OPERATING EXPERIENCE OF A COAL-FIRED BOILER RETROFIT WITH AN ADVANCED HYBRID OF COAL GASIFICATION FOR SO_2 & NO_X EMISSIONS CONTROL AND REDUCED OPERATING COST

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INTRODUCTION:

Utility and industrial boiler owners want to know; "How can my boiler stay competitive in today's environment with ever higher fuel-costs and especially with new requirements to meet EPA's stringent air-quality emission regulations?"

The recent operating experience of an **advanced hybrid of coal-gasification** retrofit on an industrial coal-fired boiler shows promise to reduce operating cost, improve boiler efficiency and control both SO_2 and NO_x emissions.

The project described herein is not an Integrated Gasification Combined Cycle (IGCC) system, but a much simpler, lower-cost air-blown entrained-flow coal gasification technology that replaces the boilers existing burners. Final combustion of the gasified coal is completed in the boiler furnace with over-fire air (OFA). Called the **Clean Combustion System™ (CCS)**, the CCS simply prevents formation of SO_2 (sulfur dioxide) and NO_x (nitrogen oxides) emissions during coal combustion. Such a boiler conversion can meet EPA's stringent new air quality regulations while burning the lower-cost coals. This hybrid of coal-gasification technology can make practical the conversion of gas, oil and coal-fired boilers to coal-firing for lower operating cost and emissions compliance.

THE CLEAN COMBUSTION SYSTEM™:

The CCS concept evolved from a confluence of rocket-engine technology and advanced combustion modeling techniques, and from experience in coal gasification and wet-bottom (slag-tap) boiler design and operation.

In conventional coal-fired boilers the fuel is fully oxidized to carbon dioxide (CO_2) and water (H_2O). The nitrogen and sulfur in the coal are also both

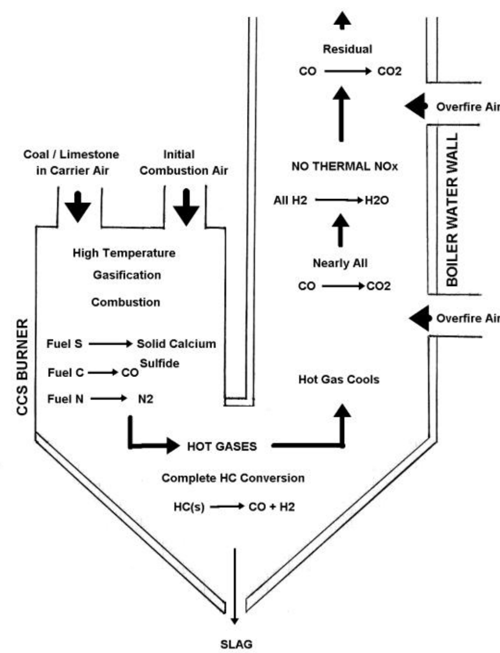

Figure 1. CCS Flow Diagram

oxidized to the pollutants nitrogen oxides (NO_x) and sulfur dioxide (SO_2). In coal-gasification, firing coal with a limited amount of air (oxygen) entails partial oxidation (of the hydrocarbons);

to create a hot gas whose major components are hydrogen (H_2), carbon monoxide (CO), and nitrogen (N_2). See Figure 1. CCS Flow Diagram.

Earlier field demonstrations of the CCS show that during controlled high temperature gasification conditions, the formation of both NO_x and SO_2 can be prevented.

The CCS operates much like a conventional pulverized coal-fired burner, using typical off-the-shelf hardware, familiar to the operators. It fires pulverized coal with some limestone added to provide the necessary calcium to capture the sulfur in the coal, developing a clean, hot, fuel-rich gas that enters the boiler furnace. Subsequent over-fire air (OFA) staged in the furnace completes the combustion with excess air, providing at least the same furnace steaming performance as before the retrofit.

BOILER RETROFIT – THE CCS-STOKER®

Phenix Limited, LLC, contracted to design, engineer and supply the equipment to install the Clean Combustion System (CCS-Stoker®) on a 1940's coal-fired stoker boiler. The client installed the equipment. The project's objective was to significantly lower the facilities energy cost by firing low-cost high sulfur coals with emissions control, in lieu of burning expensive compliance (low-sulfur) coals.

