

A REVIEW OF THE NEW
EPRI/CICIND REVISED WET STACK DESIGN GUIDE

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Most new coal fired power plants being built in the developed world or those built in developing countries which are funded by international agencies, require the plants to achieve significant reductions in the quantity of emitted pollutants, including SO₂. There are many different methods available to achieve these reductions including both wet and dry flue gas desulfurization (FGD) technologies. The choice of technology is primarily driven by the size of the unit and availability of the reactant used in the process. In countries with regulations governing mercury and hazardous air pollutant (HAPs) emissions, dry desulfurization technologies are becoming more common as these pollutants can be easily co-collected within the reactor. Dry technologies are also becoming favored in units of smaller size, <350MW, because they are cheaper to build and easier to operate. For larger units, wet scrubbing technologies such as limestone based open spray towers remain the technology of choice and with a few notable exceptions, the majority of these units operate with a wet stack. In these units, saturated flue gases exiting the absorber enter the stack directly and in combination with droplet carryover from the absorber mist eliminators and condensation, the walls of the absorber outlet ducting and stack liner will be covered with a liquid film which must be collected and drained from the system. This is called wet stack operation. If the ductwork and stack liner are not properly designed, droplets may be entrained in the flue gas flow and ejected from the top of the stack in a phenomenon called Stack Liquid Discharge (SLD).



Wet flue gas desulfurization (WFGD) systems have been around from many years. Many, if not most, of the early units operated with dry stack using a process called flue gas reheating. In this process, the temperature of flue gasses exiting the wet absorber were raised a few degrees above saturation by placing a high temperature steam coil in the absorber outlet duct or, more commonly, by bypassing between 15 and 20% of the untreated higher temperature flue gas around the absorber and remixing it with the clean but significantly cooler gasses exiting the absorber. The resulting higher flue gas temperature allowed the stack to operate dry. In the late 1970's some utilities considered the possibility of using wet ducts and stacks as a means of reducing their operating costs. As more plants began to operate this in this manner, many experienced unacceptable high levels of SLD. Because of this, it became clear that a better understanding of the physical processes involved in WFGD systems and wet stack operation was needed and in the 1980's EPRI sponsored a number of programs to determine the key variables contributing to liquid re-entrainment. The results of one of these studies were summarized in EPRI Report No. CS-2520, "Entrainment in Wet Stacks"

By the late 1990, there were many plants operating with wet duct/stack systems and a sufficient body of experience had been developed for EPRI to sponsored a another program aimed at the development of practical guidelines for wet stack design and operation. The results of this study were summarized in EPRI Report No. TR-107099, "Wet Stacks Design Guide". Since this guide was published, it has been accepted as the "de-facto" standard for the design and operation of wet stacks in the US and to a large part, around the world with hundreds of units having been built under its guidance.

Since the issuance of the original Wet Stack Design Guide, the number of wet stack installations has grown considerably and a wealth of practical real world operating and maintenance experience has been obtained. The laws of physics have not changed and most of the information presented in 1996 is just as valid today as it was when originally published. What has changed is the power generation industry's experience using this information and in the day-to-day operation of wet stacks. Much has been learned over the intervening years in the design and operation of wet stack systems, and it had become clear that some updating to the recommendations made in the original guide were needed. Based on this, EPRI, CICIND, and Alden Research Laboratory equally co-funded a project in which the recommendations and processes presented in the original Design Guide were reviewed and updated in

light of the current state-of-the art in wet stack technology. The resulting document, the Revised Wet Stack Design Guide, has been prepared to present this updated information and to provide the power generation industry with the latest information available for favorable wet stack design and operation. Much of the new document will be familiar to those who have read the original design guide. Some sections of the original guide have been reused with only minor changes while others have been significantly revised and new sections discussing the industry's experience with wet stack operation and maintenance have been added. The outline of the guide has been rearranged to be easier to use and follow, bringing the reader through the entire wet stack design process from the fundamentals of droplet collection and liquid film flow to the stack's final design, commissioning and operation. This new document strives to thoughtfully update the original guide and provide the industry with the single reference needed by the engineers and designers responsible for the specification, design, and implementation of effective wet stacks. As of the date of this paper, the revised guideline has been completed and is under final review by EPRI and CICIND.

