

APPENDIX II

BACKGROUND INFORMATION

NOMENCLATURE

Δe_x = change in exergy in a heat exchanger or turbine

h_1 = enthalpy of entering stream

h_2 = enthalpy of exiting stream

s_1 = entropy of entering stream

s_2 = entropy of exiting stream

T_o = absolute ambient temperature

Introduction

The major advantage of coal/biomass slurries is the ability to transport them over long distances, to feed pressurized energy recovery systems and to recover energy from the excess water.

As long ago as 1891 a patent was issued for a method of pumping coal and water (Wasp 1971). In 1957, the 10-inch, 108-mile Consolidation Coal line and the 6-inch, 72 mile American Gilsonite line marked the beginning of long-distance slurry lines in the U.S. In 1970, the 18-inch, 273 mile Black Mesa line was installed to feed the Mohave power plant (Elliot, 1981). This system provides all the fuel requirements for two 750-MW generating units in southern Nevada (about 5 million tons/year). The project is significant in that it was the first generating facility designed to use coal slurry directly from the start of operations. Availability of the Black Mesa pipeline system has been on the order of 99%. There are no significant technical problems in the slurry system.

Thermal coal is well suited to pipeline transport because it must be ground until approximately 70-80% can pass through 200 mesh before it is blown into the boiler. Coal pipeline hydraulics require all material to pass through about 20 mesh. Therefore the slurry fineness requirements simply cause the required size reduction to be split, some at the head end of the pipeline and the remainder at the power plant. Coal grinding normally involves conventional milling equipment. For example, the Black Mesa system employs rod mills to produce the required particle size distribution. Typical pipeline coal slurry specifications are shown in Table 1.

Table 1 Coal Slurry Specifications

Mesh	Concentration, %	
	Ohio	Black Mesa
+14	1-3	0-2
-100	35-40	35-45
-325	18-20	18-20

The required pipe diameter can also be calculated as follows:

$$D = 0.01365 (TPY/WH r_s V)^{0.5},$$

where D = required internal pipe diameter (in.),
TPY = annual requirement of bone-dry coal (short tons),
 W = bone-dry solids (wt), (expressed as a fraction),
 H = number of operating hours per year,
 V = bulk velocity (ft/s), and
 ρ_s = density of slurry.

Slurry Preparation

Feed preparation covers the physical and chemical processing necessary to give the slurry characteristics required for hydraulic transport and use. Preparation normally involves both size reduction (crushing and grinding) and addition of the liquid phase. Chemical treatment may also be part of slurry preparation for corrosion inhibition, thinning, and improving the characteristics of the final product. In the case of coal transport, a particle size specifically suited for slurry transportation must be produced (Cowper 1972). A balance has to be made between pumpability and dewatering characteristics. If sizing is too fine, pumpability may be good but the slurry may be difficult to dewater. The fine particles can have higher ash content than the parent coal. If the particles are too coarse, the slurry must be pumped above the critical velocity to maintain suspension, and costs due to pressure drop and erosion may be excessive. For gasification systems, top size particles can be only partially reacted in entrained gasifiers and can produce excessive carbon in the ash, lowering efficiency and presenting disposal problems.

Typical specifications for a coal slurry system with a 95% operating factor are 5.5 ft/s velocity and 50% concentration of solids by weight (Elliot, 1981). The effect of solids concentration on viscosity of coal slurry at 60F is shown in Fig. 1.

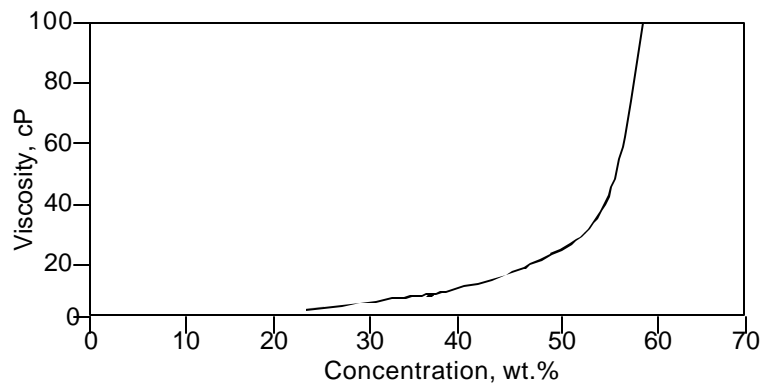


Fig. 1 Effect of Solids Concentration on Viscosity for Coal Slurries (Thomas, 1965)