The project was initiated on October, 2005. As this was an emissions control project, a permit to construct was received with waivers of NSPS (new source performance standards) and PSD (prevention of significant deterioration) and no NSR (new source review). The permit emissions limits were <0.9 # SO_2 / mmBtu and <0.25 # NO_x / mmBtu. Compliance coals were to be fired until the unit was commissioned. Construction began in August, 2006 and commissioning check-out commenced in January 2007. The unit began regular firing of coal by April with Phenix providing T&M consultant support. In May, several equipment modifications were made, and by the end of June, operational testing at design loads began.

A cross section view of a typical stoker boiler is shown in Figure 2.

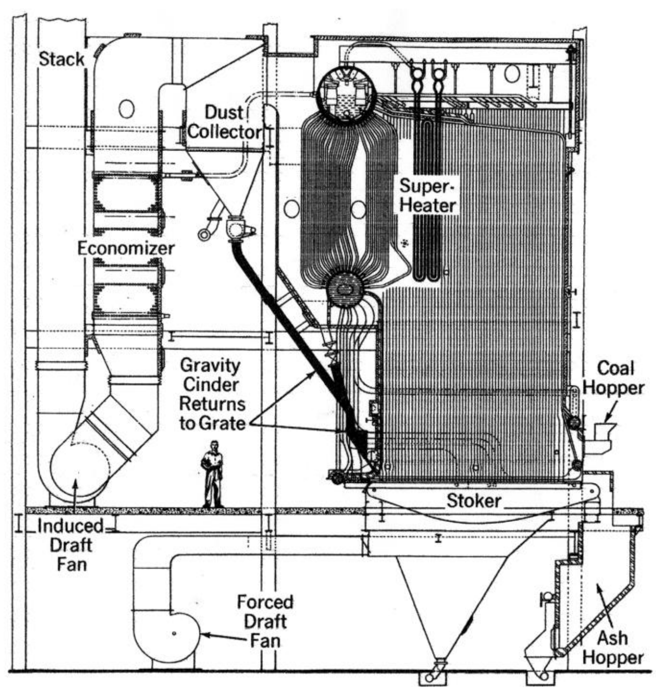

Figure 2. Typical Stoker Boiler Design

Lump stoker grade coal is fed from the coal bunker to a hopper and metered by the stoker feeder onto the boilers moving grate. The coal is suspended on the moving grate and burns with air fed from below until combustion is completed. The coal ash drops from the front of the grate into an ash pit below the grate.

The steps to a CCS-Stoker® retrofit are significant for this type of boiler, as the unit must be converted to pulverized coal firing. The CCS-Stoker® retrofit modifications include:

- Remove the existing coal stoker and ash hopper, and brick-over the grate system.
- Install new CCS Burner and gasification chamber, firing through the stoker opening.
- Add a new air preheat system and OFA distribution ducting.
- Install a coal pulverizer and coal feed system
- Provide a powdered limestone silo and metering system
- Install a new bottom ash (and slag) collection system.
- Replace the obsolete manual controls with a new redundant computerized burner management and combustion control system with operator interface screens.
- The motor control center was also replaced with new equipment as were much of the piping, wiring, and boiler instrumentation.

CCS INDIRECT COAL FIRING SCHEME:

To meet the fuel-rich requirements for coal gasification, the CCS uses an "indirect-coal-firing" scheme. Raw coal from the existing bunker is fed to a pulverizer by a metering feeder and milled and dried with a quantity of hot sweep gas extracted from the boiler exhaust. The sweep gas and powdered coal are then separated in a bag house. The dry powdered coal is collected in the bag house hopper. The spent sweep gas containing the moisture that was in the coal is then returned to the boiler exit and flows into the existing bag house. The concentrated powdered coal is then metered and conveyed by air to the CCS burners. The major CCS-Stoker® retrofit equipment is shown in the Process Flow Diagram of Figure 3.

A 3D-view drawing of the CCS-Stoker® boiler equipment layout incorporating the CCS indirect coal firing scheme are shown in Figure 4. Note that all of the equipment, except for the bag house, fits within the boiler building.