The main objectives of the Revised Guide are to:

- To provide background information and updates of previously published information.
- To summarize current state-of-the-art in wet stack design.
- To list and discuss important design parameters and options.
- To give specific recommendations for favorable wet stack design.

The information provided in the Revised Guide covers the design process and operational issues for both new and retrofit wet stack installations. Some of the important issues addressed in the document include, system design for favorable wet operation, stack liquid discharge, plume downwash, stack liner geometry, gas velocity in the liner, and liquid collection devices and drainage. In addition, the report also provides a guide to developing a wet stack specification.

The new guidelines are very similar to the original in that most of the specific recommendations, as well as the overall design process, are still valid and therefore remain unchanged. The single most important and critical change to the original Design Guide is a slight reduction in the recommended stack design velocities for the most commonly used liner materials. The new slightly lower stack liner velocities were

necessary to account for the reality of real world field construction techniques and unit operation. These new recommendations have been used effectively for the past few years by many wet stack designers and have been shown to result in significantly more robust designs that are operating well across a wide range of changing operating and environmental conditions.

World View

As part of the revision process, efforts were made to determine if stack liquid discharge was regulated in other parts of the world. To the best of our knowledge, it is not. However, as it is considered a nuisance, many countries/regions recommend the installation of a liquid collection system to minimize the potential for SLD. For example, in the EU, VGB PowerTech Instruction Sheet VGB-M 643 Ue, “Chimneys for Operation without Flue Gas Reheating after FGD”, discusses the formation of a liquid film on the liner wall and the need for an effective liquid collection system but no specific details are provided. As with the EPRI/CICIND Revised Wet Stack Design Guide, recommendations for the maximum flue gas velocities inside the liner as a function of the liner material are presented. These velocities are similar to those recommended in the Revised Wet Stack Design Guide for FRP, Alloys and Coated Surfaces, are higher for Acid-resistant brick and slightly lower for borosilicate block. The need to minimize horizontal discontinuities as well as to control plume downwash are also discussed in this document.

Wet flue gas desulfurization systems with wet stacks are quite prevalent in China, however these stacks do not incorporate liquid collection systems. Discussions with the China Electric Council have revealed that there are currently no regulations in China controlling the quantity of stack liquid discharge from their plants and none are known to have liquid collection systems installed. It is known that stack liquid discharge is an issue at many plants in China and there is currently some interest in the introduction of liquid collection technology to these plants.

Recent Wet Stack Developments

Because of cost and availability issues, most of the recent developments in wet stack technology have been focused on liner materials. Alloys have become prohibitively expensive for most utility power generation applications. Acid resistant brick is still in use but has velocity limitations. Most new wet stack liners are being built from FRP or borosilicate block lining systems installed over an existing liner, on a new carbon steel liner or in some instances directly on the inside of the concrete wind screen.

An older technology that is being successfully reintroduced into the wet stack arena is the use of wet ID fans placed downstream of the absorber. New technology, new materials and better understood WFGD chemistry has allowed these fans to operate effectively with few of the issues previously experienced when this approach was attempted in the past. The main advantage of this approach from a stack liquid discharge perspective is that if properly designed, the compression of the flue gas which occurs as it passes through the fan will increase the temperature of the gas to a few degrees above its saturation temperature, essentially drying the flue gas. This, in combination with a properly designed liquid collection system to capture the fan wash spray and with a well insulated stack to minimize heat losses to the atmosphere, can result in the stack operating dry with no possibility of stack liquid discharge. This technology has been installed at two units of the Rovinari Power Plant in Romania which is using a wet axial fan and a borosilicate lined steel flue. A recent visit to the plant revealed that the system is working very well with no reports of stack liquid discharge even during one of the coldest winters in recent memory.

Revised Wet Stack Guideline - Table of Contents

A main objective of the Revised Guide was to provide the information in a logical sequence, walking the reader through the wet stack design process starting with an understanding of the basic fundamentals through to specific design recommendations. In this manner the reader will not only understand what needs to be done but hopefully will understand why as well, thus providing a strong foundation on which to base decisions during the wet stack design process. This logical sequencing can be clearly seen in the Revised Guide's Table of Contents provide below:

1 BACKGROUND AND OBJECTIVES

- 1.1 Preface to the Revised Wet Stack Design Guide
- 1.2 Introduction
- 1.3 Scenarios for Wet Stack Operation
- 1.4 Important Considerations for Wet Duct and Stack Design and Operation
- 1.5 Contents of the Design Guide