Virtually all slurries exhibit non-Newtonian behavior. There are several shear stress - velocity gradient curves that represent various slurries. The most common is probably Bingham plastic. In this behavior, the shear stress is a straight line with a shear stress higher than Newtonian. Pseudoplastic and dilatant

behaviors are also possible. These possibilities require that slurries composed of biomass and coal are tested in a pilot system to predict operating parameters for larger systems. Process control can be improved by a test loop in the slurry preparation system, where particle size and concentration are measured in real time. A Coulter particle counter can be used for both measurements.

The Coulter LS Series delivers volume %, surface area % and particle size distributions that can be used to calculate weight %. The MS Windows software offers a data export function with 1% reproducibility that can be used to control slurry export to the transport and pumping systems.

Slurry Pumping

Multiple coal gasification plants operate GEHO piston diaphragm pumps for the transfer of coal slurry and for feeding the gasifier. Synthesis gas ($\text{CO} + \text{H}_2$) can be used to produce ammonia for fertilizers and oxo-chemicals. Slurried coal can be fed at up to 65% solids by weight at up to 300 bar (4,500 psig) at up to 40 US gpm. GEHO feed pumps have on-line proven performance within $\pm 1\%$ accuracy over a wide range of operating conditions at up to 95% efficiency. This performance is the result of proper sizing of the pump, suction and discharge dampeners, valves and speed controls.

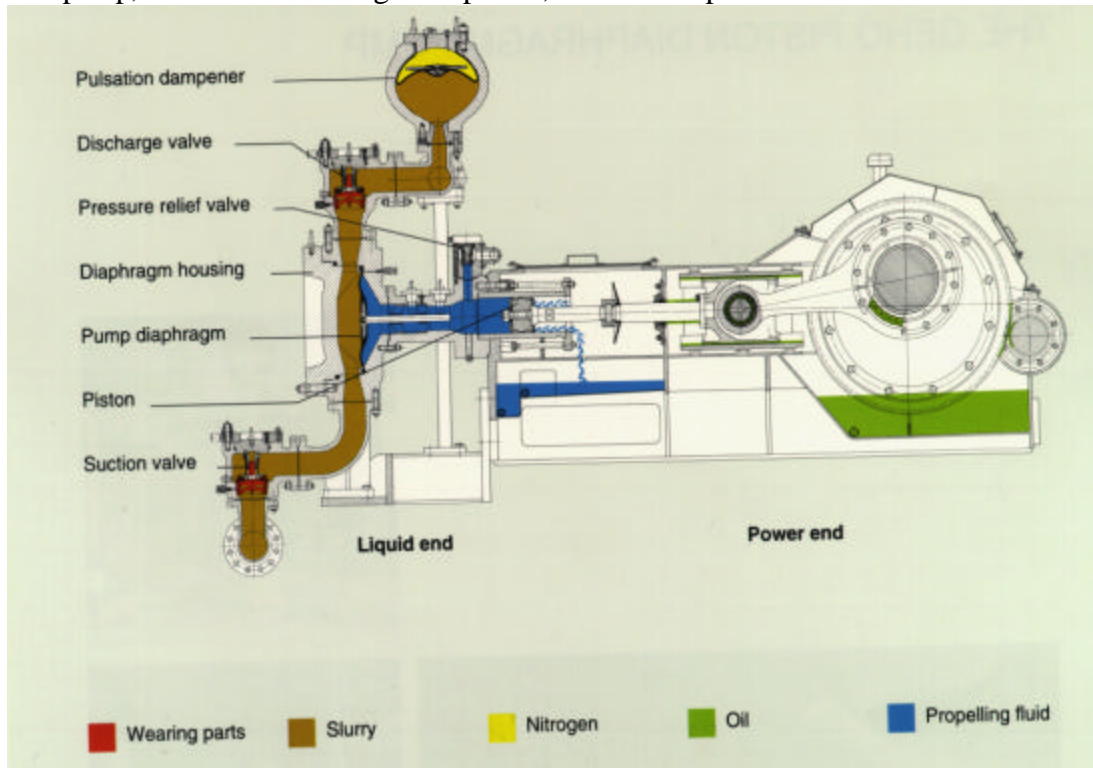


Fig. 2 GEHO TZPM piston diaphragm pump.

