

Non-thermal Methods of Achieving Zero Liquid Discharge Operation of Wet FGD Systems

3002000484



Non-thermal Methods of Achieving Zero Liquid Discharge Operation of Wet FGD Systems

3002000484

Technical Update, April 2013

EPRI Project Manager P. Chu

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

URS Corporation

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2013 Electric Power Research Institute, Inc. All rights reserved.

ACKNOWLEDGMENTS

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

URS Corporation P.O. Box 201088 Austin, TX 78720

Principal Investigator Gary Blythe, P.E.

URS Corporation 510 Carnegie Center Princeton, NJ 08540

Principal Investigator Kenneth Braunstein, P.E.

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Non-thermal Methods of Achieving Zero Liquid Discharge Operation of Wet FGD Systems. EPRI, Palo Alto, CA: 2013. 3002000484.

ABSTRACT

Wet flue gas desulfurization (FGD) systems produce recirculating process slurries that contain suspended solids, as well as dissolved solids, that are primarily salts of calcium, magnesium, and sodium with chloride, sulfite, sulfate, carbonate, and other trace species. The calcium, magnesium, and carbonate generally enter the FGD system with the limestone reagent, while the chloride, sulfite, and sulfate originate primarily from the coal. The sulfate and sulfite salts are generally of limited solubility and primarily leave the FGD system as dewatered solids, whereas the chloride salts are highly soluble, so virtually all of the chloride entering the FGD system remains dissolved in the slurry liquor.

FGD system absorbers are limited in the allowable concentration of chloride at which they can operate in order to avoid corrosion of construction materials and to achieve high SO₂ removal efficiency at acceptable limestone utilization. The chlorides enter the FGD system primarily as HCl produced from chlorine in the coal, which is removed at high efficiency by most FGD processes. In some low-chlorine coals, the FGD makeup water can be a significant source of chloride makeup to the FGD system. Once chloride enters the FGD system by removal from the flue gas and/or in makeup water, the chloride can leave the FGD system by means of one or both of the following process paths: FGD solid-byproduct-free moisture or as a separate chloride purge stream.

The latter path will generally require some sort of wastewater treatment before that stream can be discharged to a body of water. The U.S. Environmental Protection Agency is scheduled to promulgate new national effluent limitation guidelines in April 2013 that will likely place further restrictions on the quality of wastewater discharges from coal-fired power plants. This report discusses approaches for handling an FGD chloride purge stream by combining the water with the solid byproducts from the coal-fired unit, a method that is designated as "non-thermal zero liquid discharge (ZLD)" in this report. Although the method is not new, this report quantifies the operating parameters for this approach. The information presented is intended to be particularly useful for evaluating existing FGD systems, in particular for determining if non-thermal ZLD operation is suitable for the existing FGD materials of construction when using coal with a particular range of characteristics.

Keywords

Chloride purge Wastewater treatment Wet flue gas desulfurization Zero liquid discharge

1 INTRODUCTION	1-1
Background	1-1
Treatment of Absorber Chloride Purge Stream	1-2
Zero Liquid Discharge Methods	1-2
Project Approach	1-3
Report Organization	1-4
2 DESCRIPTION OF THE NON-THERMAL ZLD PROCESS	2-1
3 CALCULATION METHOD AND DATA	3-1
Approach to Presenting Factors and Data	3-1
Data Values and Ranges	3-2
Calculation Approach	3-3
4 RESULTS AND DISCUSSION	4-1
Results – Equilibrium Chloride Concentration vs. Blended Solids	4-1
Figure 4-1 – PRB Coal	4-7
Figures 4-2 and 4-3 – Bituminous Coal	4-7
Figure 4-4 and 4-5 – Bituminous Coal	4-8
Figure 4-6 and 4-7 – Bituminous Coal	4-8
Figure 4-8 and 4-9 – Bituminous Coal	4-8
Figure 4-10 and 4-11 – Bituminous Coal with Calcium Sulfite Byproduct	4-8
Interpretation of Results – Equilibrium Chloride Concentration Trends	4-8
Plant Operational Impacts	4-9
Quantities of Blended Solids	4-9
Equipment for Material Handling and Blending	4-9
Commercial Experience with Non-thermal ZLD	4-9
Materials of Construction	4-11
Potential Limitations and Other Considerations	4-12
5 SUMMARY AND CONCLUSIONS	5-1
6 REFERENCES	6-1

CONTENTS

LIST OF FIGURES

Figure 2-1 Simplified Schematic of a Non-thermal ZLD Blending System [1]	2-2
Figure 4-1 PRB Coal (20 ppm chlorine, 0.45% sulfur, 7% ash)	4-2
Figure 4-2 Bituminous Coal (500 ppm chlorine, 1-4% sulfur, 15% ash)	4-2
Figure 4-3 Bituminous Coal (500 ppm chlorine, 1-4% sulfur, 10% ash)	4-3
Figure 4-4 Bituminous Coal (500 ppm chlorine, 1-4% sulfur, 5% ash)	4-3
Figure 4-5 Bituminous Coal (500 ppm chlorine, 1-4% sulfur, 0% ash)	4-4
Figure 4-6 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 15% ash)	4-4
Figure 4-7 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 10% ash)	4-5
Figure 4-8 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 5% ash)	4-6
Figure 4-9 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 0% ash)	4-6
Figure 4-10 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 5% ash) - Inhibited Oxida	tion .4-7
Figure 4-11 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 0% ash) - Inhibited Oxida	tion .4-7

LIST OF TABLES

Table 3-1 Boiler and ESP Parameters	3-2
Table 3-2 FGD System Characteristics – LSFO System	3-2
Table 3-3 FGD System Characteristics – Natural/Inhibited Oxidation	3-2
Table 3-4 Bituminous Coal Characteristics	3-3
Table 3-5 Powder River Basin Coal Characteristics	3-3
Table 4-1 Categories of Graphs Presented	4-1
Table 4-2 Blending - Quantity of Solids Produced and Equilibrium Chloride (for "Typical" F	ower
Plant as Described in Text).	4-10
Table 4-3 FGD Alloys and PREN Values	4-12

