



## Circulating Dry Scrubbers Comply with the EPA Maximum Achievable Control Technology Limits

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*Presented at*  
POWER-GEN 2011

T-227

# CIRCULATING DRY SCRUBBERS COMPLY WITH THE EPA MAXIMUM ACHIEVABLE CONTROL TECHNOLOGY LIMITS

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## ABSTRACT

*The SO<sub>2</sub> emissions for four units recently retrofitted with Circulating Dry Scrubbers (CDS) were below the Maximum Achievable Control Technology (MACT) limits for existing Electric Generating Units (EGUs) as measured with stack continuous emission monitors. The particulate and HCl emissions measured by established EPA methods were below the limits for existing EGUs. The Hg emissions for two of the units were below the limit for existing EGUs without injecting activated carbon (the Hg emission for a third unit was not measured). A fourth unit removed 88% of the mercury without injecting activated carbon, but it was not below the signed existing EGU limit. There may be several reasons why the fourth unit did not achieve the exiting EGU Hg limit that we continue to study. The EPA set the limits for particulate matter, HCl and Hg for a new EGU between 43 to 65 times lower than the limits for an existing EGU. We believe the CDS can achieve the limits for new EGUs by adjusting operating conditions, injecting more reagent to capture more HCl and injecting activated carbon to enhance the natural capture of Hg in the scrubber.*

## U.S. EPA MACT RULES

On December 16, 2011, the U.S. EPA signed national emission standards for Hazardous Air Pollutants (HAPs) known as the Mercury and Air Toxics Standards (MATS) for Power Plants for coal and oil-fired Electric Utility Steam Generating Units (EGUs) [1]. These standards are also known as the Utility Maximum Achievable Control Technology (MACT) rules because the rules are based on the best that can be achieved with current pollutant control technology.

The signed rules include limits for filterable particulate matter (PM), HCl, and Hg. Table 1 summarizes the rules for existing and new coal-fired EGUs firing coals other than lignite (mineral matter free higher heating value  $\geq$  8300 Btu/lb coal) and not including Integrated Gasification Combined Cycle Units (IGCC). There are also signed limits for EGUs that fire liquid oil and oil-derived solid fuels (e.g., petroleum coke).

Subcategory	Filterable Particulate Matter	Hydrogen Chloride	Mercury
Existing coal firing not low rank virgin coal*	0.030 lb/10 <sup>6</sup> Btu (0.30 lb/MWh)	0.0020 lb/10 <sup>6</sup> Btu (0.020 lb/MWh)	1.2 lb/10 <sup>12</sup> Btu (0.013 lb/GWh)
New coal firing not low rank virgin coal*	0.007 lb/MWh	0.40 lb/GWh	0.0002 lb/GWh

\* >8300 Btu/lb moist, mineral matter free calorific value.

*Table 1. Signed EPA MACT Emission Limitations for Coal-Fired Electric Generating Units*

The U.S. EPA states that PM will be a surrogate measurement for non-Hg metallic HAPs, and HCl will be a surrogate measurement for acid gas HAPs. If an EGU does not have a Continuous Emission Monitoring System (CEMS) for a pollutant, then extensive and frequent measurements of the HAPs will be required. If an EGU has a CEMS for a pollutant, an initial measurement program will be performed to establish limits for the CEMS and repeated every quarter. (If an EGU installs a continuous particulate monitoring system (CPMS) for PM, the stack is tested for PM every year rather than every quarter.) The initial measurement program must take place within 30 days of the compliance date. Then, a 30-day rolling average of the CEMS measurement will be monitored after the CEMS limits are set except for mercury for which an alternate 90-day averaging is allowed.

During the initial measurement program, the PM will be measured using EPA methods 5 or 29. A PM CEMS limit will then be determined that keeps the PM within the limit. In an earlier proposed limits, the PM measurement included condensables using EPA method 202. Condensable PM consists of aerosols from condensation of SO<sub>3</sub>, volatile organic carbons (VOC) and other potential condensable species. EPA method 202 is intended to mimic what happens with potential species that condense in the atmosphere downwind of the stack.

The U.S. EPA states that SO<sub>2</sub> will be a surrogate measurement for HCl for an EGU that includes a Flue Gas Desulfurization (FGD) system. The measurement requirements for individual HAPs are less extensive and frequent if the EGU includes a FGD or other pollutant control devices. The U.S. EPA states that an EGU can use either Hg CEMS or sorbent trap system to monitor Hg. There will be periodic quality assurance testing of both Hg CEMS and sorbent trap systems.

Figure 1 illustrates the signed limits for each of the pollutants in terms of an energy numeric limit (lb/10<sup>6</sup> Btu) for both existing and new EGUs. The U.S. EPA also includes an alternate net electric output numeric limit of lb/MWh for existing units. New units must comply with the net electric output limit alone.

