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Performance and Economics of Co-Firing a Coal/Waste Slurry in Advanced Fluidized-Bed Combustion

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PERFORMANCE AND ECONOMICS OF CO-FIRING A COAL/WASTE SLURRY IN ADVANCED FLUIDIZED-BED COMBUSTION

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A study was undertaken to investigate the technical and economic feasibility of co-firing a pressurized fluidized-bed combustor (PFBC) with coal and wastes in a slurry feed. Focus was placed on the production of electricity and the efficient disposal of wastes for application in central power stations. Issues concerning waste material preparation and feed, PFBC operation, plant emissions, and regulations are addressed.

Although there are considerable data on the operation of PFBCs when feeding coal dry and as a slurry, wastes have not been co-fired with coal. There is, however, significant information on co-firing wastes in atmospheric fluidized-bed combustors. Feeding the wastes into these combustors has been the most common problem. This prompted an investigation of approach and equipment to feed coal and wastes into a PFBC.

The study investigated slurry processing of the coal and sorbent in a combined coal/sorbent and waste feed to the combustor. As an alternative approach to slurry feeding, a sensitivity study of dry feeding of coal, sorbent, and the co-fired wastes was completed. The analysis compared overall plant efficiency and cost-of-electricity to determine if an advantage exists in slurry versus dry feed. To further enhance the results of this study, performance comparisons were developed for the PFBC without the co-firing of waste.

The waste considered for co-firing was municipal solid waste (MSW) as a refuse-derived fuel (RDF). Conceptual design of a utility scale power plant rated at 250 MWe was developed. Heat and material balances were completed and costs determined including capital costs, operating costs, and cost of electricity.

With the PFBC operation at high temperature and pressure, efforts were centered on defining feeding systems capable of operating at these conditions. Since PFBCs have not been tested co-firing wastes, other critical performance factors were addressed and recommendations were developed for resolving potential technical issues. Air emissions and solid wastes were characterized to assess the environmental performance, comparing them to state and Federal regulations. This paper describes the results of this investigation, presents conclusions on the key issues, and provides recommendations for further evaluation.

BACKGROUND

The Environmental Protection Agency's (EPA) 1990 estimates place the amount of MSW generated in the United States at over 195 million tons per year, up approximately 44 million tons since 1980(1). EPA estimates that 4.3 pounds of MSW are generated per person per day. Together with industrial process waste and municipal sewage sludge, the resultant burden on our capacity to dispose of these wastes in a cost-effective and environmentally acceptable manner is an enormous management problem.

One method of waste management is through combustion or incineration with energy recovery. This alternative has been plagued with a legacy of inefficient, dirty, and poorly operated incinerators, resulting in environmental problems and leaving communities searching for solutions. However, advanced power systems that can meet new stringent environmental regulations have been developed and operated successfully. Additionally, electric utilities and non-utility generators have shown significant interest in waste management through waste-to-energy facilities.

Co-firing waste with coal in a utility scale boiler has emerged as an effective approach to produce energy from waste. Fluidized-bed combustors are becoming a primary method of burning wastes. The fluidized-bed, with its stability of combustion and temperature, provides enhanced energy recovery and environmental control while achieving cost-effective waste management.

Waste classified as MSW is extremely variable in composition on both a seasonal and location basis. To produce a fuel that can be fed to a PFBC, MSW must be processed to remove metal, glass, and other non-combustibles to produce what is called refuse-derived fuel (RDF). Methods currently in use process about 50 percent of MSW to RDF. A typical 3-inch shredded material is prepared by shredding, magnetic separation, and air classification. It can be burned as is, pelletized, or slurried. A representative RDF proximate and ultimate analysis is shown in Table 1.

Table 1. Representative RDF Analysis

Proximate Analysis As Received		Ultimate Analysis As Received	
Moisture	30.73 %	Moisture	30.73 %
Ash	11.59	Ash	11.59
Volatile	48.93	Sulfur	0.32
Fixed C	8.75	Nitrogen	0.61
	100.00 %	Carbon	28.30
		Hydrogen	4.20
Btu/lb, HHV	4,801	Oxygen	24.25
		Total	100.00 %

Recently, there has been activity in developing pressurized feeders for biomass waste materials, and both dry and slurry feeders have been tested. Dry feed systems include double lockhoppers, rotary valve feeders, piston feeders, screw feeders, and pneumatic systems. Slurry feeders include progressive cavity pumps, piston pumps, and rotary feeders. While these options have not had substantial operating experience at PFBC conditions, it is assumed that eventually a reliable system will be available.