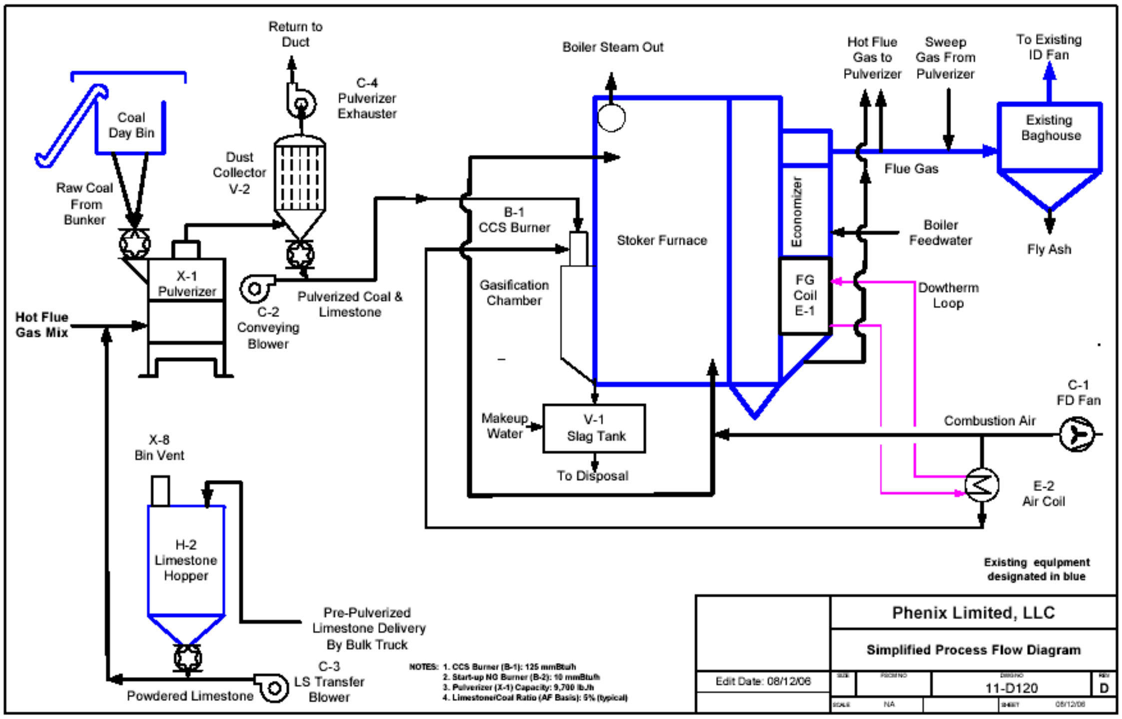

Figure 3. Process Flow Diagram

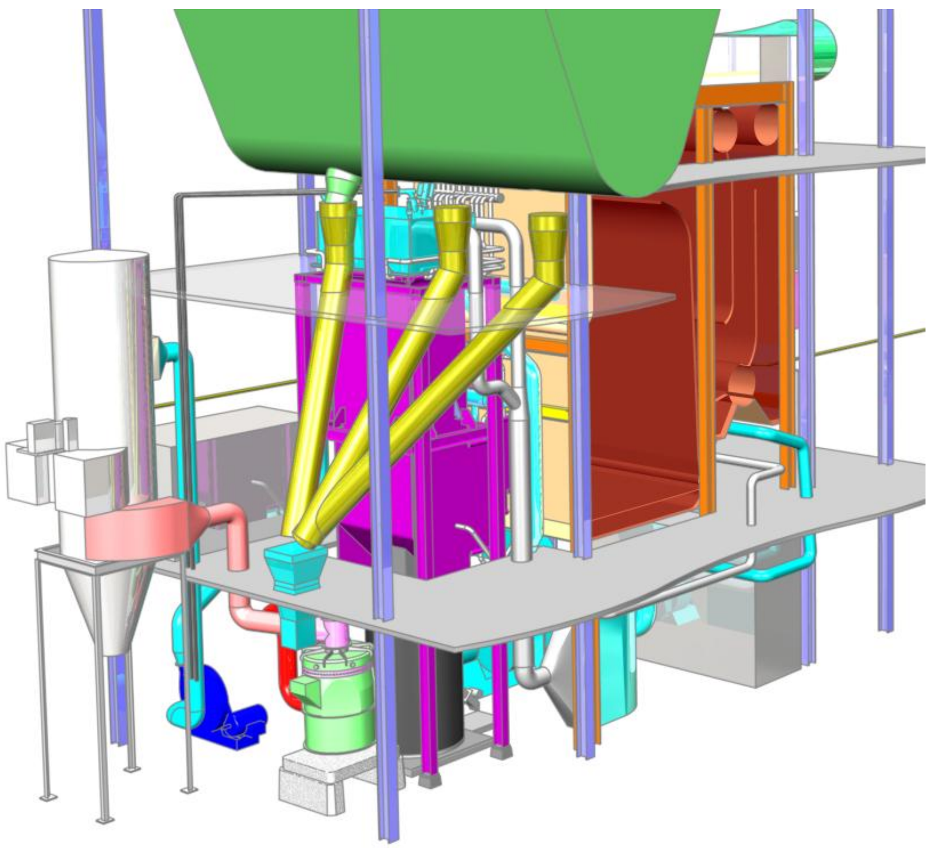

Figure 4. 3D View of the CCS-Stoker® Retrofit

Equipment Discussion

CCS Burner and Gasification Chamber:

There are two 62.5 mmBtu/h CCS burners with NFPA (National Fire Protection Association) required flame scanners and safety shut off valves mounted on the top of the gasification chamber.

A 10 mmBtu/h retractable lance natural gas fired gun is used for boiler start-up. On a start signal, a blast gate in the CCS burner face opens and the gas gun is extended and lighted. After warm-up, and after coal flow started, the gas gun will continue to fire until the fuel-rich gasification conditions are established. Then, with insufficient oxygen, the gas flame extinguishes, and the gun automatically retracts.

This view shows the gasification chamber being lifted into the boiler building and located on the front of the boiler.

The gasification chamber (GC) provides the necessary residence time to gasify the coal and provide for sulfur capture. The gasification chamber is typical of boiler membrane-wall construction. It is cooled by natural circulation of the boiler water from connections to the upper and lower boiler drums. The inside surface is studded and coated with a refractory. This surface provides a base on which the molten coal ash / slag freezes on and provides the final insulation and protection from the high combustion temperatures. The hot combustion gases exit through a 135 degree turn into the boiler furnace. This change of direction causes about half of the melted coal ash to deposit on the chamber walls and drain from the slag tap to a water quench tank below. The slag is crushed and sluiced to a storage silo for disposal.