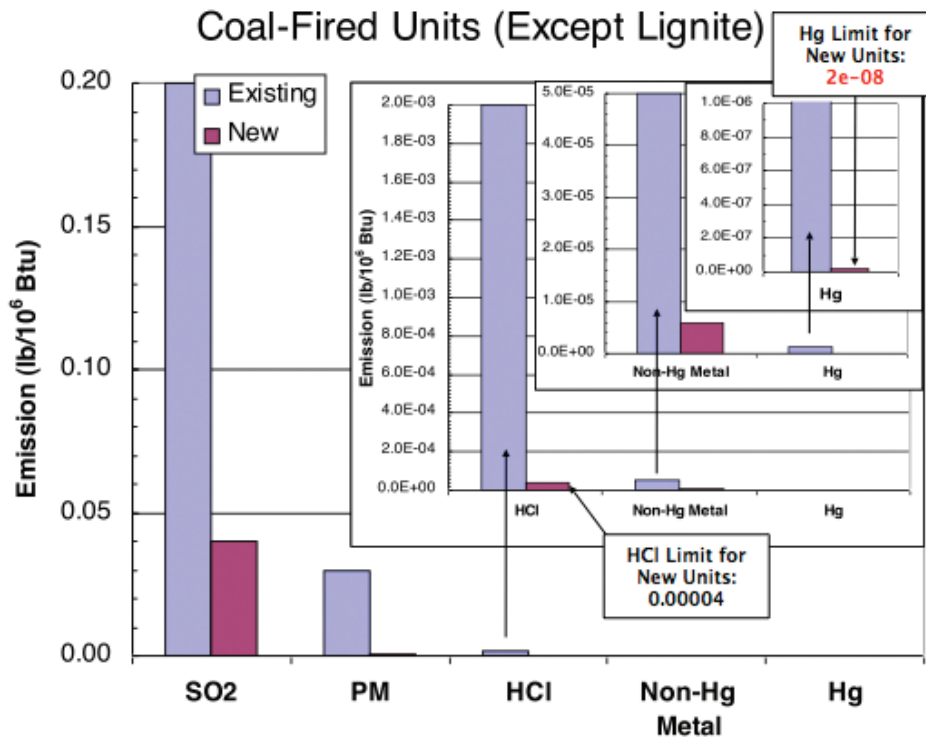


Figure 1. EPA Maximum Achievable Control Limits

The energy input and net electric output values for particulate, HCl and Hg for existing coal-fired units imply a convenient conversion that uses a net plant efficiency of 34.1% as shown by equation 1. (However, the energy input to net electric output relationship for other subcategories such as IGCC and solid is inconsistent.)

$$1 \text{ lb}/10^6 \text{ Btu} * (1 \text{ Btu}/1055 \text{ J}) * (1 \text{ J}/\text{s}/1 \text{ W}_{\text{th}}) * (3600 \text{ s}/\text{h}) * (1 \text{ W}_{\text{th}}/0.341 \text{ W}_e) = 10 \text{ lb}/\text{MWh} \quad \{1\}$$

The signed limits for existing EGUs are very challenging, and as can be seen, the limits for new EGUs are much more stringent than for existing ones. The SO<sub>2</sub> and non-Hg HAPs limits for new units are about 5 to 8 times lower than for existing units. The particulate matter, HCl and Hg limits for new units are 43 to 65 times lower than the limits for existing units.

As of this writing, the EPA is finalizing work standards for periods of startup, shutdown or malfunction of an EGU, pollutant control device, or CEMS. The numeric limits must be complied with for all other times. The possibility of emissions exceeding limits is mitigated because the limits are based on 30 rolling boiler operating day averages of the CEMS readings (or a 90-day rolling operating day average for Hg). If a regulated pollutant exceeds the limit because of malfunction, the U.S. EPA will respond based on good-faith efforts to prevent malfunctions and minimize emissions during the malfunction. The EPA is finalizing an affirmative defense to civil penalties if the regulated pollutant exceeds the limit because of malfunction.

The limits will require existing EGU to install pollution control devices and new CEMS and many EGUs will conduct stack testing programs - unless they are shut-down to avoid installing the devices and CEMS and avoid the test requirements. The signed rule is required reading for an EGU owner to know the continuous measurement and test requirements. Some have claimed that the new EGU limits are so low that they will prevent new coal-fired electric generation in the United States.

On July 16, 2011, the U.S. EPA proposed a Cross State Air Pollution Rule (CSAPR) that requires states to limit SO<sub>2</sub>, NO<sub>x</sub>, and fine particulate (PM<sub>2.5</sub>). The CSAPR will also require EGUs to install pollutant control and CEMS in certain upwind states. As of this writing, the U.S. Appeals Court for the D.C. Circuit has stayed the implementation of CSAPR. Nevertheless, we expect that either the Utility MACT rules or the CSAPR will bring about a large demand for pollution control devices that control the pollutants that the EPA has identified as the most dangerous.

## **CIRCULATING DRY SCRUBBER TECHNOLOGY**

A Circulating Dry Scrubber is a pollution control device that removes SO<sub>2</sub> and other HAPs from boiler flue gas using a dry solid sorbent. The device is unlike early scrubbers including Wet Flue Gas Desulfurization (WFGD) and Spray Dryer Absorbers (SDA) that spray a water slurry of limestone or lime to react with flue gas constituents. WFGD and SDA have been the workhorses for scrubbing flue gas since the early 70s. A WFGD scrubber washes the flue gas with slurries of limestone, CaCO<sub>3</sub>, or lime, Ca(OH)<sub>2</sub>, at the saturation temperature of the flue gas. An SDA operates at a higher temperature than a WFGD while spraying a lime slurry into a vessel where the slurry dries at the same time as it reacts with the flue gas.