2 WET STACK DESIGN FUNDAMENTALS

- 2.1 Introduction
- 2.2 Droplet and Liquid Flow Fundamentals
- 2.3 Sources of Liquid in the Wet Stack System
- 2.4 Liquid Film Behavior on Liner Walls
- 2.5 Liner Wall Discontinuities
- 2.6 Re-entrainment
- 2.7 Recommended Liner Velocities
- 2.8 Stack Liquid Discharge
- 2.9 Downwash & Icing

3 PRACTICAL DESIGN RECOMMENDATIONS

- 3.1 Introduction
- 3.2 New Wet Stack Designs
- 3.3 Retrofit Wet Stack Designs
- 3.4 Wet Duct/Stack Operation
- 3.5 Absorber Design and Placement
- 3.6 Wet Ductwork Design
- 3.7 Flow Control Devices
- 3.8 Fans
- 3.9 Stack Liner Design
- 3.10 Miscellaneous Materials of Construction
- 3.11 Basic Liquid Collection System Design
- 3.12 Laboratory low Modeling
- 3.13 Downwash & Icing

4 GUIDE TO DEVELOP SPECIFICATION FOR WET STACKS

- 4.1 Specification Overview
- 4.3 Wet Stack Bid Preparation Process
- 4.4 What to Specify in a Bid Document
- 4.5 What to Ask For in a Bid

5 WET STACK EXPERIENCE

Recommendations for the Design of Effective Wet Stack Systems

The remainder of this paper will outline the important design aspects, as detailed in the Revised Wet Stack Design Guideline, which must be addressed to minimize liquid discharge from both new and retrofit wet stack installations.

One of the key steps in the development of an effective wet stack installation is the proper fluid dynamic design of the wet duct/stack system. The design process, usually performed by a flow modeling laboratory with experience in this area, typically consists of five distinct phases:

Phase 1 - Initial Review of Proposed System Designs

Phase 2 - Condensation Calculations

Phase 3 - Liquid Collection System Design and Development

Phase 4 - Plume Downwash Study

Phase 5 - Field Installation and Operational Inspections

Using the results of the first four phases the unit design can be finalized and the specifications for the construction bids can be written. The fifth phase supports the installation of the recommended liquid collection system.

Phase 1 – Initial Review of Proposed System Designs

Past experience has shown the value of an early review of the plant's initial or proposed absorber outlet duct and stack breach/inlet geometry with respect to making the geometry more suitable for wet operation. This review should be performed by an organization with experience in wet stack system design and operation so that the industry's experience with such systems can be utilized. Key system design variables such as gas velocities, breach height, breach width, and liner diameter will be evaluated with respect to values which have been proven to be favorable for wet operation at other installations. Simple changes in the system geometry, such as adjusting the breach aspect ratio or relocation of a liner expansion joint, can often result in significant improvements in the efficacy of the liquid collection

system by improving the flow patterns in the lower liner, minimizing the potential for liquid re-entrainment, reducing the total number of liquid collectors required, and/or reducing the complexity of the required liquid collection system.

While there are many economic drivers for minimization of the stack liner diameter, it must clearly be understood that the primary controlling parameter for effective wet stack operation is the liner gas velocity. Different liner materials and construction techniques have different velocities for favorable wet operation. Figure 1 presents the liner gas velocities recommended in the Revised Wet

Liner Material	Recommended Wet Stack Design Velocites	
	(ft/s)	(m/s)
Borosilicate Block	60	18.3
FRP	55	16.8
Alloy	55	16.8
Coatings	55	16.8
Acid Resistant Brick	45	13.7

Figure 1: Recommended Wet Stack Liner Velocities

Stack Design Guide. These values are slightly lower than those recommended in the Original Design Guide which were developed primarily based on laboratory testing of different liner material surfaces in a vertical wind tunnel. Since this testing was performed, it has become clear that slightly lower velocity recommendations were required to accommodate issues related to the field installation liberties and to account for increases in the flue gas flow rate due to changes in fuel source, increases in plant efficiency and/or future increases in the plant output. If a wet stack system is designed to operate at the high end of the recommended gas velocity range from the start it will have little margin to accommodate issues which otherwise would result in stack liquid discharge. Based on this experience the Revised Wet Stack Design Guide recommends that C276 and FRP liners should ideally be operated at a velocity of 55 ft/s (16.8 m/s) while brick liners which inherently have a less smooth surface should operate at gas velocities no higher than 45 ft/s (13.7 m/s) . If properly installed, modern materials, such as borosilicate block liners can operate effectively at velocities in excess of 60 ft/s (18.3 m/s).