1 INTRODUCTION

Background

Wet flue gas desulfurization (FGD) systems produce recirculating process slurries that contain suspended solids as well as dissolved solids that are primarily salts of calcium, magnesium and sodium with chloride, sulfite, sulfate, carbonate and sometimes other sulfur species. Trace species such as arsenic, boron, bromide, fluoride, iodide, mercury, selenium, iron and manganese are also found in FGD waters as dissolved and/or suspended solids. The calcium, magnesium, carbonate, iron and manganese generally enter the FGD system with the limestone reagent, while the remaining chemical species listed above originate primarily from coal combustion or makeup water.

FGD system absorbers are limited in the allowable concentration of chloride at which they can operate in order to avoid corrosion of construction materials and to achieve high SO₂ removal efficiency at acceptable limestone utilization. The chlorides enter the FGD system primarily as HCl produced from chlorine in the coal, which is removed at high efficiency by most FGD processes. In some low-chlorine coals, the FGD makeup water can be a significant source of chloride going to the FGD system. Once chloride enters the FGD system by removal from the flue gas and/or in makeup water, it can leave the FGD system by one or both of the following process paths:

- FGD Solid Byproduct Free Moisture In natural oxidation or inhibited oxidation FGD systems that produce primarily calcium sulfite hemihydrate (CaSO₃·½H₂O) as a solid byproduct, there is generally enough free moisture associated with the dewatered product to control chloride concentrations to acceptable levels. However, most newer wet FGD systems operate in a forced oxidation mode and produce gypsum (CaSO₄·2H₂O) as a solid byproduct. Gypsum typically dewaters more effectively than calcium sulfite hemihydrate, so chloride concentrations could build to unacceptable levels unless a separate wastewater stream is purged from the FGD system. Furthermore, many forced oxidation FGD systems produce gypsum used as feedstock to wallboard plants. These systems must wash the gypsum filter cake with fresh water so that the gypsum will meet the wallboard manufacturers' limits for chloride and total halogen concentration. This washing further decreases the amount of chloride that can leave the FGD system by this process path.
- Absorber Chloride Purge Stream A blowdown stream may be required to remove chloride from limestone forced oxidation (LSFO) FGD systems, either because the gypsum holds less free water than might be required to remove chloride from the system or the gypsum is precluded from containing a significant concentration of chloride by a wallboard manufacturer's specification. This blowdown or "chloride purge" stream is separated from the gypsum by processing the absorber slurry with hydrocyclones followed by vacuum belt filters, drum filters, or centrifuges. The hydrocyclone underflow contains a high concentration of suspended solids, consisting primarily of gypsum. The overflow contains a relatively low concentration of suspended solids, mostly fine particles of gypsum, unreacted

limestone, and inert materials. Most of the hydrocyclone overflow is returned to the absorber, but a portion is withdrawn from the FGD system as the chloride purge stream. In some cases a second stage of smaller hydrocyclones is used to further decrease the suspended solids content of this purge stream and improve limestone utilization. The liquid phase of this stream is essentially the same as the liquid phase of the absorber reaction tank slurry, being slightly acidic, with a relatively high concentration of dissolved chemical species, including gypsum at slightly supersaturated conditions, chloride, and the trace species mentioned above.

Treatment of Absorber Chloride Purge Stream

For some plants located on large rivers or other water bodies, it has been permissible to direct the FGD wastewater to the station ash pond for settling of suspended solids and pH adjustment This is accomplished simply by mixing the smaller FGD wastewater stream with the larger ash pond water flow rate. For these plants, the combined ash pond discharge stream has been able to meet the NPDES permit requirements for the station outfall. More commonly in recent times, dedicated wastewater treatment (WWT) systems have been required. The most commonly used WWT system in current FGD retrofit projects consists of physical/chemical treatment to reduce total suspended solids, adjust the pH, de-supersaturate the stream, and reduce heavy metals concentrations.

Some new FGD systems have requirements for more complex WWT systems to remove specific dissolved and suspended species such as arsenic, mercury, and selenium to increasingly lower concentrations. Some stations are also evaluating the need to reduce the discharge of chloride. To date, the treated effluent requirements for FGD WWT systems throughout the U.S. have been regulated as low volume wastes under the current steam electric effluent limitation guidelines (ELGs) in 40 C.F.R. Part 423. However, the U.S. EPA is currently reviewing the steam electric ELGs and may establish technology-based limits specific to the category of FGD wastewater. Although ELGs usually set wastewater treatment goals on the basis of established treatment technologies, individual state water quality criteria could result in local agencies setting even more restrictive effluent limits than the ELGs. For example, some states might limit the total dissolved solids to concentrations which cannot be achieved by available wastewater treatment technologies.

It is likely that the implementation of new ELGs and stricter state water-quality-based requirements will set more stringent requirements and will result in more widespread need for treatment of FGD wastewater. Also, as the effluent limits become more restrictive, additional unit processes may be required beyond those that have been established to date, resulting in an extensive array of treatment equipment.

Zero Liquid Discharge Methods

In cases where multiple unit processes would be required or where limits cannot be achieved by available treatment technologies, the preferred solution might be to eliminate the discharge of the FGD chloride purge stream altogether. Two possible methods for achieving zero liquid discharge (ZLD) are: 1) thermal evaporation and 2) byproduct blending and fixation.