The WFGD scrubber is more effective at removing SO<sub>2</sub> for high sulfur fuels than an SDA but less effective for SO<sub>3</sub> and other acid gases and Hg. The WFGD reaction vessel is constructed from high-grade stainless steels or tile and includes high horsepower pumps to circulate the limestone slurry. The SDA vessel is constructed from mild steel and uses a high-speed rotary or dual fluid atomizer to spray the lime slurry. An SDA includes a fabric filter particulate removal device to collect the dried reaction byproduct. The fabric filter also removes flyash with the byproduct controlling dust emissions to the stack. Often some of the byproduct circulates back to the SDA vessel by a wetted slurry to complete reaction. While a WFGD removes most particulate, an upstream fabric filter or ESP is needed to totally control particulate emissions. A WFGD scrubber with blowers and dewatering equipment can make a dry byproduct, gypsum, CaSO<sub>4</sub>, that can be sold, but it generates a high chloride waste water stream at the same time. The water used in an SDA is completely vaporized and exits the stack with a slightly visible plume because it operates at a higher temperature than a WFGD that has a very visible white plume of water vapor at it operates.

A CDS works by circulating dry solids consisting of dry hydrated lime and reaction products through a reactor, fabric filter, and air slides that control the circulation rate. It also uses water to effect the reaction of the solids with the flue gas constituents, but unlike the SDA, the water is injected separately from the dry hydrated lime powder sorbent in the reactor. As in an SDA, the water is completely vaporized and a dry flue gas exits to the stack, and a fabric filter controls dust emissions while capturing the solids from the reactor. Unlike an SDA where the lime slurry must dry within a certain time for reaction, the water spray in a CDS controls the reactor temperature separately from the injected hydrated lime that controls the outlet SO<sub>2</sub> emission. As in a WFGD scrubber, the reaction between solids and flue gas in a CDS is intimate because of a high degree of solids circulation to the reactor. In the CDS, the reaction byproduct is removed from the air slides to keep a constant inventory of solids in the system. There is no saleable byproduct as is possible from a WFGD, but it is a stable landfill material, and there is activity to render it useful for some construction.

Figure 2 is a flow schematic of the CDS showing the reactor, fabric filter, and air slides. A feature of the CDS reactor is the venturi or multiple venturi section that accelerates the flue gas in manner such that a fluidized bed of solids can be suspended in the reactor. The fluidized bed is maintained at the desired density by modulating dosing valves from the air slides that control the pressure drop in the reactor. (The dosing valve positions are biased to keep the levels in the air slides the same.) There is a high degree of contact between flue gas and solids in the fluidized bed. The solids also circulate within the reactor with solids flowing up through the center and down the walls so that there is little chance the flue gas can sneak up the walls without encountering solids available for reaction.

As in an SDA, there is also contact and reaction between flue gas and the solid cake on the bags of the fabric filter. The fabric filter collects the solids and returns them at a high rate back to the reactor through the air slides.

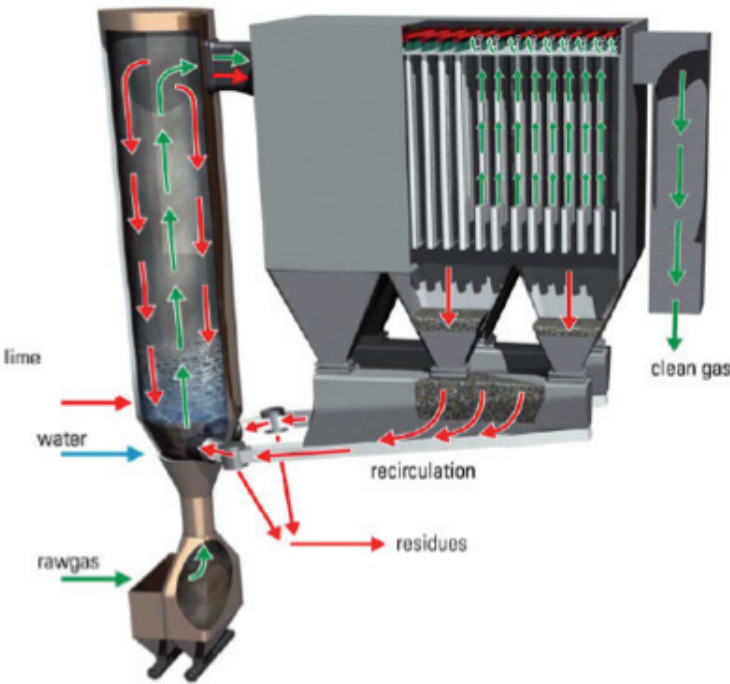
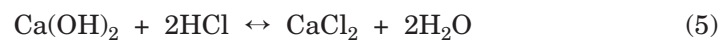
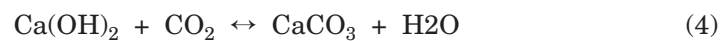


Figure 2. Circulating Dry Scrubber Schematic

As with any scrubber, booster fans or upgraded Induced Draft (ID) fans overcome the scrubber pressure drop. As with an SDA, the fans are downstream, and they maintain negative pressure in the CDS. In the CDS, at low boiler loads, when the flue gas flow is low, some of the flue gas is returned from the discharge of the ID fans to the inlet of the CDS reactor to maintain sufficient velocity through the venturis to maintain the fluidized bed throughout a range of boiler loads.