These velocity ranges are safe for the different liner materials in fully developed turbulent and axial symmetric flow in the liners. This condition exist in stack liners only 3 to 4 liners diameters above the breeching duct. Special care must be taken to design the stack entrance area where the gas flow is 3-

dimensional and highly non uniform, with velocities two or more times higher than the area average value.

Phase 2 - Analytical Calculation of Liner Condensation

One of the major sources of liquid that must be collected and drained from a wet stack is from condensation on the duct and stack liner walls. This condensation is from two main sources: 1) thermal condensation on the wall as a result of heat transfer from the flue gas to the outside air through the liner, insulation, annulus air, and concrete shell, and 2) adiabatic condensation in the bulk of the gas flow due to the expansion of the saturated gases as a function of the pressure change along the height of the stack.

The quantity of thermal condensation on the duct and liner surfaces is a function of the stack construction and thermal conductivity, the internal flow conditions, the atmospheric temperatures, wind velocity, and in some instances, wind direction.

Thermal insulation is a key parameter in controlling the quantity of thermal condensation experienced within a stack liner. Previous condensation studies have shown that the addition of two inches (50mm) of liner insulation can reduce the quantity of thermal condensation by a factor of approximately four.

The second source of condensation experienced within a stack liner is caused by adiabatic expansion along the height of the stack. The relatively small pressure drop due to the change in elevation from the breeching duct to the top of the stack may produce an appreciable rate of liquid by adiabatic condensation. A small fraction of this liquid will deposit on the liner surface due to turbulent diffusion and the rest will be discharged from the liner as part of the bulk gas stream in the form of very small droplets. These droplets do not represent a problem because the size of these droplets is very small and they will evaporate before reaching the ground.

The total quantity of liquid collected on the stack liner walls due to thermal and adiabatic condensation are calculated using specially developed heat transfer computer programs. The rate of liquid condensation is a function of ambient air temperature, wind velocity and liner design variables are necessary for the development of an effective liquid collection system as it will affect the number, sizing

and location of the various liquid collection gutters and drains. In addition to the liquid generated due to thermal and adiabatic condensation, the contribution from mist eliminator carryover is also calculated and added to the total liquid load on the liner surface.

Phase 3 - Development of Wet Stack Liquid Collection Devices

The problem of stack liquid discharge from a power plant duct and stack system operating in an "all scrubbed" mode is caused by a two-phase flow interaction of gas and liquid. The liquid enters the ducts and stack as droplets and water vapor carried over from the mist eliminators of the absorbers. These liquid carryover rates can increase significantly over their "as designed" rates during normal wash cycles or should the mist eliminators become fouled with time. This liquid accumulates on the walls and internal structures within the ducts and stack by inertial deposition of droplets and by condensation of water vapor from the saturated gas. The amount of deposition is governed by the gas velocity, duct and stack geometry, the liquid loading level, and droplet size distribution. The deposited liquid and condensate will form a liquid film on the exposed surfaces which will be moved under the influence of gravity and gas shear forces. This liquid film will either move to locations where it will accumulate or be re-entrained from liner walls, internal struts, dampers or vanes, and stack top by the high velocity gases. The re-entrainment process is dependent on gas velocity, the amount of liquid on the wall, surface roughness and discontinuities such as duct/liner weld seams or FRP liner joints. Liner expansion joints can be major source of liquid re-entrainment if not properly located and arranged. Most of the liquid re-entrained within the stack does not redeposit on the liner wall and will exit the stack in the form of droplets that are sufficiently large to reach the ground before fully evaporating.

The behavior of droplets entrained in the gas flow from the absorber mist eliminators and the motion of the resulting liquid films on the duct and stack liner surfaces must be evaluated in physical flow model of the subject unit. Using this model, effective internal liquid collection devices can be designed and developed to optimum to improve primary droplet deposition and liquid collection as well as minimize the potential for re-entrainment of droplets from liquid pools and films. Computational fluid dynamic (CFD) models cannot be used for liquid collection system development because the computer codes, while effective at predicting droplet trajectories and droplet collection patterns, are currently not capable of accurately simulating the development of liquid films on the duct and liner walls due to

droplet deposition and condensation or the subsequent motion of these liquid films under the influence of gravity and gas shear forces.