• Thermal Evaporation ZLD - Various forms of the thermal evaporation ZLD process have been installed to treat FGD wastewater at a few power plants in the U.S. and Europe. The

process generally consists of softening the FGD chloride purge stream and then concentrating it in several steps, using a falling-film evaporator (also known as a brine concentrator), followed by evaporation in a crystallizer to produce a salt cake. Both evaporation steps produce distillate, which is reused in the power plant. Evaporative ZLD systems incur high capital and operating costs. Therefore, in cases of a relatively high wastewater flow rate, it can be advantageous to reduce the flow rate of the stream to the thermal evaporation system by using a reverse osmosis (RO) system to produce a concentrated reject stream, which is directed to the brine concentrator. The RO permeate (clean water) in such cases can be reused in the power plant in combination with the distillate produced by the thermal evaporative system. A lifecycle economic analysis is usually required to determine if a RO system is beneficial. For lower flow rate chloride purge streams, the thermal evaporative system alone is usually the indicated choice, without the additional RO system equipment.

Non-Thermal ZLD (Byproduct Blending and Fixation) - As mentioned previously, FGD water leaves the system as free moisture included with FGD solid byproducts. Therefore, as an alternative to the evaporative ZLD, it may be advantageous to implement "non-thermal ZLD", by maximizing the amount of water that leaves the FGD system with the FGD solid byproducts, so that no separate liquid discharge stream is required. This process usually requires fly ash and/or quicklime to be blended with the FGD wastewater and gypsum, both to provide sufficient solids content and to produce a stable product suitable for landfill disposal. In the case of LSFO systems, this process would preclude the use of the gypsum byproduct as wallboard plant feedstock, because of high dissolved solids in the free water and the blending of the gypsum with fly ash and lime. However, as more gypsum-producing FGD systems go on line, and in the current economic climate in the U.S., there is little capacity in the wallboard industry to use additional FGD gypsum as a feedstock. Therefore, disposal of FGD gypsum is becoming more commonplace, which makes this alternate ZLD approach more attractive. It should be noted that although numerous systems for fixating and stabilizing byproducts from natural or inhibited oxidation FGD systems have been installed, there has been limited application of this process to oxidized FGD systems, because of the previous market for selling the gypsum byproduct.

Project Approach

This project was conducted to investigate options for achieving non-thermal ZLD by maximizing the water leaving FGD systems with the solid byproducts, such that no separate FGD liquid discharge is required, while maintaining dissolved chloride concentrations in the FGD system at acceptable levels. The evaluation involved spreadsheet analyses of how the steady-state FGD chloride concentration would vary with different combinations of coal chloride-to-sulfur ratios, ash-to-sulfur ratios, and the percent moisture in the FGD byproduct. The majority of the calculations were made for 100% gypsum (CaSO₄·2H₂O) as the FGD solid byproduct; two graphs were prepared for a calcium sulfite hemihydrate (CaSO₃· $\frac{1}{2}$ H₂O) byproduct for comparison purposes. This latter byproduct does not dewater as easily as gypsum and therefore retains more free water, on a unit weight basis, than gypsum. In all cases, a realistic operating window was targeted with regard to FGD steady-state chloride concentration and the blended cake percent moisture.

Report Organization

The remainder of this report is organized into four sections. Section 2 presents a description of the non-thermal ZLD process. Section 3 presents the calculation method and the design data used for the calculations. Section 4 presents the results of the calculations and discusses the impact on plant operations and equipment resulting from use of the non-thermal ZLD method. Section 5 presents the conclusions. The references used in the document are listed in numerical order in a separate section at the end of the report.

2 DESCRIPTION OF THE NON-THERMAL ZLD PROCESS

Dewatering of gypsum cake by vacuum filters produces a stabilized byproduct suitable for either wet stacking or landfill operations. However, because gypsum dewaters so effectively (to approximately 85-90% solids, or 10-15% moisture by weight), there often is not sufficient gypsum to accept all of the FGD blowdown required to remain at or below a target equilibrium chloride concentration. In such cases blending of the gypsum with at least a portion of the unit's fly ash would be required if zero liquid discharge is to be achieved (i.e., additional solids are required to blend with the FGD chloride purge stream to avoid the need for a WWT system). In addition, the free water in the gypsum cake contains dissolved and/or entrained trace element solids that are subject to leaching when the gypsum is placed in a landfill. To minimize leaching, fixation can be accomplished by mixing quicklime and fly ash with the gypsum to initiate pozzolanic reactions to form a concrete-like byproduct. The dissolved solids in the FGD blowdown are then bound up in the concrete-like substrate, which becomes a repository for both chloride and heavy metals. High alkalinity ash, such as from Powder River Basin coal or from circulating fluid bed (CFB) boilers, or lime kiln dust can be substituted for lime. Historically, only naturally or inhibited oxidation FGD byproduct (a mixture of calcium sulfate and sulfite salts) has required fixation for landfill disposal. Fixation of dewatered gypsum cake has been rare because, as stated earlier, much of the gypsum byproduct has been sold for wallboard manufacture.

The optimum proportions of the mixture for the pozzolanic reactions can vary with fly ash and water properties, and should be determined in bench-scale tests or full-scale trials. Based on previous results from bench tests and some operational full scale systems, typical blend percentages include approximately:

- 35-40% gypsum solids,
- 35-40% fly ash,
- 20-25% free water, and
- 1-3% quicklime.

Anecdotal information from the field indicates there is a nominal limit of 25% free water in the fresh mixture (i.e., prior to setting up) to prevent it from separating out during transport to the landfill. The moisture content for inhibited or naturally oxidized systems can be much higher.

The blend composition ranges indicated above are only guidelines. One issue to consider is the effect of chloride on the strength development and degree of fixation of the pozzolanic mixture. Strength is of concern with regard to the stability of the landfill. The permeability or degree of fixation affects the potential for leaching, which could release regulated chemical species. The leachate may also be subject to regulation under national ELGs, or may need to be returned to the FGD system. Bench-scale testing is required to investigate these issues (strength and leachability) and should be performed in the early phase of a project considering non-thermal ZLD. If landfill leaching is expected, the FGD and blending system design could be impacted if the leachate and/or surface runoff need to be returned to the FGD system.