Biomass/Coal Slurries

In addition to water required to prepare a biomass slurry, biomass generally has very high inherent moisture. For example sewage sludge from secondary treatment can have over 80% inherent moisture and cannot be easily pumped above 12-14% solids in a slurry. EnerTech Environmental has designed a sewage sludge carbonization facility for South Kearney, NJ to produce a fuel oil substitute having about 50% moisture by weight. EESI and General Atomics (GA) have produced a pumpable biomass slurry

containing over 40% solids by weight from compost. The compost was prepared in a Bedminster aerobic digester from two-thirds municipal packer truck waste and one-third by weight of about 18% solids sewage sludge.

Coal can be used to increase the concentration, or "energy density" of biomass slurries. For example a slurry composed of about 50% coal and compost and 50% water may be a practical limit for these slurries. For conventional combustion systems, oxygen and inherent moisture that are chemically bound in the coal particles reduce heat value and efficiency. In conventional gasification systems, such as the Texaco process, water in the feed reduces efficiency because all of the water must be evaporated in the reactor by burning additional coal with oxygen. Excess water is subsequently condensed at low efficiency. These processes require maximum practical concentrations to have any hope of meeting Vision 21 goals.

Energy Recovery from Slurries

The ability of steam to perform useful work is called availability or exergy. Exergy analysis uses the formula

$$\Delta e_x = h_1 - h_2 - T_o (s_1 - s_2), \quad (1)$$

Exergy analysis indicates that exergy loss is proportional to the heat transferred and the temperature difference across the heat transfer surface. Exergy analysis shows that over fifty percent of the ability of fuels to perform useful work is lost in conventional low-pressure steam generators.

As we have seen, inherent moisture and slurry moisture also subtract from the efficiencies of conventional combustion and gasification systems, where the resulting excess moisture in the products does not produce significant energy. In low-pressure systems, this is just the difference between the lower heating value (LHV) and the higher heating value (HHV) minus the heat required to evaporate the feed moisture and bring it to the exhaust condition. For example, the LHV of Illinois No. 6 coal is about 10,500 Btu/lb at 10% inherent moisture and about 11,000 Btu/lb HHV. The heating value of 50% solids slurry using this coal can be calculated by reducing the combustible solids by half to about 5,250 Btu/lb, and subtracting the heat required to evaporate 0.5 lb of water and discharge it as vapor at exhaust conditions, say 350 F. and 14.7 psia. This enthalpy of the excess moisture in the exhaust is about

$$1,150 + 65 = 1,215 \text{ Btu/lb.}$$

The net LHV of the slurry is then

$$5,250 - 1,215 \times 0.5 = 4,640 \text{ Btu/lb.}$$

The HHV of the slurry adds back the enthalpy of the excess moisture, resulting in a value of about

$$11,000 \div 2 = 5,500 \text{ Btu/lb.}$$

Note that the difference between LHV and HHV is much larger in the slurry than the raw coal. The concentration of a slurry of Illinois No. 6 coal that has no net LHV can be calculated with

$$10,500 \times C - 1,215 \times (1 - C) = 0,$$

resulting in $C = 10.4\%$. The HHV at this concentration is $11,000 \times C = 1,140$ Btu/lb.

LHV is used more often in Europe, where the lack of recovery of energy from discharge moisture in conventional energy systems is realized. This illustrates the errors that may be associated with using either LHV or HHV to calculate efficiency in conventional slurry-fed energy systems.

A more useful concept is *exergy*, used in ASME "thermoeconomic" analysis. For example, the exergy of Illinois No. 6 coal is about 11,350 Btu/lb, or 3% higher than the HHV. The exergy of slurries is slightly higher than the HHV of the slurries, as illustrated above.