The set of reactions between  $\text{Ca(OH)}_2$  and  $\text{SO}_2$  and acid gases in the flue gas for the CDS as listed next. These reactions are the same as in a SDA.



The CDS provides opportunity for the hydrated lime particles to react more than once as shown in Figure 3. When the hydrated lime particle goes through its first pass, a reaction layer is formed on the surface. On subsequent passes, fresh hydrated lime is exposed as the surface crystals grow when they encounter water.

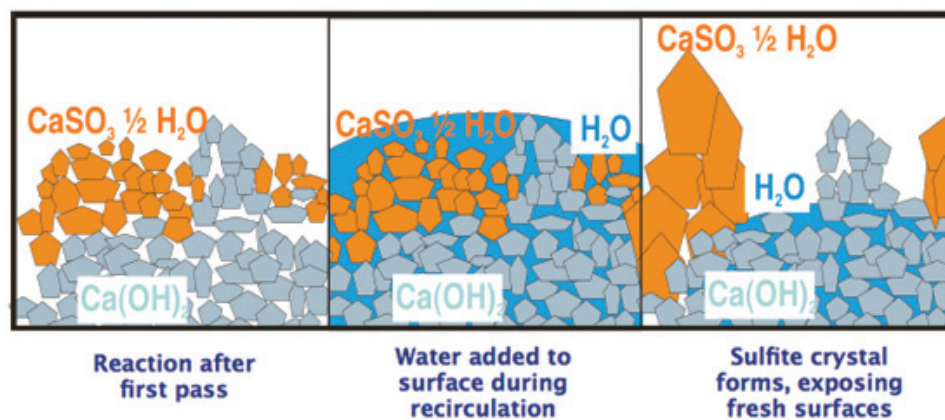


Figure 3. Reactivation of  $\text{Ca(OH)}_2$  sorbent in a CDS



Recently, many coal-fired power stations have changed from operating at high constant capacity to operating much more variably because of reduced electricity demand, cheaper natural gas prices, and the increasing use of renewable energy such as wind, solar, and biomass. The effects of load variability on boiler components are a large concern because of thermal fatigue of boiler tubes and corrosion. Flue gas desulfurization performance is also affected because precise control is required to maintain high and constant SO<sub>2</sub> removal. As will be shown, a CDS controls SO<sub>2</sub> as load varies at rapid rates because the SO<sub>2</sub> is controlled separately from temperature.

Table 2 lists the typical removals of SO<sub>2</sub> and HAPs in a CDS scrubber and the maximum fuel SO<sub>2</sub> that a CDS can scrub. The SO<sub>2</sub> that can be removed by a CDS is similar to a WFGD scrubber. The CDS fuel SO<sub>2</sub> maximum is lower than a WFGD scrubber, but the removals for other acid gases are greater in a CDS than a WFGD. An SDA achieves similar removals as a CDS, but at lower fuel SO<sub>2</sub>.

SO <sub>2</sub>	95 – 98%
SO <sub>3</sub>	95 – 99%
HCl	95 – 99%
HF	95 – 99%
Hg	90 – 95%*

\* Without activated carbon.

*Table 2. CDS Removal Summary for Coals Up to 6 lb of SO<sub>2</sub>/10<sup>6</sup> Btu*

In summary, there is a high degree of reaction between the reaction solids and flue gas SO<sub>2</sub> and acid gases in a CDS because of the fluidized bed in the reactor, the solid filter cake in the fabric filter, and because the solids pass through the reactor many times. The fabric filter is very effective in removing solids keeping dust emissions to the stack low. A CDS probably responds better to variable load than either a WFGD or SDA because of separate hydrated lime and water control loops in the CDS.

Let's now review actual particulate matter emissions data, including condensables, and SO<sub>2</sub> and HCl emissions data from a CDS and compare them to the EPA Utility MACT rules.



## PARTICULATE MATTER

Figure 4 shows PM measured in the stack from four power stations with Babcock Power’s Turbosorp® CDS system compared to the signed Utility MACT rule for PM. The particulate matter emissions from first two power stations were well below the limit for existing power stations.