Figure 2-1 illustrates a simplified process flow diagram for a non-thermal ZLD system in which only the minimum required fly ash is blended with the gypsum. This leaves the balance of the fly ash available for sale or separate disposal.



Figure 2-1 Simplified Schematic of a Non-thermal ZLD Blending System [1]

Numerous systems for fixating and stabilizing byproducts from natural or inhibited oxidation FGD systems have been installed, especially with early generation FGD systems, in order to be able to dispose of the calcium sulfite hemihydrate byproduct safely and efficiently. Although the process has been applied to oxidized FGD systems, the number of installations is limited, because there has historically been an available market for selling the gypsum byproduct.

3 CALCULATION METHOD AND DATA

Approach to Presenting Factors and Data

Evaluation of non-thermal ZLD, accomplished by blending FGD wastewater with gypsum and fly ash, involves multiple variables, as discussed below. There are numerous possible ways to parameterize the calculations and to present the results. This report presents calculated graphs of "Blended Cake Solids Content" versus "Equilibrium Chloride Concentration" for multiple combinations of coal sulfur, coal chlorine, and coal ash content. The result is a series of curves, with each curve representing one combination of these coal characteristics. The coal content for each curve is also described by the ratios of chlorine:sulfur and ash:sulfur, to allow for interpretation of the results for coals with similar ratios to those presented, even if they have different chlorine, sulfur, and ash content.

The benefit of plotting blended cake solids content versus equilibrium chloride is that it allows for visualization of the optimal band of approximately 75% to 85% solids in the blended cake. At solids concentrations below 75%, the cake can be too watery and above 85%, the cake can be too stiff to work with. The plots therefore allow for estimation of the equilibrium chloride concentration corresponding to the target cake solids range.

Percent moisture in the cake is calculated simply as:

100 - (blended cake percent solids)

Therefore the optimal band described above for percent solids in the cake (75-85%) corresponds with 15-25% moisture in the blended cake.

There are numerous independent factors besides the coal sulfur, chlorine, and ash content which affect the calculation of blended cake solids percent versus equilibrium chloride concentration. These factors include: percentage of coal ash which becomes fly ash (since it is assumed that bottom ash is not suitable for use in the blending process); ESP efficiency for removal of fly ash and HCl; FGD system efficiency for removal of SO₂, fly ash, and HCl; limestone stoichiometry; and chloride content of the makeup water. For the calculations presented in this report, all of these independent factors were assigned fixed values, considered to be representative of modern power plant and FGD systems.

Although the chlorine:sulfur and ash:sulfur ratios are sufficient for obtaining the described parametric curves, it is also important to calculate actual mass rates associated with a typical power plant, in order to have an understanding of the quantities of material to be handled, stored, and landfilled. Major factors affecting this calculation are: power plant output, power plant heat rate, and coal higher heating value.

Selected values of all of the required parameters are presented in tables in the following subsection.

Data Values and Ranges

Tables 3-1 through 3-5 summarize the values selected as representative data for a power plant for use in the non-thermal ZLD calculations. Table 3-1 shows the boiler and ESP parameters, Tables 3-2 and 3-3 show FGD system parameters for LSFO and sulfite-producing FGD systems, respectively, and Tables 3-4 and 3-5 show coal parameters for bituminous and Powder River Basin (PRB) coal, respectively.

Table 3-1	
Boiler and ESP P	arameters

Item	Value	Units
Boiler MW (Gross)	500	MW
Boiler Gross Heat Rate	10,000	Btu/kWh
Boiler Load	100	%
ESP Efficiency	99	%

Table 3-2FGD System Characteristics – LSFO System

LSFO Design Basis	Value	Units
SO ₂ Removed	95	%
HCl Removed	95	%
Fly Ash Removed	50	%
Limestone Purity	95	%
Degree of Oxidation	100	%
LS Stoichiometry	1.03	Ratio
Gypsum Cake Solid Content	85	%
Chloride in Make Up water	30	ppm

Table 3-3

FGD System Characteristics – Natural/Inhibited Oxidation

Sulfite-producing FGD Design Basis	Value	Units
SO ₂ Removed	95	%
HCl Removed	95	%
Fly Ash Removed	50	%
Limestone Purity	95	%
Degree of Oxidation	15	%
LS Stoichiometry	1.03	Ratio
Gypsum Cake Solid Content	65	%
Chloride in Make Up water	30	ppm

Table 3-4 Bituminous Coal Characteristics

As-Received Coal	Value	Units
Coal Heating Value	12,500	Btu/lb
Ash Split (fly ash - of total)	80	%
Coal Sulfur Content	1, 2, 3, 4	%
Coal Chlorine Content	500, 1000	ppm
Coal Ash Content	0, 5, 10, 15	%

Table 3-5Powder River Basin Coal Characteristics

As-Received Coal	Value	Units
Coal Heating Value	11,900	Btu/lb
Ash Split (fly ash - of total)	80	%
Coal Sulfur Content	0.45	%
Coal Chlorine Content	20	ppm
Coal Ash Content	0, 7	%

The MW rating of a specific power plant can be used to adjust the mass flow rates which are presented later in Table 4-2, by using the ratio of the power plant MW to 500 MW.

The example data in Table 3-4 encompass the composition of many of the commercially available bituminous coals [2]. The PRB coal values in Table 3-5 are based on data collected by the authors. For both categories of coal (Tables 3-4 & 3-5), calculations that follow for the case of 0% ash content represent blending of FGD wastewater with only gypsum and a small percentage of lime, and none of the available fly ash.