Physical flow models of wet duct and stack installations are normally built to a scale of between 1:12 and 1:16 and typically encompass the system from the outlet of the absorber mist eliminator to a point in the stack liner approximately 3 to 4 liner diameters above the roof of the breaching duct. Typical single and multiple absorber wet stack flow models are shown in Figures 2 and 3 respectively. To the extent possible, models are primarily fabricated from clear plexiglass to allow detailed visualization of the internal gas and liquid flows. To ensure that the liquid film motion in the primary collection zone of the lower liner are accurately simulated, care must be taken however to ensure that the surface of the material used in this area has wetting properties similar to that in the field.



Figure 2 - Typical Single Absorber Wet Stack Flow Model

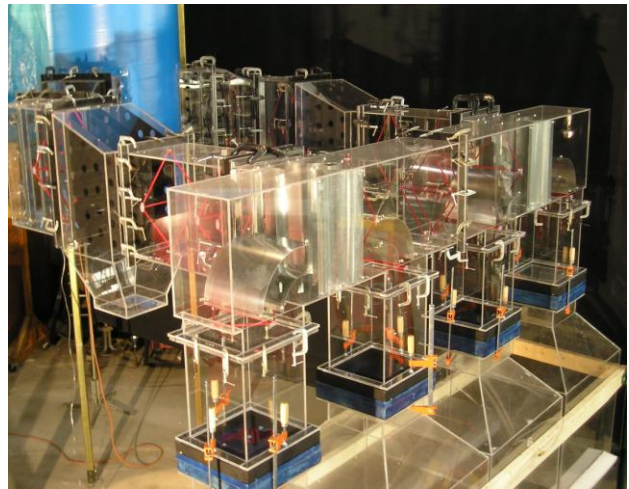


Figure 3 - Typical Multiple Absorber Wet Stack Flow Model

Using the physical flow model, droplet trajectories and the motion of the resulting collected liquid films are observed. Based on these flow patterns turning vanes, liquid collection gutters, ring collectors, dams, baffles and drains are developed and optimized until a system has been developed which works effectively across all expected boiler loads and operating scenarios. To the extent possible, liquid collectors and gutters are fabricated from commercially available structural shapes made of non-corrosive materials such as C276 or FRP. All drains must discharge through a loop seal or discharge back into the absorber reaction tank below the liquid level ensure that no gas is allowed to back flow up the drain pipes. This back flow would result in significant levels of liquid being re-entrained back into the gas flow. All drains should incorporate a cleanout “Tee” where the piping penetrates the liner wall and ideally should incorporate the ability for the drainage flow to be measured or at least visually monitored. This capability will be invaluable should the unit start to experience a SLD issue.

Phase 4 - Stack Downwash Modeling

A cross-wind at the top of the stack will deflect the plume from its vertical path. As the ratio of vertical plume momentum to horizontal wind momentum decreases, the plume may become partially entrained in the wake that is formed on the downwind side of the liner and stack shell. At lower momentum ratios the reduced static pressure in the wake can draw the flue gas into a downwash pattern along the downwind side of stack shell, Figure 4. The saturated flue gas that is drawn into the wake comes into contact with the roof and sides of the stack liners and shell leading to problems of metal corrosion, concrete deterioration and ice build-up during winter months. This is a particularly important problem for stacks with multiple liners and interacting discharge plumes. Severe downwash situations can also allow contact with lower surrounding plant structures and, in extreme cases, even produce plume touch down at ground level near the stack.