Limestone Feed and Conveying System:

Limestone is purchased pre-pulverized and stored in a nominal 100 ton hopper. The system includes a slide gate, rotary feeder and a small hopper / metering screw feeder driven by a variable-speed-drive. The feeder follows the coal feed rates at the mill to maintain the proper limestone/coal ratios. A pressure blower conveys the limestone to the pulverizer sweep air inlet.

AIR PREHEATING:

The CCS-Stoker® burners require hot (500F) combustion air. Industrial stoker furnace designs do not provide pre-heated combustion air. The installation cost of a conventional air-to-air heat exchanger at the boiler exit exceeded the project budget, so a lower-cost hot-oil Dowtherm loop was selected. A Dowtherm heat exchanger at the boiler exit was plumbed to an oil-air heat exchanger on the first floor after the FD fan.

PULVERIZER:

The pulver izer supplied was a refurbished 453 CE/Raymond mill (45" diameter bowl, three rollers) designed to process about 11,500 lb/h of bituminous coal.

The mill is supplied with hot flue gas from the boiler exit to dry the coal and sweep the pulverized coal into a down stream coal-air separator. As boiler flue gas is low in oxygen (<10%), its use as a source of sweep gas provides a measure of improved safety from coal fires and mill puffs in the coal preparation system.

COAL-AIR SEPARATOR:

A specially designed bag house located down stream of the pulverizer separates the pulverized coal and limestone from the sweep gas. The bag house hopper holds ~30 minutes of powdered coal. Level switches in the hopper signal the pulverizer feeder to maintain a level of powdered coal in the hopper. The powdered coal is metered by a variable-speed drive rotary valve and conveyed to the CCS burners.