For all calculations, the quantity of quicklime to be added was estimated as 0.9% of the dry solids weight of the blend (gypsum or calcium sulfite hemihydrate, fly ash, limestone inerts, and unreacted limestone). This value was selected as a representative optimum value based on previous URS laboratory evaluations of the blending and fixation method. The quicklime therefore has negligible impact on the determination of blended cake weight percent solids.

The calculations do not account for the potential return of landfill leachate and/or surface runoff. However, as noted in Section 2, this issue must be considered during detailed design.

Calculation Approach

Individual spreadsheets were used to calculate the quantity of water required to achieve a series of steady-state chloride concentration values for a specific set of coal characteristics (i.e., sulfur, chloride, and ash). The calculation logic was as follows:

• From the plant output, heat rate, and coal higher heating value, determine the coal firing rate.

- From the coal firing rate and coal sulfur content, determine the uncontrolled mass rate of SO₂ produced.
- From the coal firing rate and coal chlorine content, determine the uncontrolled mass rate of HCl produced.
- Determine the mass rate of HCl captured by ESP (for PRB coal only due to alkaline fly ash).
- From the coal firing rate and coal ash content, determine the mass rate of fly ash produced in the boiler and captured by the ESP.
- Calculate the mass rate of SO₂ and HCl captured by the FGD system.
- Calculate the mass rate of FGD byproduct solids (gypsum or calcium sulfite hemihydrate, excess limestone, limestone inerts, fly ash) based on SO₂ capture, percent oxidation, limestone stoichiometry, limestone purity, and fly ash captured by the FGD system.
- Calculate the mass rate of gypsum byproduct free water, based on the gypsum byproduct solids mass rate and the "standard" gypsum byproduct percent solids. This is the steady-state mass flow rate of water that would be removed from the absorber system producing "standard" gypsum without a separate chloride purge stream.
- Calculate the steady-state chloride concentration assuming no separate chloride purge stream (i.e., with water leaving the FGD system only as "standard" gypsum byproduct free water). This is a reference value and is the steady-state chloride level which would result if no additional measures, such as blending, were to be implemented and if there were to be no other water blowdown from the FGD system.
- For a series of steady-state chloride concentration target values:
 - Calculate the TOTAL mass rate of water (which includes the gypsum free water at "standard" gypsum percent solids value) that must be removed from the absorber system to achieve the target steady-state chloride concentration.
 - Calculate the separate chloride purge mass rate required to achieve the target maximum chloride concentration. This is the difference between the calculated TOTAL mass rate of water and the mass rate of gypsum byproduct free water at the "standard" gypsum percent solids value. This chloride purge mass rate is what would be sent to a WWT system but will instead be added as additional free water to the gypsum and ash blend.
 - Calculate the mass rate of total blended cake dry solids. In the case of no blending, this consists of only the gypsum byproduct solids (gypsum, calcium sulfite hemihydrate, excess limestone, limestone inerts, and fly ash captured by the FGD system). In the case of blending, this mass rate also includes the fly ash captured by the ESP/baghouse
 - Calculate the total cake mass rate, consisting of the dry solids mass rate plus the TOTAL water mass rate.
 - Calculate the blended cake weight percent solids (dry solids/total cake weight).
 - The blended cake weight percent free water = 100 (blended cake weight percent solids).

4 RESULTS AND DISCUSSION

Because of the numerous combinations of coal characteristics, the parametric curves of blended cake solids (gypsum and ash) versus equilibrium chloride concentration are presented in a series of graphs. Table 4-1 summarizes the graphs by figure number .

Table 4-1 Categories of Graphs Presented

Figure No.	Coal Chlorine Content (ppm in dry coal)	Coal Ash Content (wt% in dry coal)	Coal Sulfur Content (wt% in dry coal)	Coal Type	FGD Type
4-1	20	7%	0.45%	PRB	LSFO
4-2	500	15%	1%, 2%, 3%, 4%	Bituminous	LSFO
4-3	500	10%	1%, 2%, 3%, 4%	Bituminous	LSFO
4-4	500	5%	1%, 2%, 3%, 4%	Bituminous	LSFO
4-5	500	0%	1%, 2%, 3%, 4%	Bituminous	LSFO
4-6	1000	15%	1%, 2%, 3%, 4%	Bituminous	LSFO
4-7	1000	10%	1%, 2%, 3%, 4%	Bituminous	LSFO
4-8	1000	5%	1%, 2%, 3%, 4%	Bituminous	LSFO
4-9	1000	0%	1%, 2%, 3%, 4%	Bituminous	LSFO
4-10	1000	5%	1%, 2%, 3%, 4%	Bituminous	Natural/inhibited oxidation
4-11	1000	0%	1%, 2%, 3%, 4%	Bituminous	Natural/inhibited oxidation

Results – Equilibrium Chloride Concentration vs. Blended Solids

The calculation results for blended gypsum byproduct are shown on 11 graphs (Figures 4-1 through 4-11) for easier viewing, with parameters as described in Table 4-1. Each figure or graph is briefly discussed in the subsections below. Each graph illustrates the range of equilibrium chloride corresponding to the target range of weight percent solids (weight percent moisture), for a specific coal composition (sulfur, chlorine, and ash). The case of 0% ash implies that none of the ash collected by the ESP/baghouse is used for blending; i.e., the characteristics of the "standard" gypsum are indicated. The indicated operational range of equilibrium chloride can be evaluated with the respect to the design range required to achieve the SO₂ removal efficiency and ensure the suitability of materials of construction. This comparison of the calculated chloride range and design range can help in the determination of whether non-thermal ZLD operation is suitable for the current FGD materials of construction in an existing installation when using a particular range of coal characteristics.



