Environmental Protection Technology Series

# LIME/LIMESTONE SCRUBBING
# IN A PILOT DUSTRAXTOR-KEY WEST

# LIME/LIMESTONE SCRUBBING
# IN A PILOT DUSTRAXTOR-KEY WEST

by

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# SECTION 1

## INTRODUCTION

Abatement of the air pollutants commonly associated with electric
power generation--particulates, sulfur dioxide ($SO_2$), and oxides of
nitrogen ($NO_x$)--is a primary goal of the public utility industry and
government. Particulates can be controlled through use of commer-
cially available and proven technology; however, processes for control
of the oxides of sulfur and nitrogen formed in the combustion process
have not reached the same state of commercial availability. $SO_2$ is
formed when sulfur-bearing fuels, either solid or liquid, are used in
the combustion process; hence, two $SO_2$ control strategies become
immediately apparent: use low-sulfur or sulfur-free fuel or remove
the $SO_2$ from the flue gas. The use of low-sulfur or sulfur-free fuel
depends upon the availability of these fuels. Currently, the demand
greatly exceeds the supply. Therefore, removal of $SO_2$ from flue gas
is receiving considerable attention from both the public utility
industry and government.

The major problem in removing $SO_2$ from flue gases is not the techni-
cal problem of $SO_2$ absorption or adsorption, but how to accomplish
this economically without adversely affecting the reliability of
electrical generation. Handling the required volumes of flue gas by
standard chemical engineering unit operations (such as absorption
towers) is a complex engineering problem which must be thoroughly
investigated in a broad-based research and development program prior
to commercial operation of any process. Thus, a primary task of the
*Control Systems Laboratory*, Office of Research and Development, Environ-
mental Protection Agency, has been to investigate a variety of research
and development processes potentially amenable to this problem.

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Wet scrubbing of flue gases by various aqueous absorbents capable of reacting with $SO_2$ has been one of the most vigorously investigated approaches for control of $SO_2$. The obvious technical advantage of wet scrubbing is the well-established unit operation of particulate collection and gas absorption by aqueous scrubbing processes in other industries. The Environmental Protection Agency, therefore, undertook a program to develop the potential of the calcium base or limestone process for $SO_2$ control from power plants. The process appeared to be technically simple and the least expensive to install among the potential first-generation wet scrubbing processes.

There are many variations of the lime/limestone wet scrubbing process including:
- Boiler injection with subsequent wet scrubbing
- Open-loop, tail-end lime/limestone wet scrubbing
- Closed-loop, tail-end lime/limestone wet scrubbing

The dry limestone injection into a power plant boiler followed by wet-lime scrubbing has been studied on a large prototype test facility by the Tennessee Valley Authority (TVA). Other studies are currently underway on both open and closed-loop tail-end systems since potential problems related to limestone injection into a boiler are eliminated with these processes.

Initial pilot plant testing of the Zurn Air Systems Division (ZASD) limestone wet scrubbing system on boiler flue gas took place in 1969 with favorable results. Based upon the favorable results from this early effort, Zurn Industries, Inc. proposed a cost-shared pilot plant study with the National Air Pollution Control Administration (now EPA) to investigate certain variables important to the success of the tail-end limestone wet scrubbing process. On April 30, 1970, Engineering-Science, Inc. was awarded a contract for an in-depth study of the tail-end limestone wet scrubbing process utilizing the ZASD scrubber.

The contract included the design, fabrication, and operation of a
limestone wet scrubbing pilot plant.

The object of this contract was to evaluate $SO_2$ removal capabilities
of this limestone wet scrubbing system on flue gases from both oil-
fired and pulverized coal-fired boilers while utilizing a series of
different calcium based reactants.

Several additional goals of the program were the:
- Investigation of potential operating difficulties
- Generation of data for a scaled-up design
- Evaluation of the process economics

The test program was divided into two major segments:
- Key West, Unit No. 3, City Electric System, Key West, Fla.
- TVA Shawnee Units No. 9 and No. 10, Paducah, Ky.

The Key West phase of the study took place while the pilot plant was
installed on the No. 3 unit of the Utility Board of the City of Key
West, Florida. This unit was a 20 MW base-loaded steam generator
firing 1-2% sulfur No. 6 fuel oil. The sulfur content of the fuel was fairly
constant due to the method of mixing of fuel shipments; however, on
the days that fresh fuel was received, the sulfur concentration in the
flue gas varied widely.

The Paducah phase of the study took place while the pilot plant
was located between the No. 9 and No. 10 units of the TVA Shawnee
generating station. Both of these units were 150 MW steam generators
firing 2-4% sulfur pulverized coal. The No. 9 unit was conventional while
the No. 10 unit had been modified to allow dry limestone injection for
testing under another EPA contract.

A series of statistical design tests was developed to evaluate
the effects of design characteristics, reactant properties, catalysts,
and operating conditions on primary dependent variables such as:

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- SO$_2$ absorption
- Scale formation
- Corrosion
- Operating problems
- Process costs

The test program resulting from the experimental designs included over 200 tests related to:

- Reactant type
- Stoichiometry
- Particle size
- Slurry concentration
- Catalysts
- Liquid/gas ratio
- Pressure drop

Twelve series of tests were conducted at Key West and Paducah from January 1971 through August 1971 to study the aforementioned variables. Table 1-1 is a list of the test series conducted during this project, the test site location, and test dates.

The initial salt water tests (S-XX series) were performed to determine the operational limitations of the scrubber and monitoring equipment. During this period mechanical and electrical malfunctions were identified and eliminated to produce a reliable system. Once accomplished, the testing program proceeded to the primary test series.