STUDY DESCRIPTION

Economic and performance results were developed for PFBC advanced generation plant configurations with a nominal ratings of 250 MWe. Performance considerations were given to fuel handling, emission control, and residual solids handling. Thermal performance for all cases was calculated by using an Aspen/SP^{TM} modular computer program. The program modeled the PFBC, gas turbine, heat recovery and steam generator, and the steam turbine cycle in a single, integrated calculation process. Plant material and energy balances were developed along with the net plant power, thermal efficiency, and net heat rate.

The capital costs, operating costs, and expenses were established consistent with EPRI Technical Assessment Guide (TAG)(2) methods and are expressed in 1992 dollars. An assumed 65 percent capacity factor was used. A baseline was established without co-firing waste materials. Comparisons were then made with alternative feed systems to define the effects on plant performance and costs.

RESULTS

The performance and economic analyses for the PFBC power plant co-fired with RDF assumed a utility base load application with electrical production of 250 MWe. Application specifics were then based on this scenario including the definition of site and ambient conditions, fuel, waste, and sorbent feedstock, and method of fuel/waste handling. The PFBC advanced-generation plant configuration as presented in Figure 1 was the basis for this study and is used to establish the baseline performance. The study utilized defined plant boundary conditions including ISO ambient conditions, Pittsburgh 8 coal, Plum Run dolomite, and waste feedstock for each PFBC application analysis. An 80:20 coal-to-waste ratio on an as-received weight basis was used to define the maximum amount of co-fired waste products.

Design Review

Major subsystems specifically influenced by the waste material feedstock are fuel handling, emission control, and residual solids handling. Of particular concern to this study is the impact on system performance from variations in the fuel/waste handling process.

Fuel Handling Options. The analyses investigated processing of the coal, sorbent and waste materials in either: (1) separate dry combustor feed of the coal, sorbent, and waste streams, or (2) combined coal/sorbent and waste fired in a slurry media. Figure 2 shows a schematic of the dry feed components, and Figure 3 shows the feed components for a combined slurry of coal,

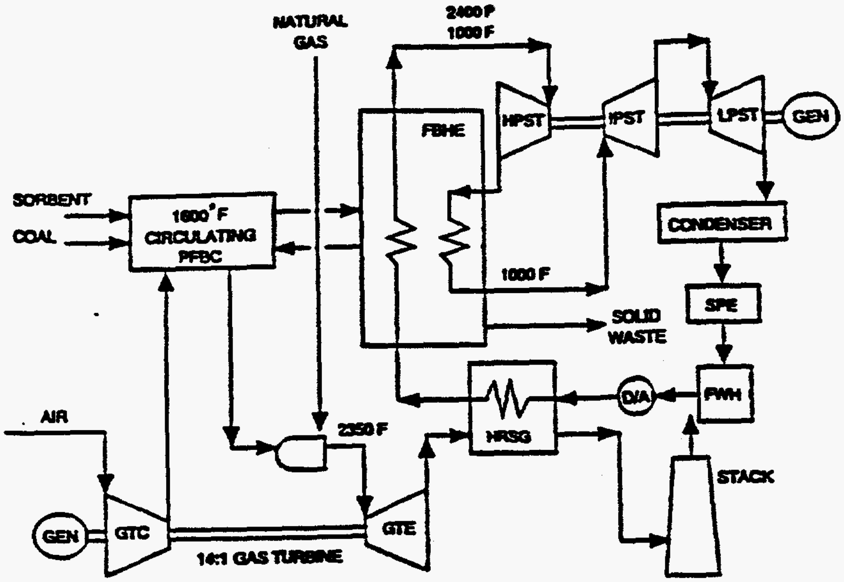

Figure 1
PFBC Advanced Generation Configuration

limestone, and waste. The analysis compared overall plant efficiency and cost-of-electricity to determine if an advantage exists in dry versus slurry feed.