Figure 4-1 PRB Coal (20 ppm chlorine, 0.45% sulfur, 7% ash)







Figure 4-3 Bituminous Coal (500 ppm chlorine, 1-4% sulfur, 10% ash)



Figure 4-4 Bituminous Coal (500 ppm chlorine, 1-4% sulfur, 5% ash)



Figure 4-5 Bituminous Coal (500 ppm chlorine, 1-4% sulfur, 0% ash)



Figure 4-6



Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 15% ash)





Figure 4-8 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 5% ash)



Figure 4-9 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 0% ash)





Figure 4-10 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 5% ash) - Inhibited Oxidation

Figure 4-11 Bituminous Coal (1000 ppm chlorine, 1-4% sulfur, 0% ash) - Inhibited Oxidation

As stated in Section 3, for all calculations the quantity of quicklime added was estimated as 0.9% of the dry solids weight of the blend (gypsum, calcium sulfite hemihydrates, fly ash, limestone inerts, and unreacted limestone). This value was selected as a representative optimum value based on URS laboratory evaluation of the blending and fixation method. The quicklime therefore has negligible impact on the determination of blended cake weight percent solids.

Figure 4-1 – PRB Coal

The best scenario for operating at low equilibrium chloride concentration is shown in Figure 4-1, which is for the PRB coal with very low chlorine content (20 ppm). The FGD system can operate in the range of 4,000 - 9,000 ppm chloride without ash addition. Using all of the collected fly ash to blend with the gypsum, the system can operate at the very low equilibrium chloride concentration of 2,000 - 3,000 ppm because of the additional solids capable of accepting more free water.

Figures 4-2 and 4-3 – Bituminous Coal

The best scenarios for bituminous coal are illustrated in Figures 4-2 and 4-3, which are based on relatively low coal chlorine content (500 ppm) and relatively high coal ash content (15% and 10%, respectively). For the coal sulfur cases examined, the equilibrium chloride concentrations are within the range of 5,000 to 15,000 ppm except for the case of 1% sulfur and 10% ash, for which the equilibrium chloride range is 12,000 to 20,000 ppm.

Figure 4-4 and 4-5 – Bituminous Coal

Figures 4-4 and 4-5 illustrate results for the same coal chlorine content (500 ppm) as presented in Figures 4-2 and 4-3, but with lower coal ash contents of 5% and 0%, respectively. The curves "shift to the right" relative to Figures 4-2 and 4-3. The 2%, 3%, and 4% sulfur coals can operate below 20,000 ppm chloride with either no ash added to the gypsum or by blending with fly ash resulting from 5% coal ash content. The 1% sulfur coal would require operation above 30,000 ppm chloride without the addition of ash and in the 15,000 to 30,000 ppm chloride region with blending of all of the fly ash collected from the 5% ash coal.

Figure 4-6 and 4-7 – Bituminous Coal

Figures 4-6 and 4-7 illustrate that for the higher chlorine coal content (1000 ppm), and coal ash content of 15% and 10%, respectively, the 3% and 4% sulfur coals can operate in the range of approximately 10,000 to 20,000 ppm equilibrium chloride. The 2% sulfur coals require operation at 15,000 ppm to 30,000 ppm chloride and the 1% sulfur coals require operation at 20,000 to 40,000 ppm chloride.

Figure 4-8 and 4-9 – Bituminous Coal

Figures 4-8 and 4-9 illustrate that for the higher chlorine coal content (1000 ppm), and coal ash content of 5% and 0%, respectively, the 3% and 4% sulfur coals require a minimum steady-state chloride concentration of approximately15,000 ppm, The 1% and 2% sulfur coals require steady-state chloride concentrations ranging from 20,000 ppm to beyond 50,000 ppm.

Figure 4-10 and 4-11 – Bituminous Coal with Calcium Sulfite Byproduct

Figures 4-10 and 4-11 show the results for the same coal characteristics as shown in Figures 4-8 and 4-9, except the byproduct is only 15% oxidized, while the remaining 85% byproduct is calcium sulfite hemihydrate (CaSO₃· $\frac{1}{2}$ H2O). Because the molecular weight of calcium sulfite hemihydrate is less than that of gypsum, the curves are slightly "shifted to the right" relative to the equivalent curve for 100% gypsum. However, the sulfite byproduct does not dewater as easily as gypsum and therefore the band of target weight percent solids can extend lower, to approximately 65% as shown on the graphs in Figures 4-10 and 4-11.

Interpretation of Results – Equilibrium Chloride Concentration Trends

Equilibrium chloride concentration limits are required in the absorber to avoid pitting corrosion of FGD construction materials and to achieve high SO₂ removal efficiency at acceptable limestone utilization. For LSFO systems producing wallboard grade gypsum, there is also the requirement to ensure that halogen content specifications for washed gypsum can be met, which is influenced by the equilibrium chloride concentration and the water washing efficiency. However, this consideration does not apply when a blending ZLD system is used, because the gypsum is not intended to be used in drywall products.

The best scenario, in terms of low equilibrium chloride concentration, occurs for the coals containing the lowest chlorine content and the highest sulfur and ash content, because there is more mass of gypsum byproduct solids and fly ash available to accept the chloride purge as free moisture. The coals containing higher chlorine and lower sulfur and ash composition trend towards operation at higher equilibrium chloride concentrations. To operate at a lower equilibrium chloride concentration than shown on a specific curve (which represents one coal

composition) would require additional ash beyond the indicated design condition. For the 0% ash case, which implies other use of all of the ash collected by the ESP/baghouse, this means using some of that ash. For the other curves, which are based on using all of the collected ash, operation at a lower equilibrium chloride concentration would require "importing" ash from another unit to provide additional solids to accept a higher purge water rate. Conversely, if a scenario indicates possible operation at relatively low equilibrium chloride concentrations, this indicates that some of the fly ash collected by the ESP or fabric filter could instead be made available for sale, assuming the equilibrium chloride concentration could be increased beyond what is indicated on the curves. This possibility would depend on the FGD materials of construction and on the ability to achieve the required FGD SO₂ removal efficiency at an acceptable limestone stoichiometry.