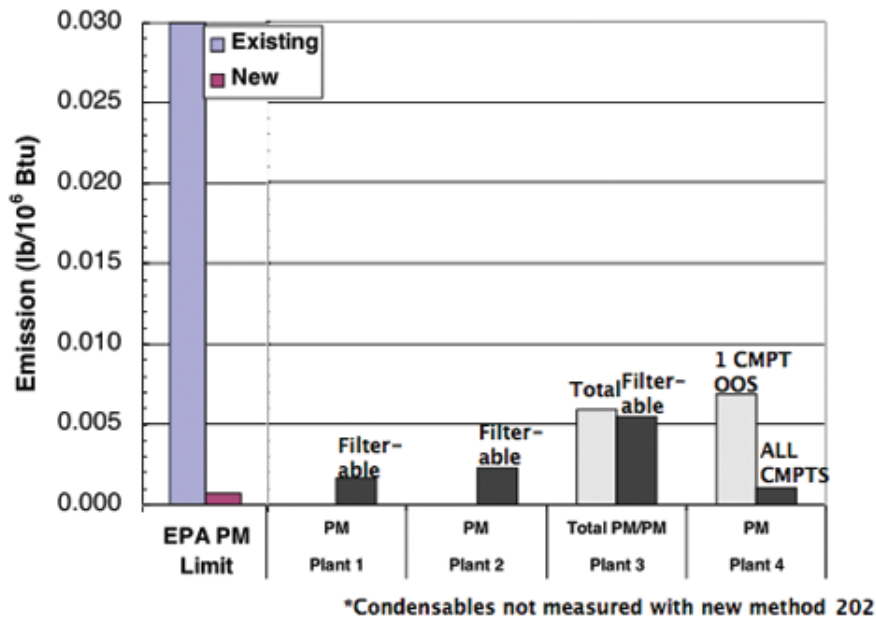


Figure 4. Turbosorp® CDS Particulate Matter Emissions Compared to EPA MACT

At power station 3, both filterable PM and condensable PM were measured to determine a total PM. These particulate matter measurements were also well below the limit for existing power. The condensable PM measurement was measured using EPA method 202 before an update proposed by the EPA in December 2010. The updated method 202 is supposed to remove artifacts that can result from drawing the sample through a water-filled impinger. However, some claim that the new method introduced different artifacts. The condensables measured by the older method was very small for power station 3 with or without potential artifacts. However, the filterable PM was higher than expected possibly due to a developing problem with the bags. About a week after the test, opacity spikes appeared after several bags failed due to rubbing on an internal structural member. After the test, the failed bags were isolated on-line, and the interference was removed at a following outage.

The PM measurements at all four power stations were above the limit for a new power station. At power station 4, the filterable PM was measured when one fabric filter compartment was not in service and when all compartments were in service. The filterable PM for power station 4 approached the new power station limit when all compartments were placed in service increasing the exposed cloth area and lowering air to cloth ratio in the fabric filter. These results show that it is possible to meet the PM limit for new units if the fabric filter is designed with a low enough air to cloth ratio.

## HCl and SO<sub>2</sub>

Figure 5 shows that the HCl emissions measured for our operating Turbosorp® CDS systems were below the limit signed by the EPA for existing units. The HCl emissions were not directly controlled but they were measured while scrubbing 95% of the SO<sub>2</sub> from the boiler.

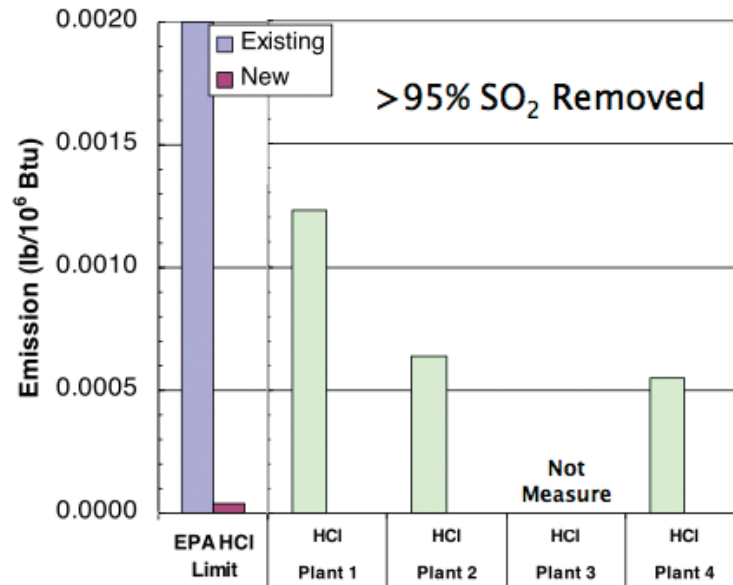


Figure 5. Turbosorp® CDS HCl Emissions Compared to EPA MACT

As can be seen, the signed HCl limit for new units is very low. We have not tested for lower HCl, but it may be possible to achieve the much more stringent limit for new units by injecting more lime reagent. The limit for new units is equivalent to 0.03 ppm at 6% O<sub>2</sub>. The detection limit for EPA method 26 for HCl is 0.1 ppm. A cursory review of available HCl CEM equipment shows that the best detection limit is 0.1 ppm. The HCl limit that the EPA signed for new EGUs is lower than what normally can be measured. However, in the signed rule, the EPA states that the new EGU HCl limit is measurable using CEMS designed for waste-to-energy facilities.

As signed by the EPA, continuous SO<sub>2</sub> emissions will be a surrogate measurement for HCl for an EGU that includes a scrubber. The Turbosorp® CDS routinely reduces the SO<sub>2</sub> for a power station well below the EPA limit for existing boilers (0.2 lb/106 Btu equivalent to 130 ppm @ 6%O<sub>2</sub>), and it is able to reduce SO<sub>2</sub> below the new unit limit (0.04 lb/106 Btu equivalent to 26 ppm @ 6%O<sub>2</sub>) for coals that generate uncontrolled emissions up to 6 lb/106 Btu. In the earlier proposed rule, numeric limits for a pollutant were to be maintained regardless of startup, shutdown, or malfunction. In the signed rule, the EPA will finalize work standards rather than numeric limits for these operating modes.