For the slurry feed analysis, the coal and sorbent are conveyed and sized using conventional equipment. The combined feedstock is then slurried for transport via a water media at 75 percent total solids (t.s.). RDF is combined with coal and sorbent in the slurry preparation tanks to 75 percent t.s. The combined slurry is then pumped into the PFBC. The inherent moisture of RDF was not considered as part of the slurry water content.

In the case of dry feed, coal and sorbent are pneumatically conveyed to the PFBC. MSW is delivered to the site and converted into RDF using conventional equipment. First an initial separation of large items is completed, then conveyed to a crusher. The material from the crusher is fed into an air table, which separates light material from non-combustibles. A shredder is used to size the material to 3x0 inch. The RDF is then fed to the PFBC via a screw conveyor. Separate feed systems allow different fuel injection points in the combustor. In this manner the relatively light RDF material can be fed to the PFBC at a point to assure complete combustion.

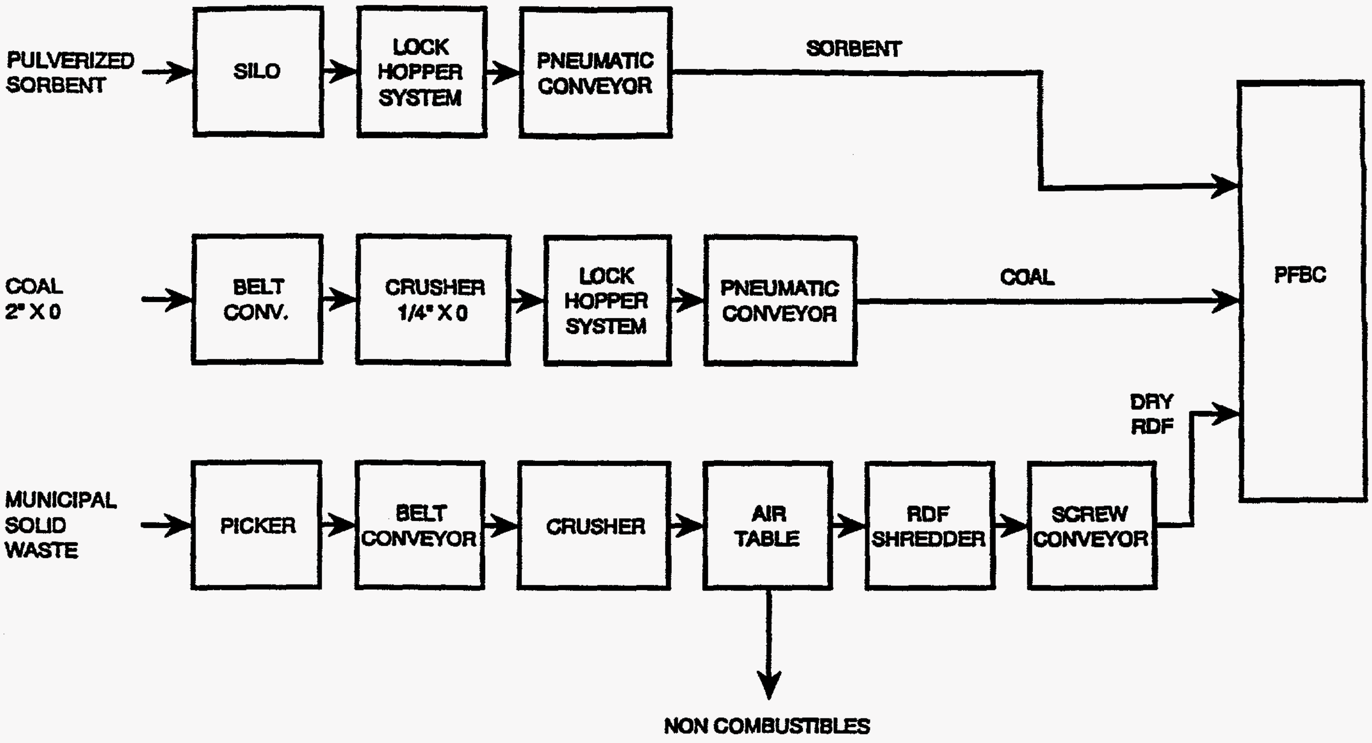

Figure 1
RDF Dry Feed Components

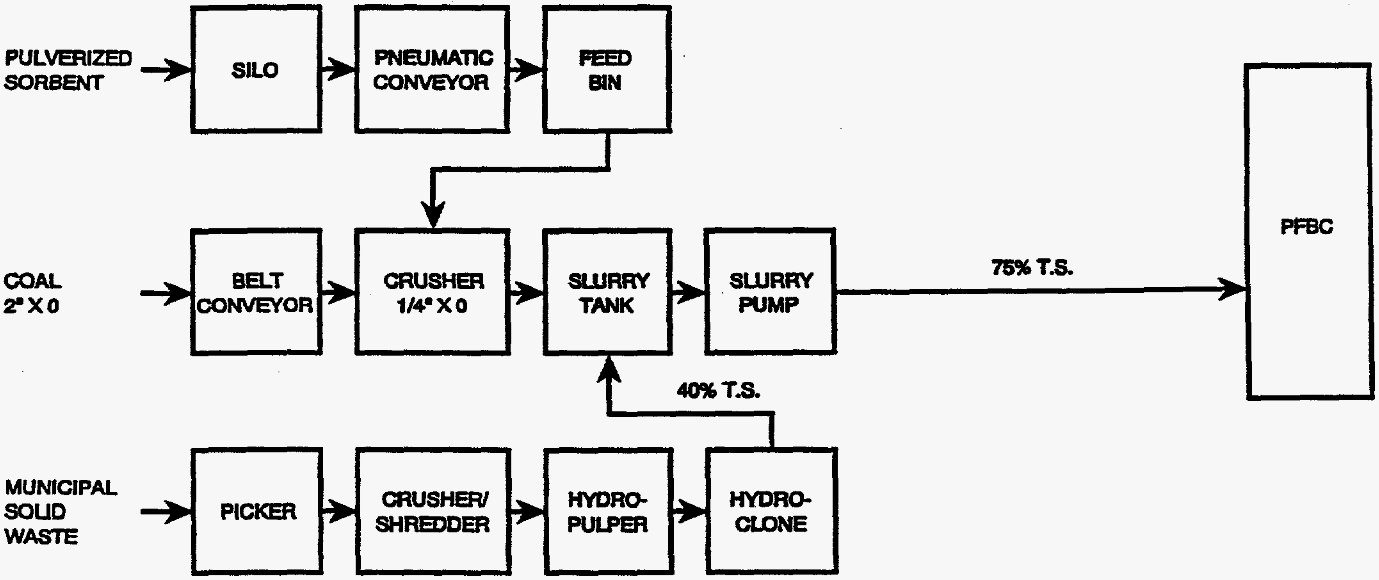

Figure 2
RDF Slurry Feed Components

Material Handling. A major concern for PFBC co-firing waste materials is the operation of the fuel feed and handling equipment. The flow and handling characteristics of coal and RDF are affected by quality, moisture content, particle size, and extraneous contaminants. Feeding these materials into pressure vessels differs greatly from feeding into atmospheric processes due to pressure influences in the tension and compression strength of the feed material. High pressure feeders have been designed for coal, in both dry and slurry form, but only recently has there been activity in developing pressurized feeders for biomass waste materials.

There are many advantages for feeding solids in a slurry form over dry, including:

- the equipment is proven and commercial,
- control is simplified,
- several fuel or waste streams can be fed with one system, and
- flow measurements are more accurate.

The main disadvantage for slurry feeding of waste materials can be the effect on performance from the additional water. Depending on the coal type and size distribution, feeding coal slurries at 75 percent total solids has been successfully demonstrated; however, higher moisture contents can be undesirable.

Three slurry feeders and their operating characteristics are described below:

- Progressive cavity pumps are well known and have a demonstrated history pumping a wide variety of slurries. These pumps can operate up to 450 psi.
- Double piston pumps are also commercially available for pumping slurries of various materials. One pump is capable of pumping at high capacity (over 20 tons per hour) and at high pressures of over 725 psi.
- A continuous high-pressure lockhopper feeder has been developed for feeding wood chips into a pulp digester. This feeder could be adapted for RDF. It was designed for 150 psi service, but could be operated at higher pressures.

Dry feed systems can be grouped into the following types:

- lockhopper (gravity and screw feed) tested to 500 psi,
- rotary valve feeders tested to 350 psi,
- piston feeders tested to 2175 psi,
- screw feeders tested to 1450 psi, and
- pneumatic.