CCS-STOKER® OPERATION OBSERVATIONS

BOILER START-UP AND SHUT-DOWN:

To start-up the boiler, the 10 mmBtu NG Warm Up gun located on the CCS burner is inserted and fired to bring the furnace to operating temperature. This energy is sufficient to bring a cold boiler up to operating temperature in about 3 hours. When the boiler's exit flue gas has warmed to about 150°F, the pulverizer is started and a small amount of coal can be milled, dried and stored in the bag house hopper. When the hopper has filled, the boiler can then begin coal firing at ~50% load. This causes the boiler flue gas exit temperatures to rapidly rise and support full load operation

However, during the initial start-ups, we learned that the boiler exit gas temperature would not get hot enough to heat the Dowtherm. With extensive firing, we could warm the combustion air up to only ~300°F, and even with the NG warm-up gun firing adjacent to the CCS burners, the coal would not light. So, a 3 mmBtu/h direct fired NG burner was ordered and installed in the CCS combustion air duct. Now with combustion air heated to +500°F, and with the NG Warm-up Gun, the boiler could be brought on line and firing coal on a regular basis in 5 to 6 hours. Further, with hot combustion air, the CCS burner was stable and the detail start-up commissioning began.

Boiler shutdowns are straight forward by simply stopping coal flow to the mill and allow time to burn all of the coal in the bag house hopper. The mill sweep gas and limestone flows are maintained to coat the interior of the mill, bag house and ducting with an inert layer of limestone powder for protection from potential coal fire, condensation and corrosion during boiler outages.

FURNACE FLY ASH:

When operated as a stoker furnace, it is noted that large slag deposits extend into the furnace a foot or more from the refractory surfaces between the boiler tubes. Also, ash and slag fouls the furnace ceiling boiler tubing. Normal stoker operating practice is to schedule outages to conduct a vigorous cleaning of the furnace walls and ceiling.

With the CCS-Stoker® retrofit, the bright orange radiant gases entering the boiler furnace from the Gasification chamber are fairly clear; it is possible to see across the furnace floor to the opposite wall. The gases include a fair amount of fine coal fly ash that is tan in color and low in carbon. **The adjacent**

photos of the boiler furnace were taken after many days of operation. It can be seen that are almost no ash deposits stuck to the furnace wall or ceiling tubes. Any furnace ash deposits that tended to form between the boiler tubes are a soft fluffy material that falls and collects on the furnace floor. This product was allowed to accumulate and removed when convenient. The furnace residence time was sufficient to mix in over-fire air and complete the combustion of the carbon, CO and H_2 before the gases exited the furnace. A limited quantity of fly ash was collected in the ash hoppers under the boiler back-pass sections.

GASIFICATION CHAMBER:

The GC and slag tap performed as designed. As was expected, initial boiler operation at low (~50%) boiler loads did not generate sufficient temperatures to fully melt the coal ash. Adjustments of the fuel-air ratios to the design point at the higher boiler loads were being made to resolve this detail. There was no evidence of any refractory deterioration.

DOWTHERM LOOP:

After several months of operation, and at higher boiler loads, the oil in the Dowtherm loop over heated and boiled. After several attempts to resolve this issue, the oil was drained and the combustion air-preheat loop not used. The in-duct burner was sufficient to maintain the necessary combustion air preheat for operation. If the project budget had permitted installation of a conventional air to air heat exchanger that Phenix had specified earlier, there is little doubt that combustion air temperatures could have been controlled properly over the boiler load range.

PULVERIZER:

With the CCS-Stoker® retrofit boiler operating at full load (95,000 #/h of steam), a bolt failed in the coal pulverizer causing it to jam and the motor tripped. There was no significant damage to the mill. It has been repaired and operation could have resumed with little interruption of commissioning operation. Phenix was prepared to continue the project with the next phase of boiler tune-up, optimization set-point tests, and continuous operation. However, for reasons that have not been explained to Phenix, the owners have terminated the project.

In the opinion of Phenix, the preliminary CCS emissions performance data is very compelling evidence that this technology can provide a cost-effective emissions control for the coal-fired industry.

CCS-STOKER® PRELIMINARY PERFORMANCE SUMMARY

CCS PERFORMANCE:

The preliminary emissions data collected during the commissioning and check-out phase confirmed the CCS-Stoker® boiler retrofit should be able to meet the projects environmental permit requirements. It is Phenix opinion that this multi-pollution control performance could also meet the EPA's new Clean Air Interstate Rules (CAIR) for SO_2 and NO_x when firing most bituminous coals.