Plant Operational Impacts

Quantities of Blended Solids

As stated earlier, it is valuable to calculate actual mass rates associated with a typical power plant, in order to have an understanding of the quantities of material to be handled, stored, and landfilled. Major factors affecting this calculation are: power plant output, power plant heat rate and coal higher heating value. For this report, the plant data shown in Tables 3-1 through 3-5 were used to calculate quantities. Average cases for some of the graphs presented in Figures 4-1 through 4-11 are shown in Table 4-2. The MW rating of a specific power plant can be used to adjust the quantities in Table 4-2 by using the ratio of the power plant MW to 500 MW.

Equipment for Material Handling and Blending

The calculation results presented in Figures 4-1 through 4-9 illustrate the equilibrium chloride concentrations resulting from blending chloride purge water with gypsum or with a blend of gypsum and fly ash. Figures 4-10 and 4-11 show similar results for calcium sulfite hemihydrate as a solid byproduct. For each type of coal, there is one curve based on no ash in the blend and a curve based on using all of the ash that would be captured by the ESP when burning that particular coal. The non-thermal ZLD system could be designed to blend only the minimum amount of fly ash required for the fixation reaction with the balance of the fly ash retained for sale. This operational flexibility would increase the complexity of the material handling equipment, though. Alternatively, the non-thermal ZLD system can be designed to remove all fly ash and gypsum produced by the plant so that there is only one solid waste stream (the blended byproduct). This method of operation would require increased material storage capacity, larger blending equipment, and increased truck traffic, and would result in reduced sales of fly ash.

Commercial Experience with Non-thermal ZLD

As mentioned previously in this report, there is considerable experience with this technology in scrubbed plants that produce calcium sulfite hemihydrate as a solid byproduct. The term Poz-O-Tec was trademarked by IU Conversion Systems in 1973 to describe a stabilized mixture of calcium sulfite sludge, ash and quicklime, and there were dozens of applications of this technology in the U.S. In general, if the water balance on sulfite-producing Poz-O-Tec FGD systems was adequately controlled, they could operate with no liquid discharge other than the water in the stabilized sludge.

Table 4-2 Blending - Quantity of Solids Produced and Equilibrium Chloride (for "Typical" Power Plant as Described in Text)

		Figure Number					
Parameter	Units	4-1	4-2	4-4	4-6	4-8	4-10
Coal type	-	PRB	Bituminous	Bituminous	Bituminous	Bituminous	Bituminous
Byproduct	-	Gypsum	Gypsum	Gypsum	Gypsum	Gypsum	Sulfite
Byproduct "standard" solids	%	85	85	85	85	85	65
Coal chlorine, ppm	ppm	20	500	500	1,000	1,000	1,000
Coal sulfur, %	%	0.45	2	2	2	2	2
Coal ash, %	%	7	15	5	15	5	5
Byproduct total	lb/hr	11,900	50,700	50,500	50,750	50,550	52,650
Byproduct dry solids		10,100	43,100	43,000	43,150	42,950	34,200
Byproduct free water		1,800	7,600	7,500	7,600	7,600	18,450
Equilibrium chloride concentration with byproduct only	ppm	8,090	27,250	27,250	53,700	53,700	22,100
Available fly ash	lb/hr	23,300	47,500	15,850	47,500	15,850	15,850
Additional purge water required to blend byproduct with fly ash and achieve 85% solids	lb/hr	4,100	8,400	2,700	8,400	2,800	8,650 (65% solids)
Blend total	lb/hr	39,500	106,650	69,100	106,600	69,200	77,150
Equilibrium chloride with blend	ppm	2,440	12,900	20,000	25,400	38,550	15,000
Additional purge water required to blend byproduct with fly ash and achieve 75% solids	lb/hr	9,400	22,600	12,000	22,600	12,000	n/a
Blend total	lb/hr	44,700	120,850	78,700	120,900	78,400	n/a
Equilibrium chloride with blend	ppm	1,290	6,800	10,500	13,450	20,700	n/a

However, over the past 15 years nearly all wet FGD systems installed in the U.S. have employed LSFO technology, and many previously sulfite-producing wet FGD systems have been converted to forced oxidation and are now producing gypsum. As stated previously, most of the early gypsum-producing FGD systems were able to sell their gypsum. These plants either had WWT systems installed along with the FGD system to treat the wastewater prior to discharge, or they were able to permit their FGD system to discharge through their ash pond to a receiving body of water with no further treatment. Therefore, wastewater permitting requirements did not drive these plants towards non-thermal ZLD practices.

There are perhaps a dozen plants with gypsum-producing FGD systems that do not sell their gypsum and operate with some form of non-thermal ZLD. This includes at least two plants that fire PRB or low-chlorine western coals that operate their FGD systems with elevated chloride concentrations and discharge chlorides only with the free moisture included in the unwashed gypsum byproduct. Another variation is a plant that has a unit with a gypsum-producing FGD system alongside a unit with a sulfite-producing FGD system. In this case the chloride purge water from the gypsum-producing FGD system is mixed with the sludge from the sulfite-producing system, quicklime and fly ash to be landfilled. There are also several known instances of the configuration described in this report, where gypsum, fly ash and chloride purge water are mixed with quicklime for landfill disposal. The experiences of several of these plants have been reflected in this report in making assumptions such as quicklime and water concentrations in disposal mixtures.

FGD Materials of Construction Impacts

As shown on Figures 4-1 through 4-11, retrofitting a blending ZLD system onto an operating plant may require a rise in FGD absorber chloride concentration beyond the present levels. This could occur if there are not sufficient blend solids available (either from the collected ash or the collected ash supplemented with imported ash) to accept the chloride purge flow rate required to maintain existing conditions.