These systems have not been fully demonstrated on a PFBC system and some have been designed for capacities too low for commercial PFBC plant sizes. The conceptual designs for this study use both slurry feeders and dry feeders. In order to cost the systems, a choice of feed systems was made even though there is not sufficient operating experience on which to base a final decision. The devices chosen are the double-piston pump for slurry and the piston feeder for dry materials.

Emission Control. Predicting the amounts and types of flue gas emissions is difficult with this class of systems. There are no data from circulating PFBC's co-firing coal with RDF; however, some generalizations can be made based on AFBC data. It is encouraging to note that emissions from facilities co-firing RDF and coal are within regulatory limits. Each new co-fired waste burning facility would have to address their flue gas and solid waste emissions potential before and after the combustor design as is the case with conventional combustors.

Performance Analysis Assumptions

Operational conditions were established assuming a utility base load application located in the United States Mid-Atlantic region. The PFBC combustor design parameters were assumed to follow the design assumptions defined in previous reports(3). The PFBC is a circulating bed with an operating temperature in the 1600°F range. A 99.3 percent carbon conversion efficiency was assumed for performance modeling along with a 93.3 percent sulfur removal. The 250 MWe application includes the use of a Westinghouse 501D5 gas turbine with an 1800 psi/1000°F/1000°F steam turbine bottoming cycle.

The case profile used to define the performance assumptions is as follows:

- The baseline case firing Pittsburgh 8 coal and Plum Run dolomite pneumatically conveyed to PFBC.
- Pittsburgh 8 coal, Plum Run dolomite, and municipal solid waste as RDF in a combined slurry feed at the 80:20 coal-to-waste ratio.
- Pittsburgh 8 coal, Plum Run dolomite, and municipal solid waste as RDF in separate dry feeds at the 80:20 coal-to-waste ratio.

Performance Analysis Results

The PFBC plant, as presented in Reference 3, is the basis for this study and was used to establish nominal performance without co-firing waste. The performance for the 250 MWe PFBC plant without co-firing is shown in Table 2. Also shown are performance values for the same facility co-firing RDF as a slurry and in a dry form.

As indicated, an overall conversion efficiency of 41.38 percent was defined for the facility without co-firing of waste materials. With waste co-firing, conversion efficiencies decreased in the range of 2.4 percent for slurry feed to 1 percent for dry feed operation. Moisture content in the feedstock and auxiliary power requirements were the drivers for performance differences.

Economic Analysis Results

The cost evaluations for the various PFBC plants were developed by performing a consistent evaluation of the capital and operating costs for each plant and subsequently performing an economic analysis based on the cost of electricity (COE) as the figure of merit. The conceptual

Table 2. 250 MW PFBC Plant Performance Comparison

	W/O Waste Co-firing	RDF (Slurry)	RDF (Dry)
ENERGY INPUT			
Coal Feed, lb/hr	128,861	118,313	117, 691
Coal HHV, Btu/lb	12,450	12,450	12,450
Natural Gas, lb/hr	19,257	19,635	19,251
Natural Gas HHV, Btu/lb	21,799	21,799	21,799
Waste Feed, lb/hr		29,578	28,367
Waste HHV, Btu/lb		4,103	4,103
Plant Energy Input, MW	595.181	592.713	588.256
ENERGY OUTPUT			
Gas Turbine, MW	87.501	98.882	89.139
Steam Turbine, MW	169.369	151.897	163.932
Auxiliaries, MW	10.590	11.407	12.030
Net Plant Power, MW	246.280	239.372	241.041
Thermal Efficiency, %	41.38	40.39	40.98
Net Heat Rate, (Btu/kWh)	8,247	8,449	8,327

cost estimates for each plant were determined on the basis of previous evaluations of conventional pulverized coal and advanced PFBC power plants(3). The detail values from these referenced cost data were adjusted for capacity, design condition changes, and cost base.

Costs for the as-received waste materials were not included in the operating cost analysis. Additionally, economic incentives in the form of tax credits or direct payment to the facility were not included. Significant cost savings can be achieved through the application of credits including tipping fees, state and local tax credits, demand-oriented initiatives, and direct payments from municipalities for waste-to-energy disposal.