How well does the Turbosorp® CDS hold the continuous SO<sub>2</sub> limit regardless of operating mode? The state consent decree for one of the power stations had a similar limit as the EPA SO<sub>2</sub> limit, but the decree allowed an allowance for startup, shutdown, and malfunction. Figure 6 shows the hourly, daily, and 30-day rolling averages of SO<sub>2</sub> emissions for a Turbosorp® CDS for a year (from one spring outage

to the next) from the EPA data base of all power stations in the country [2]. It shows that except for a period in late December, the 30-day rolling average of the stack SO<sub>2</sub> was below the limit for coals that were fired ranging from 3 to 5 lb/10<sup>6</sup> Btu. The other power stations have operated less frequently because of low power demand or operate under different limits than the signed EPA SO<sub>2</sub> limit.

Figure 7 shows the SO<sub>2</sub> control during a typical startup for a Turbosorp® CDS during a boiler startup. Typically, a circulating fluidized bed is immediately established in the reactor after the boiler reaches a minimum load, and some SO<sub>2</sub> is immediately removed. Once the flue gas temperature reaches a minimum operating temperature, water is injected, and SO<sub>2</sub> immediately reduces to zero as it and the acid gases react with the circulating solids. After the solids are spent, hydrated lime is injected to control the SO<sub>2</sub> outlet emission. During load changes, SO<sub>2</sub> removal is kept at setpoint.

Figure 8 shows an example response to load changes. In a load ramp test, the Turbosorp® CDS controlled SO<sub>2</sub> for a load change of 1.2%/min matching the load ramp limit of the boiler.

What scrubber performance is required to meet the 30-day rolling average limit considering startup, shutdown, and malfunction operating modes? The rolling average figure above indicates that the scrubber should normally operate at about half the EPA limit, or 0.1 lb SO<sub>2</sub>/10<sup>6</sup> Btu, to keep the 24 hour moving average mostly below the limit. If so, then the normal removal for a 3 to 5 lb SO<sub>2</sub>/10<sup>6</sup> Btu would be 96% to 98%. Operating at half the limit would also decrease other pollutants. However, as shown later in the figure, it is possible to operate with the 30-day moving average closer to the limit to use hydrated lime more economically.

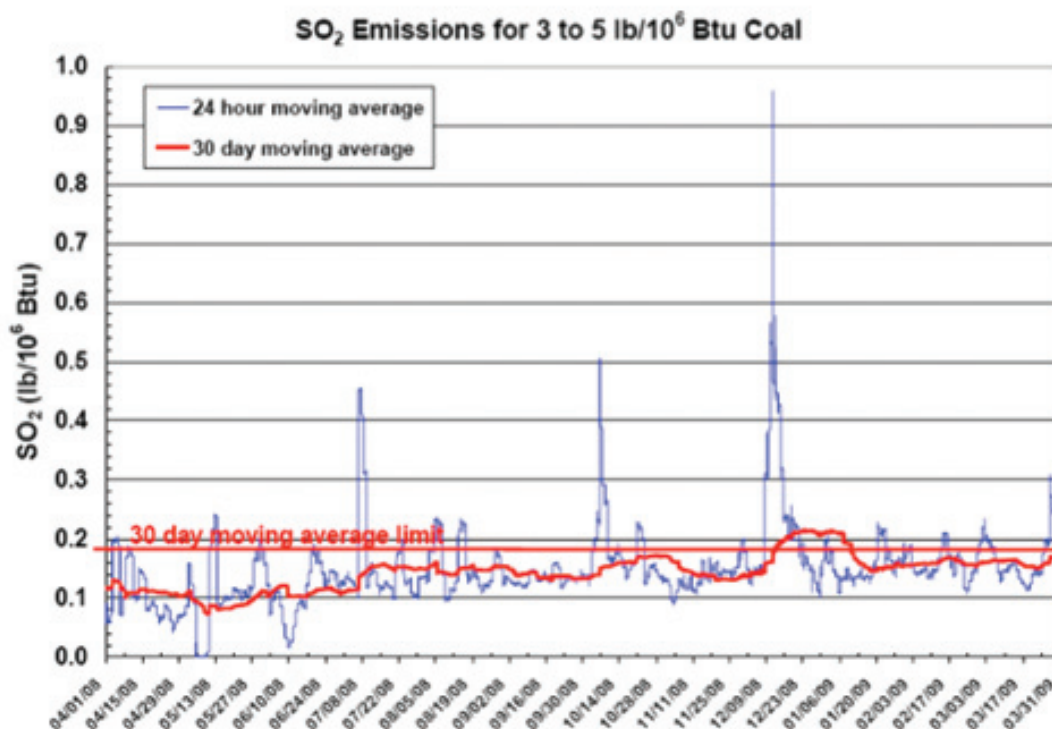


Figure 6. Example Daily, and 30-day Average SO<sub>2</sub> Emissions for a Turbosorp® CDS

