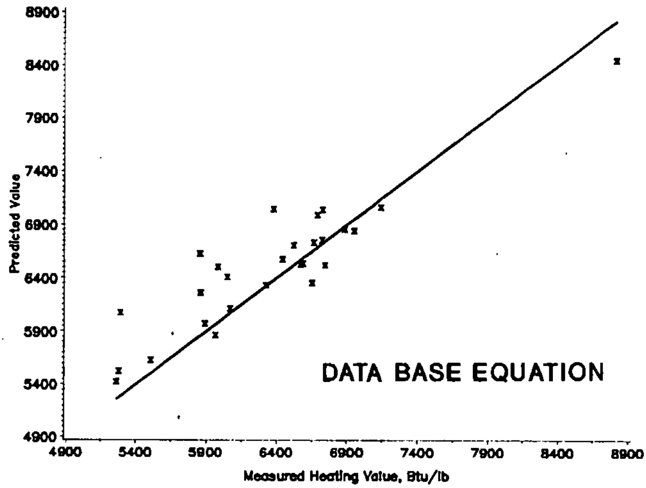


Figure 6

Predicted & Measured Heating Value For Sludge



Predicted & Measured Heating Value For Sludge

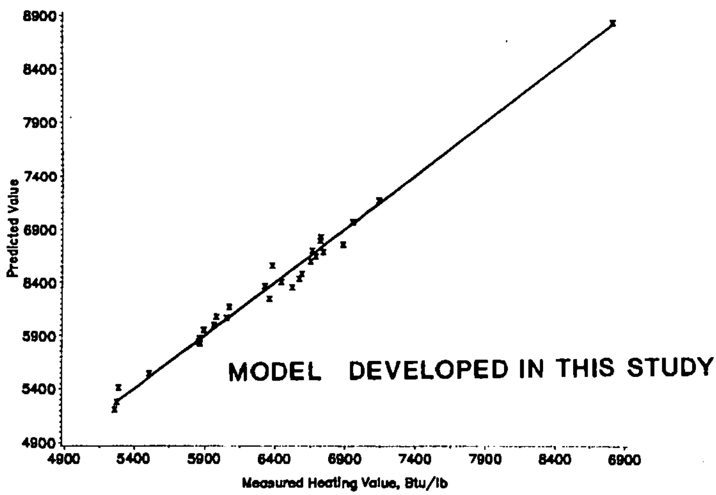


Figure 7