Combined Cycle Systems

A typical combined-cycle gas turbine system is shown in Figure 3.

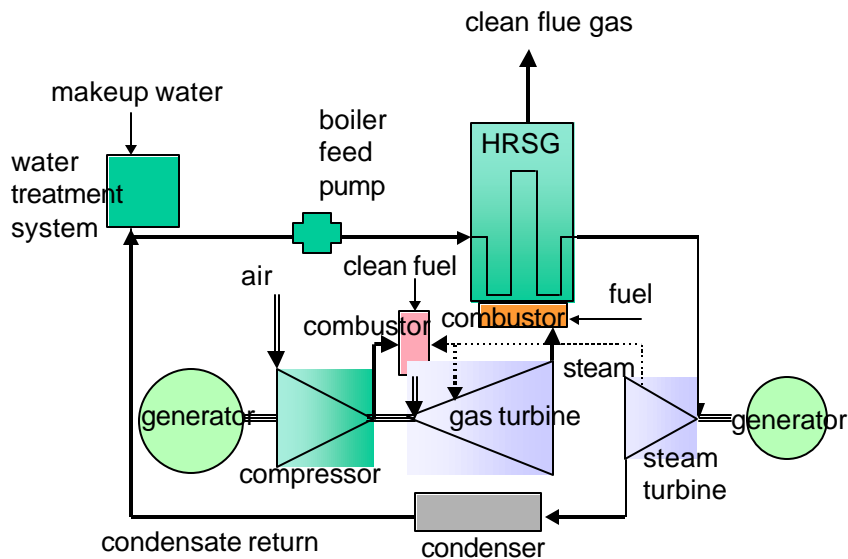


Fig. 3 Combined Cycle System

This configuration is limited to clean fuels and produces electricity at over 50% efficiency. Excess air is used to control turbine inlet temperature at the cost of additional power required for the compressor. Steam is produced in a conventional HRSG that can operate at over 100 bar (1500 psia) and over 540 C (1000 F). HRSGs are available in once-through design (without drum), with alloy 800H tubes that have fins for improved heat transfer from combustion products. Steam can be extracted from the steam turbine and injected to control NO_x emissions and cool the high-temperature turbine blades. Additional steam can be injected to significantly increase power output, as in the dual-fluid or Cheng cycles. This steam replaces excess air, lowering compressor flow rate. Steam increases the specific heat of the gases

The Vapor Transmission Cycle

A simplified VTC concept is shown in Figure 5.