The following table summarizes the results developed by the CCS-Stoker® project to date with reference to the original boiler base line testing parameters:

Item	Stoker Base Line Test	Preliminary CCS Performance	% Change from Base Line
SO_2 Stack Emissions (lb/MMBtu)	1.80	0.72	-67 %
NOx Stack Emissions (lb/MMBtu)	0.50	0.14	-72 %
Boiler Efficiency	77.0	86.9	+ 12.8 %
CO_2 Reduction: Ton/yr GW credits (%)	94,019	73,720	- 20,300T/y (-21.6%)
Project Cost Recovery (fuel savings)		~ 3 years	

COAL SPECIFICATION

The CCS-Stoker® was designed to fire local Illinois coal with a nominal sulfur content of 2.5 # SO_2 /mmBtu. During commissioning, the unit fired the 1.8 # SO_2 /mmBtu compliance coal, so as to not be concerned about exceeding the SO_2 permit limits. This coal was a 50 / 50 blend of Indiana low-sulfur coal and local high-sulfur Illinois coal. The necessary limestone additive for sulfur capture is estimated to cost < $ 1.00 per ton of coal fired.

CCS-STOKER® SO_2 EMISSIONS:

Daily emissions monitoring confirmed the SO_2 emissions met the project permit goals at all operating loads. SO_2 capture efficiency of up to 76% was measured during normal operation; however, parametric testing opportunities to optimize SO_2 capture were not available.

CCS-STOKER® NO_X EMISSIONS:

The NO_x emissions at full load were 0.14 # NO_x / mmBtu (~88 ppm NO_x), well with in the permit requirements. Further, NO_x was consistently very low at lower operating loads, averaging .087 # NO_x / mmBtu (~50ppm).

CCS-STOKER® BOILER TUNE UP AND EFFICIENCY:

Had the project continued as was planned, the next steps would have been to conduct a series of boiler tune-ups, followed by a 30-day period of continuous operation that included emissions testing of the stack gases.

The fundamental reason for the improved boiler efficiency is that there is a substantial reduction in the quantity of coal needed to achieve the same amount of steam production. This improved efficiency is achieved by these factors:

- The CCS-Stoker® combustion achieves high carbon burn-out compared to the original stoker grate system. Consequently, there is very little / no carbon remaining in the fly-ash and slag products. A further significant benefit is that the CO at the boiler exit is less than 100ppm, controllable with OFA adjustments.
- The CCS-Stoker® can operate with low excess air, so as to minimize the source of this heat loss.
- The removal of coal moisture by the pulverizer reduces the heat losses from that moisture passing through the furnace.
- Of course, with concern for Global Warming CO_2 emissions, the improved CCS-Stoker® efficiency results in an estimated 21.6% reduction of CO_2, ~ 20,300 Ton/yr.

CONCLUSIONS AND RECOMMENDATIONS:

Most of the project objectives were met even though the project was not completed to the degree that Phenix would have liked. Consequently, Phenix is confident the results obtained from this project can be applied to follow-on projects.

As the CCS process provides an inherent emissions control of both SO_2 and NO_x right in the combustion step, the boiler simply becomes a heat recovery steam generator, needing only a bag house for particulate control. A new boiler integrated with the CCS provides a very competitive design with the largest MW per ton of steel and the smallest footprint of any boiler technology. Boiler scale-up is straight forward with a multiple of burners. Planning is underway for much larger projects from 100 to 600 MW, either retrofit or new, to obtain the cost benefits of scale available in all boiler and utility projects.

With increasing fuel costs and with the very critical energy needs that America faces at this time, Phenix is certain that the Clean Combustion System™ can make a significant contribution to improve the performance of America's electric generating power plants, to reduce our dependence on foreign fuels and better utilize our domestic coal resources.

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- The Project Owner (who wishes to remain anonymous) – Project Management, Construction and Installation, and for the initiative to conduct this project
- The Phenix Team – Program Lead, CCS Process Design & Analysis, and CCS burner
- The McBurney Corporation – Boiler Modifications, Gasification Chamber, controls & instrumentation, and start up services
- PDS Solutions Inc. – Balance of Plant Design and Equipment Supply
- Reaction Engineering International – CFD Analysis
- Zewski Corporation – 3D Design

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