In general, higher equilibrium chloride concentrations in the absorber circuit are more aggressive with regard to corrosion of the absorber materials of construction. Therefore, the predicted operating chloride concentration for a given coal should be evaluated with regard to the existing materials of construction if a plant is considering changing to operation in a non-thermal ZLD mode.

The suitability of alloys for FGD applications can be ranked by the Pitting Resistance Equivalent Number (PREN), which is calculated by the formula:

PREN = % chromium + $3.3 \times (\% \text{ molybdenum}) + 16 \times (\% \text{ nitrogen})$

Table 4-3 lists several potential alloys for FGD absorber construction and their PREN values. The PREN number indicated on the table is sometimes replaced with the PRENW number, which takes into account the amount of tungsten in the alloy. Resistance to chloride in FGD systems based on PREN or PRENW values is based on pitting corrosion and assumes best practices for welding, pickling, and passivating of the fabricated alloys. Because other factors are involved in corrosion of FGD systems (for example, crevice corrosion under deposits of manganese), the table does not include recommended operating chloride limits.

Table 4-3 FGD Alloys and PREN Values

Material	Typical Product	UNS No.	PREN
Type 316L SS	-	S31603	24
Type 317 LNM SS	-	S31703	36
22% Cr Duplex SS	Alloy 2205	S32205	35
25% Cr Super duplex SS	Zeron 100 Alloy 2507	\$32760 \$32750	41 43
6% Mo Super Austenitic	AL6XN	N08367	45
13/16% Mo Nickel Alloy	Alloy C-22 C-276	N06022 N10276	65 69

Potential Limitations and Other Considerations

This report presents the quantitative impact of blending of FGD wastewater with gypsum, fly ash, and quicklime, to produce a stable and fixated product suitable for landfill. The primary result is a series of parametric graphs illustrating blended cake solids content versus equilibrium FGD chlorides for a range of coal characteristics. There is also a brief discussion of equipment requirements, byproduct quantities, and materials of construction.

However, due diligence must be exercised when evaluating implementation of non-thermal ZLD, to consider plant operational impacts and potential limitations to implementation of the process. Some of the considerations listed below might apply to installing any technology at a power plant while others are unique to the subject process:

- Total economic evaluation,
- FGD system materials of construction inadequate for equilibrium chlorides level,
- Adequate plant space for blending operations and interim storage,
- Adequate landfill space to develop new landfill or upgrade existing landfill to handle new solids load,
- Management of the solids/liquid (blending) process parameters,
- Impact to FGD system operating conditions,
- Design for upsets and need for re-blending,
- Modifications to the existing wastewater treatment and/or discharge system to tie in to the blending system,
- Modifications to the existing fly ash system to tie in to the blending system,
- Installation of new material handling systems,
- Required upgrades to plant electrical system,

- Integrate new controls within the plant's existing control system,
- Underground utility relocations,
- Interconnecting yard piping, runoff systems, and sump systems,
- Roadwork to support increased truck traffic and access to the blending facility, and
- Environmental permitting.

5 SUMMARY AND CONCLUSIONS

A "non-thermal" zero liquid discharge (ZLD) method for FGD blowdown may be achievable by blending of the FGD wastewater with gypsum, fly ash, and quicklime, to produce a stable and fixated product suitable for landfill. Blending the water with the byproduct and ash can potentially allow for elimination of treatment and discharge of an FGD blowdown stream to surface waters, resulting in a ZLD operation.

The information presented in this report is intended to be useful for evaluation of existing FGD systems, in particular to determine if non-thermal ZLD operation is suitable for the FGD materials of construction when using coal with a particular range of characteristics.

This report presents parametric graphs of blended cake percent solids (100 – blended cake percent moisture) versus absorber equilibrium chlorides. The evaluated parameters are coal sulfur, coal chlorine, and coal ash content. "Typical" power plant boiler and FGD system performance factors are used for the calculations. The absorber equilibrium chloride concentration corresponding to a target band of 75-85 percent solids (15-25% moisture) in the blended cake is presented for multiple combinations of the coal parameters. This moisture range is applicable to gypsum and gypsum blended with fly ash and lime. A higher moisture content is included in the sulfite byproduct resulting from an inhibited oxidation FGD process.

The graphs illustrate the range of equilibrium chloride concentration for multiple combinations of coal characteristics and allow for visualization of the decrease in the chloride concentration that can be achieved by blending the FGD byproduct with fly ash, lime, and purge water (additional water beyond that which is present as free water in the dewatered byproduct). These factors can be evaluated in combination with design values for absorber steady-state chloride concentration to determine if "non-thermal" ZLD is feasible for a facility, considering its current or future coal characteristics.

The report also includes a table with mass rates of FGD byproducts, ash, and byproducts blended with ash, for representative coal characteristics. This table also shows the additional water (beyond the standard byproduct free water) required to achieve upper and lower limits of byproduct blend moisture, as well as the resulting equilibrium chloride concentration.

A summary of plant operational impacts and potential limitations to implementation of nonthermal ZLD is also presented to illustrate the due diligence that must be exercised when evaluating implementation of non-thermal ZLD. Some of these considerations might apply to installing any technology at a power plant while others are unique to the subject process.

This report does not address the impact of additives used to enhance mercury capture, as data are not available on their effects on the blending process.

6 REFERENCES

- 1. "Wet FGD Wastewater Treatment Options: Planning for the Future Regulatory Environment"; I. Brodsky, K. Braunstein, J. Kelly; paper presented at CoalGen 2010
- 2. http://geology. Utah.gov/emp/mercury/pdf/mercuryrpt.pdf, accessed October 2012

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute Inc., EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass

Together...Shaping the Future of Electricity

© 2013 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

3002000484