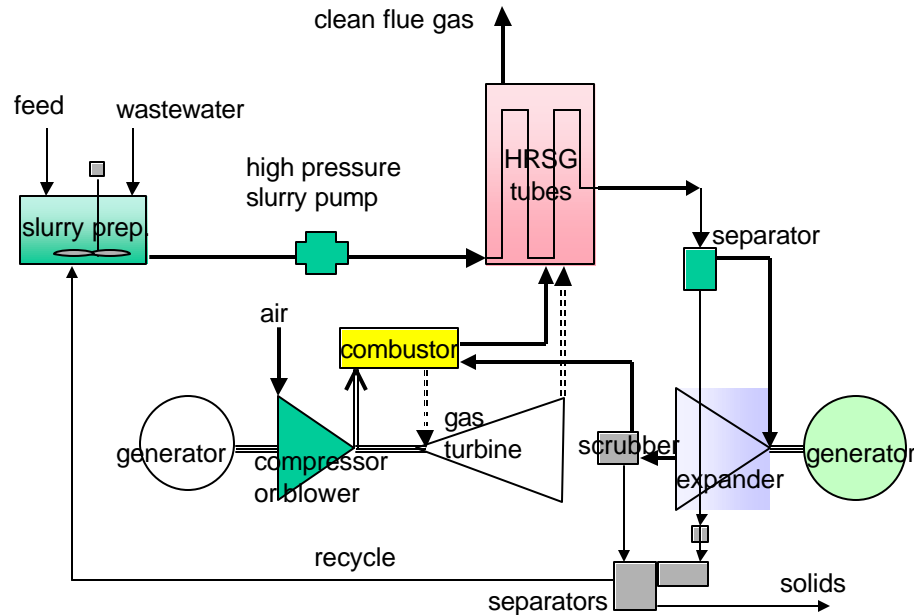


Fig. 5 Simplified Vapor Transmission Cycle Concept

This concept incorporates supercritical water gasification in HRSG tubes with a compressor and gas turbine, or in an existing steam plant with a blower to supply combustion air at low pressure. Emissions are minimized by two cleaning stages. Liquid effluents are eliminated by recycling condensate back to slurry preparation. This concept will be thoroughly evaluated using test data and thermoeconomic analysis in Stage 4.

Life Cycle Costs

Preliminary life-cycle cost analyses have been prepared for 50MW model plants capable of serving cities of 250,000 to 300,000 population. A preliminary baseline cost analysis for a new 50MW natural gas fired combined cycle plant operating in peaking service (3,600 hrs/year) at 60% thermal efficiency is shown in Figure 6. Natural gas cost is assumed to be \$3.00/million Btu and capital cost is assumed to be \$500/kW. The analysis predicts that average revenue must be \$100/MWh to pay back the capital investment within five years.

The same natural gas fired combined cycle plant operating in base load service (7,200 hrs/year) is shown in Figure 7. This analysis predicts that average revenue must be \$58/MWh to pay back the capital investment within five years.

For compost feed, each model plant will handle about 300 tons/day of municipal packer truck waste (MSW) and 100 tons/day of secondary sewage sludge at 18% solids. Disposal fees must

be sufficient to pay the capital investment, operating and maintenance costs, resulting in a compost fuel price of \$1.00/million Btu. This price is similar to delivered costs for coal.

Bedminster Bioconversion of Georgia has justified the construction of six operating composting plants without a guaranteed compost price. A separate life cycle cost analysis was not prepared for compost plants for this project. Co-locating composting plants with VTC power facilities at municipal landfills will allow land reclamation through mining existing refuse, eliminate compost curing, and allow wet compost to be used for power generation at lower cost.

For comparison with the natural gas plant, Fig. 8 shows a preliminary life cycle cost analysis for a new VTC plant fed by compost at \$1.00/million Btu. This analysis predicts that average revenue must be \$100/MWh to pay back the capital investment within five years. This is the same revenue required for the natural gas plant operating in peaking service.

A similar life cycle cost analysis has been prepared for retrofit of VTC equipment to an existing natural gas fired combined cycle plant operating in base load service, shown in Fig. 9. Capital costs are for the retrofit equipment only, assumed equal to the entire cost of the natural gas plant. This analysis predicts that average revenue must be \$50/MWh to pay back the capital investment within five years, lower than any of the other costs evaluated.

Improvements in efficiency through process optimization, reductions in fuel costs for wastes through disposal fees, and byproduct sales, will all improve the operating economics. The VTC system promises to reduce power costs, while maintaining the advantages of natural gas fired systems.

Preliminary Life Cycle Cost Analysis - 50 MW Natural Gas Fired Combined Cycle Plant - Base Load Service