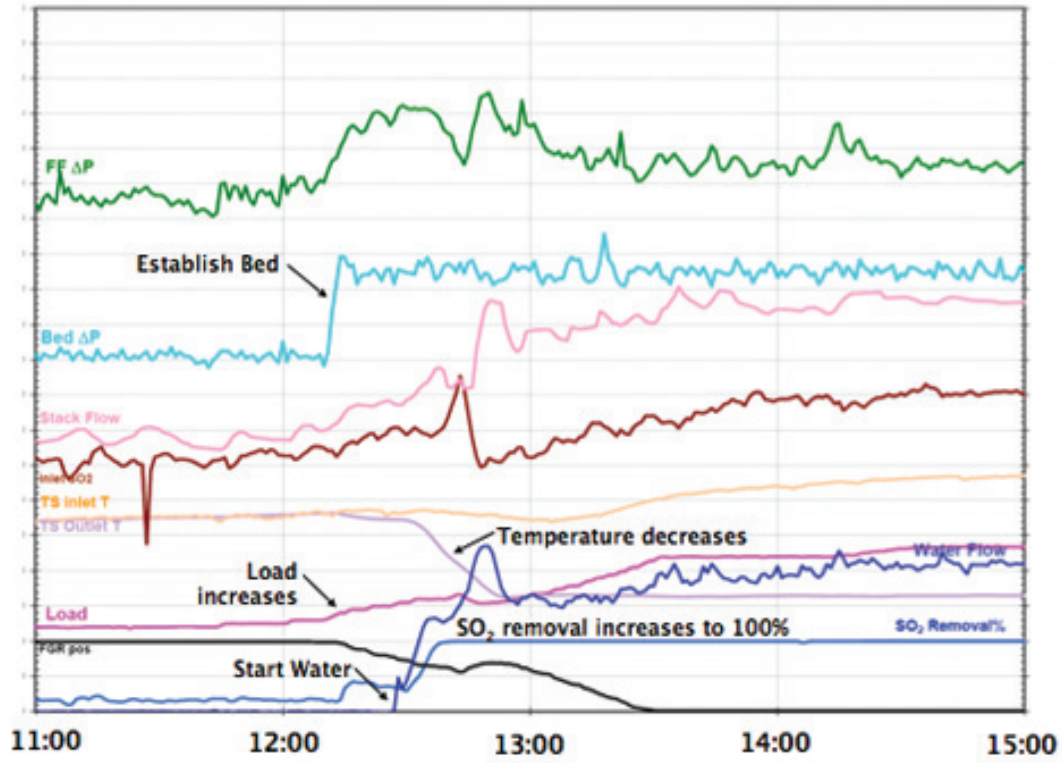


Figure 7. Example Startup of a Turbosorp® CDS

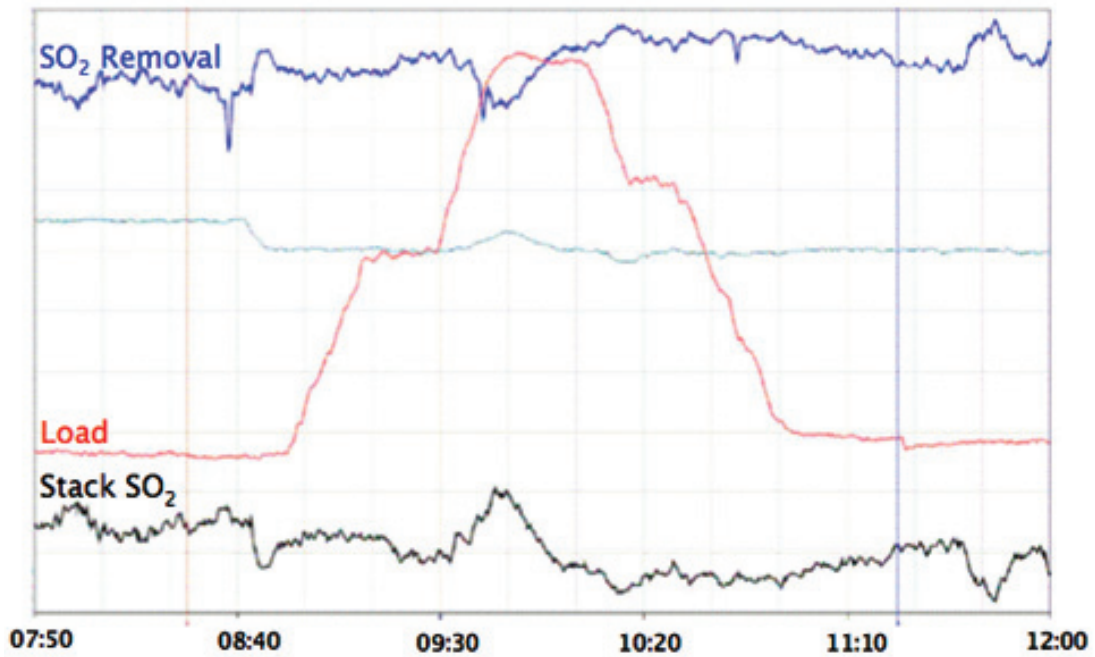


Figure 8. Example Load Ramp Change for a Turbosorp® CDS

## Hg

Figure 9 shows measured Hg emissions from three of the four power stations with a Turbosorp® CDS compared to the signed EPA limits for existing and new units. (Hg emissions were not measured at one station.) Power stations 1 and 3 tested below the EPA Hg limit for existing units. Over 95% of the inlet mercury was removed for these power stations. The emissions resulted from natural removal in the scrubber. Activated carbon injected in a flue gas stream also removes Hg from the flue gas. While it is possible to similarly inject activated carbon in the scrubber to remove mercury, no activated carbon was injected for the results shown in the figure.