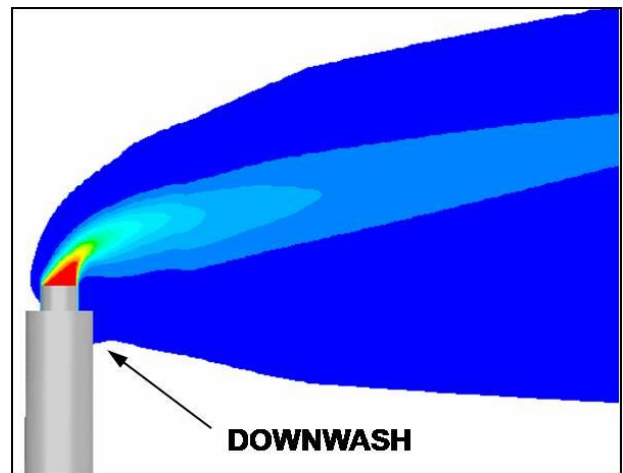


Figure 4 - Plume Downwash

Computational fluid dynamic modeling is ideally suited for this type of evaluation which is typically limited to gas-gas interactions. Various liner velocity/atmospheric conditions can be evaluated to determine the liner extension height or exit choke size reduction required to eliminate downwash or the extent to which the top of the stack shell should be covered with an acid resistant coating. The evaluation of stack top icing potential can also be evaluated by including heat transfer in the model and predicting cooling of the plume after it exits the stack.

The interactions between the prevailing wind and the individual plumes will also play a significant role in the propensity and extent of downwash for stacks with multiple flues. The wind direction relative to the plumes can result in differing degrees of downwash. For a given momentum ratio, plume downwash will be greater in a dual liner stack if the prevailing wind direction is perpendicular to the axis of the two liners as compared to conditions where the wind direction is parallel to that axis. Evaluating the downwash potential for two (or more) wind directions allows the maximum downwash potential to be defined and the appropriate liner extensions or stack top geometry developed to mitigate the problem.

Phase 5 - Field Installation and Operational Inspections

The first four phases described the steps necessary for the development of an effective wet duct/stack system. The final phase provides support to the field installation. A number of units have experienced stack liquid discharge immediately after the unit has gone on-line. Experience has shown that most of the issues related to these underperforming wet stacks could have been identified and rectified before the unit went into operation if the liquid collection system fabrication drawings had been reviewed by the modeling company that performed the flow study and a post installation inspection of the liquid collection system had been performed before the unit went on line. The Revised Wet Stack Design Guide highly recommends that the field construction and installation drawings of the liquid collection system should be reviewed by the group that developed the system design to ensure their recommendations have been interpreted correctly and to evaluate any changes made by installation company to accommodate fabrication, assembly, installation or structural support.

During the field installation process deviations from the specified design are often required due to unanticipated interferences and installation issues. Errors can also be made by the installers because of misinterpretation of the installation instructions, rushing, etc. To ensure that the liquid collectors have been installed properly, an onsite inspection and leak check of the installation by the liquid collection system designer is recommended for a day when the installation is 80% to 90% complete. This way, errors can be identified, on-the-spot modifications can be defined if necessary, and corrections can be made while the construction crew is on site and before the liner scaffolding has been removed. This inspection is also required to ensure that the collectors and drains are free from construction debris and trash which typically accumulates in them during the installation process.

Inspecting the liquid collection system after several months of operation is also recommended. If any stack emission incidents occurs during normal operation, the need for inspection is obvious. However, if stack liquid discharge is not experienced, it is still important to inspect the liquid collectors to ensure satisfactory long-term operation. Different problems such as solid depositions and liquid drainage problems can be detected and corrective measures developed which can be addressed during future scheduled or unscheduled outages. The inspection must be performed before any cleaning of the ductwork or liner is performed as this would remove the deposition and liquid flow patterns which are indicators of system performance. A visual inspection of all liquid collection gutters and drains should also be performed at the first opportunity to see if any debris has collected which could compromise the performance of the liquid collection system. This is particularly important in FRP liners where a number of plants have reported liquid collection system fouling by the plastic film used as a separating media when the FRP cans were formed on the mandrel. If this media is not completely removed during the liner construction process, sheets or flakes of this material can come off the wall when the unit comes on line, collect in the gutters and plug the drains.

Summary

In the years since the original EPRI Wet Stack Design Guide was published, a significant amount of wet stack field experience has been obtained and new technologies developed. Because of this, a joint project was developed between EPRI, CICIND and Alden Research Laboratory to review and update the guide. The resulting document, the Revised Wet Stack Design Guide, has been prepared to present this

updated information and to provide the power generation industry with the latest information available for favorable wet stack design and operation in a clear and logically presented manner. The newly revised EPRI/CICIND Wet Stack Design Guideline will carry on the legacy of the Original EPRI Wet Stack Design Guide and will continue to be the industry's primary resource for wet stack design information and its application to real world situations.