Based on G.E. LM2500 STIG

Assumed Discount Rate		10												
Assumed Inflation rate		3												
		Project Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
		millions \$US	\$25	10 Year financing (including contingency)										
Capital Cost														
Payments	Interest Rate, %	10	-4.1	-3.8	-3.6	-3.3	-3.1	-2.9	-2.7	-2.6	-2.4	-2.3	0.0	0.0
Operating Costs (3% Of capital costs)			CONSTRUCTION in 2003											
Labor & Supervision			-0.7	-0.7	-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4	-0.4
Maintenance Costs (4% Of capital costs)														
Labor			-0.5	-0.4	-0.4	-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2
Materials			-0.5	-0.4	-0.4	-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2
Feed materials costs and fees														
Catalysts & chemicals	\$/tonne	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Consumption	TPY	0												
Fuel Costs	\$/Mbtu	3.00	-5.8	-5.4	-5.0	-4.7	-4.4	-4.1	-3.9	-3.6	-3.4	-3.2	-3.0	-3.0
Consumption	MBtuh	285												
Residue disposal costs	\$/tonne	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quantity to landfill	TPY	0												
Total Expense		millions \$US	-4.1	-11.2	-10.5	-9.8	-9.2	-8.6	-8.1	-7.6	-7.1	-6.6	-4.1	-3.8
Revenue														
Power sales	MWh/Yr.	360,000	CONSTRUCTION in 2003											
Disposal fees	\$/MWh	58	19.6	18.3	17.1	16.1	15.0	14.1	13.2	12.3	11.6	10.8	10.1	10.1
Consumption	\$/ton	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Byproduct sales	wet TPY	0												
Production	\$/tonne	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	TPY	0												
Total Revenue		millions \$US	0.0	19.6	18.3	17.1	16.1	15.0	14.1	13.2	12.3	11.6	10.8	10.1
Discounted Cash Flow			-4.1	8.3	7.8	7.3	6.9	6.4	6.0	5.6	5.3	4.9	6.7	6.3
Cumulative Cash Flow		millions \$US	-4	4	12	19	26	33	39	44	50	55	61	68

Capital cost recovered

Note: Average power output = **50 MW**
 Capital cost = **500 \$ per kW installed**
 Efficiency assumed = **60 % to electric power**

Fuel cost assumed = **3.00 \$/MJ (~million Btu)**
 Power sales assumed = **58 \$/MWh**
 Operating hours assumed = **7200 per year**

Figure 7

Preliminary Life Cycle Cost Analysis - 50 MW Biomass Combined Cycle Retrofit - Base Load Service

Based on G.E. LM2500 STIG

		Present Value, US\$millions (rounded to nearest US\$100,000)													
		Project Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
Assumed Discount Rate	10														
Assumed Inflation rate	3														
		10 Year financing (including contingency)													
Capital Cost	millions \$US	\$25													
Payments Interest Rate, %	10	-4.1	-3.8	-3.6	-3.3	-3.1	-2.9	-2.7	-2.6	-2.4	-2.3	0.0	0.0		
Operating Costs	(4% Of capital costs)		CONSTRUCTION in 2003												
Labor & Supervision			-0.9	-0.9	-0.8	-0.8	-0.7	-0.7	-0.6	-0.6	-0.6	-0.5	-0.5		
Maintenance Costs	(6% Of capital costs)														
Labor			-0.7	-0.7	-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4		
Materials			-0.7	-0.7	-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4		
Feed materials costs and fees															
Catalysts & chemicals Consumption	\$/tonne TPY	100 1,118	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1		
Fuel Costs Consumption	\$/Mbtu MBtuh	1.00 285	-1.9	-1.8	-1.7	-1.6	-1.5	-1.4	-1.3	-1.2	-1.1	-1.1	-1.1		
Residue disposal costs	\$/tonne	20	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2		
Quantity to landfill	TPY	18627													
Total Expense	millions \$US		-4.1	-8.5	-8.0	-7.5	-7.0	-6.6	-6.1	-5.7	-5.4	-5.0	-2.6	-2.4	
Revenue			CONSTRUCTION in 2003												
Power sales	MWh/Yr. \$/MWh	360,000 50	16.9	15.8	14.8	13.8	13.0	12.1	11.4	10.6	10.0	9.3	8.7		
Disposal fees Consumption	\$/ton wet TPY	0 0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
Byproduct sales Production	\$/tonne TPY	0 0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
Total Revenue	millions \$US		0.0	16.9	15.8	14.8	13.8	13.0	12.1	11.4	10.6	10.0	9.3	8.7	
Discounted Cash Flow			-4.1	8.3	7.8	7.3	6.8	6.4	6.0	5.6	5.3	4.9	6.7	6.3	
Cumulative Cash Flow	millions \$US		-4	4	12	19	26	33	39	44	49	54	61	67	
		Capital cost recovered													
Note:	Average power output =	50 MW						Fuel cost assumed =	1.00 \$/MJ (~million Btu)						
	Capital cost =	500 \$ per kW installed						Power sales assumed =	50 \$/MWh						
	Efficiency assumed =	60 % to electric power						Operating hours assumed =	7200 per year						

Figure 9

References

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