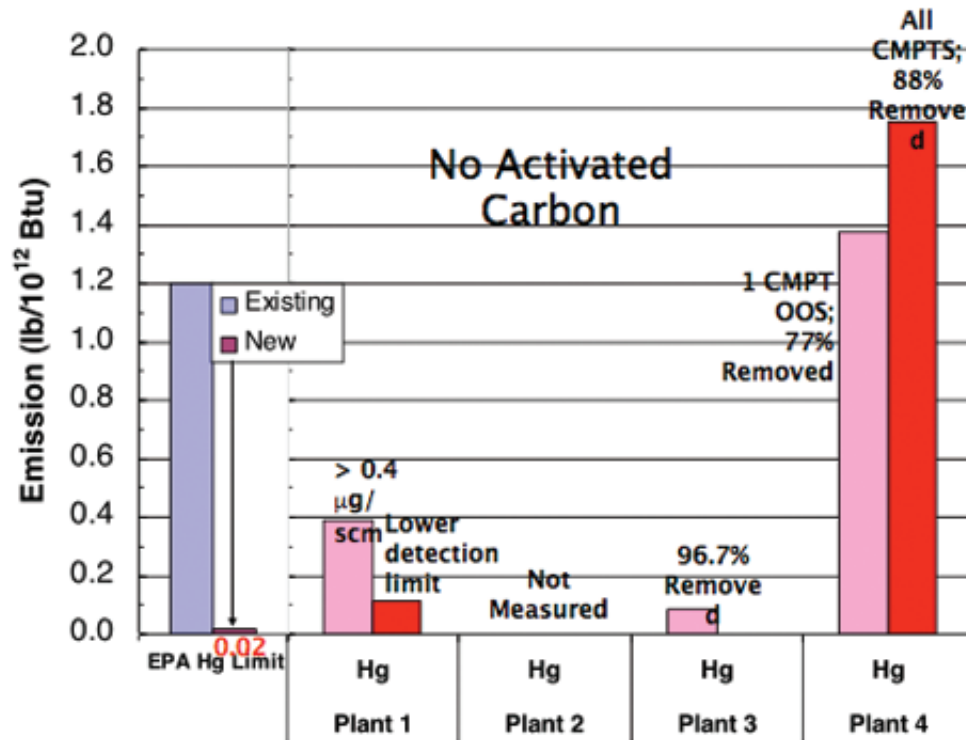


Figure 9. Turbosorp® CDS Hg Emissions Compared to EPA MACT

The Hg emissions on power station 4 were above the limit. As indicated in the figure, the inlet Hg was higher than the other units, and in one test all the fabric filter compartments were not in service. We continue to study Hg removal in power station 4.

The figure also lists the emission limit for new units. It is equivalent to 0.025 µg/m<sup>3</sup> at 6% O<sub>2</sub>. The detection limit for a Hg CEMS instrument is 0.05 µg/m<sup>3</sup>. The detection limit for Ontario Hydro method for measuring mercury in flue gas (ASTM-6784) is 0.01 µg/m<sup>3</sup>. A cursory review of other methods cannot detect Hg below 0.005 µg/m<sup>3</sup>. We are unsure how a Hg CEMS instrument can measure the limit for a new EGU.

## SUMMARY

The EPA has signed very challenging rules for existing power stations for particulate matter, non-Hg metallic and acid gas HAPS, SO<sub>2</sub>, HCl, and Hg with high requirements for measurement and compliance. The EPA states that a continuous measurement of particulate matter can be a surrogate measurement for the non-Hg metallic, HAPS and continuous SO<sub>2</sub> can be a surrogate for HCl for stations that include scrubbers. The circulating dry scrubber is a new pollution control scrubber that continuously controls SO<sub>2</sub> emissions for a power station while also removing acid gases including HCl, particulate matter, and also Hg.

The scrubber controls SO<sub>2</sub> below the limit based on a 30-day rolling average. It also controls filterable particulate below the limit for existing coal-fired power stations. We also showed that the HCl measured at three power stations was below the limit for existing power stations. We also showed that Hg was below the existing station limit for two power stations with a circulating dry scrubber. In another station, the Hg emission was above limit.

The EPA included even more stringent rules for new power station including PM, HCl, and Hg limits 43 to 65 times lower than for existing power stations. We show that the CDS can approach the new power station limit for PM by decreasing the fabric filter air to cloth ratio. We believe the signed HCl and Hg limits are below the best detection limits of existing CEMS instrumentation. Nevertheless, it may be possible to meet the new power station limit for HCl with the CDS by injecting more reagent. We can also inject activated carbon in the CDS to enhance the natural Hg removal in the scrubber and possibly meet the new power station limit for Hg.

## REFERENCES

1. <http://www.epa.gov/mats/>
2. <http://camddataandmaps.epa.gov/gdm/index.cfm>

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