Table 3 shows the economic analysis results as unit capital costs, defined as Total Plant Cost (TPC), and relative COE. As a reference, the table includes a comparison to the same size plant without the co-firing of wastes as the baseline for COE. Capital costs and COE's are within 4.2 percent and 3.4 percent, respectively, of the waste free plants. The estimated TPC in 1992 dollars ranges from $1,107 for the co-fired slurry fed plant to $1,167/kWe for the co-fired dry feed operation. For the same plant without waste co-firing, the TPC is approximately $1,120/kWe. Capital, operating, maintenance, and consumable costs are shown in Table 4. As indicated, slurry processing of the fuel and waste feed provides a more cost effective approach to PFBC operation than a comparable dry feed system.

Table 3. Economic Analysis Results

	Net Power MWe	Total Plant Cost $/kWe	COE % Change
Co-Firing RDF			
250 MW (Slurry)	239	1,107	+1.9
250 MW (Dry)	241	1,167	+3.4
Without Co-Firing Wastes			
250 MW	246	1,120	Baseline

Table 4. 250 MWe Plant Comparison
(1992 dollars)

Case Description		Base Plant (Waste-free)	RDF (Slurry)	RDF (Dry)
Net Power	MW	246	239	241
Heat Rate	Btu/kWh	8,247	8,449	8,327
Capital Cost				
Fuel Prep & Feed	$M	17.4	9.4	25.4
PFBC	$M	38.8	37.5	38.2
Turbine-Generator	$M	68.4	65.6	67.2
PFB HGCU	$M	16.8	17.5	16.9
Rest of Plant	$M	134.4	135.1	133.7
Total Plant Cost	$M	275.8	265.1	281.4
TPC	$/kW	1,119.8	1,107.4	1,167.3
Change from Base		-	-1.1%	+4.2%
Cost of Electricity				
Fixed O&M	$/MWh	9.4	10.9	11.1
Variable O&M	$/MWh	5.1	5.8	6.0
Consumables	$/MWh	5.2	5.1	5.1
Fuel	$/MWh	27.3	26.4	26.1
Change in COE		-	+1.9%	+3.4%

In summary, the key issues for co-firing are feeding waste materials against system pressures (solids handling), materials concerns due to the addition of potentially corrosive constituents, and environmental impact of solid wastes and gaseous emissions. In order to address these issues, pilot-scale testing co-firing waste materials should be performed and the results used to predict commercial-scale performance. The testing should be performed in a facility of adequate size so that commercially representative fuel feed sizes and gas residence times can be evaluated.

The fuel prep and feed component of the TPC has the greatest variance within the cases. The coal (waste-free) and the RDF (dry) cases are the highest values. This is due to the pneumatic design for fuel feeding. Slurry feed systems were shown to be less costly to install than dry feed systems. However, also included in this cost component are the waste preparation and delivery equipment. The dry-feed system combined with waste preparation and feed equipment makes the RDF (dry) case the most expensive. The plant with slurry feed system combined with the waste preparation and feed equipment is equitable on the TPC $/kW basis with the coal (waste-free case).

The capital costs associated with the waste feedstock preparation and feed ranged from a high of $37/kW for the RDF dry feed approach to $15/kW for the RDF slurry. The fuel cost component of the COE varies between cases due to the plant efficiency and the percent of the Btu input supplied by the waste fuels. The fixed and variable O&M cost components of the COE are higher for all plants with waste co-firing than for waste-free plants due to the additional equipment train required to process the waste fuel feedstocks.

FUTURE WORK

This study's objective was to investigate co-firing a pressurized fluidized-bed combustor with coal and refuse-derived fuel for the production of electricity and the efficient disposal of waste. Performance evaluation of the PFBC power plant co-fired with RDF showed only slightly lower overall thermal efficiency than similar sized plants without waste co-firing. Capital costs and COE's are within 4.2 percent and 3.4 percent, respectively, of waste-free operation.

The results also indicate that there are no technology barriers to the co-firing of waste materials with coal in a PFBC power plant. The potential to produce cost-competitive electrical power and support environmentally acceptable waste disposal exists with this approach. However, as part of technology development, there remain several design and operational areas requiring data and verification before this concept can realize commercial acceptance.

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