The first series of reactant tests (C-XX series) used a crushed coral slurry to evaluate its potential use as a reactant for the full scale demonstration scrubber. A half factorial statistical design schedule was followed to gain maximum scrubber operation information from a minimum number of test runs. The data generated were later compared with tests which used the more commonly used slurries such as limestone and lime. In addition, specific additives which purportedly enhance SO$_2$ removal were investigated during this testing period.

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Table 1-1.  PILOT PLANT TEST SERIES

| Test identification | Test series | Dates |
|---|---|---|
| S-XX | Key West-Initial Salt Water Shakedown Test Series | 1/7/71 - 1/18/71<br>1/19/71 - 1/28/71 |
| C-XX | Key West - Coral Test Series | 1/28/71 - 5/25/71 |
| F-XX | Key West - Fredonia Valley Limestone Test Series | 2/6/71 - 5/20/71 |
| HL-XX | Key West - Lime Test Series | 4/16/71 - 4/20/71 |
| D-XX | Key West - Dolomite Test Series | 4/20/71 - 4/28/71 |
| PC-XX | Key West - Precipitated Calcium Carbonate Test Series | 4/27/71 - 4/30/71 |
| X-XX | Key West - Recycled Limestone Test Series | 4/29/71 |
| P-XX | Paducah - Shawnee No. 9 Limestone Test Series | 6/14/71 - 8/6/71 |
| PS-XX | Paducah - Shawnee No. 9 Simulated Key West Limestone Test Series | 7/10/71 |
| PA-XX | Paducah - Shawnee No. 9 Aragonite Test Series | 7/9/71 - 8/3/71 |
| IPA-XX | Paducah - Shawnee No. 10 Aragonite Injection Test Series | 6/23/71 - 6/25/71 |
| IP-XX | Paducah - Shawnee No. 10 Limestone Injection Test Series | 7/14/71 - 7/28/71 |

Fredonia Valley Limestone (FVL), the second principal reactant to be evaluated in this study, was used as a primary standard in gauging the scrubbing efficiency of the coral slurry. As with test series C-XX, a half factorial test design was followed during F-XX series to gain maximum information concerning scrubber operation.

Test series HL-XX was conducted with a lime slurry which normally produced $SO_2$ removal efficiencies in the 90% and greater range. The purpose of this test series was to establish the maximum $SO_2$ removal efficiency obtainable with the ZASD scrubber design. However, lime slurry was considered a secondary reactant for this program due to the high purchase costs.

A fourth reactant, dolomite, was investigated during test series D-XX as a potential scrubbing agent possessing lower reactivity and high magnesium oxide content.

Precipitated calcium carbonate, considered a secondary reactant for these test purposes, was used as the $SO_2$ scrubbing agent during test series PC-XX. This material is a highly reactive calcium carbonate material and was therefore included in this program.

A special test run (X-XX) was performed with a slurry derived from "spent" coral-limestone material that had made one pass through the scrubber. The purpose of this experiment was to investigate the availability of unused calcium carbonate in a "spent" slurry.

The pilot plant was relocated to a coal-fired power plant in Paducah, Kentucky, after the Key West series had been completed. Scrubber operating conditions during these test series duplicated or simulated those during the Key West tests. In addition, several new conditions were investigated.

The first Paducah test series (P-XX) studied the effect of using a Fredonia limestone and untreated river water slurry in removing $SO_2$ from flue gases generated by a coal-fired power plant. During the

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majority of the test runs, a fly ash collector preceded the scrubbing
system; however, several tests were conducted with the dry collector
bypassed to investigate its effect on the total system. A half fac-
torial statistical design was followed during this test series.

A secondary test series (PS-XX) was conducted in Paducah to investi-
gate the effects of slurry ionic strength on $SO_2$ removal efficiency.
An attempt was made to simulate the Key West salt water slurry by
adding rock salt to river water.

A new reactant was introduced into the program in Paducah during the
PA-XX test series. The use of aragonite during the Key West tests had
been considered; however, it was unavailable in sufficient quantities
or desired grind size. Aragonite was reported as a highly reactive
calcium carbonate material possessing a crystal lattice structure
different from the limestone or coral and was therefore included in
the Paducah test series.

A brief two day experimental test series (IPA-XX) was designed to
investigate the effect of injecting dry aragonite into the boiler
while attempting to remove $SO_2$ gases in the scrubber with river water.
Similar tests were conducted with dry limestone during test series
IP-XX.

An addendum to this report, available through EPA's Control Systems
Laboratory, contains the raw data collected during the course of this
study.

# SECTION 2

## PILOT PLANT EQUIPMENT

The flexible design of the pilot plant allowed for modifications
to suit the varied physical configuration expected at each of
the plant sites. Discussed in this section are the physical arrange-
ments and specifications of system components as installed in Key
West and Paducah, general descriptions of the operation of each com-
ponent, and descriptions of the sampling and laboratory facilities.

### PILOT PLANT

A mobile 8 x 40 foot* flat bed trailer supported the entire pilot plant,
including a scrubber, a primary particulate collection device, pumps,
mixing tanks and a test house. After utilities and duct connections
to the flue gas system were provided, the pilot plant became self-suffi-
cient. Figure 2-1 illustrates the mobility of the system and includes
pertinent design information.

### PARTICULATE REMOVAL SYSTEM

Approximately 1% of the flue gas leaving the boiler passed through a
primary particulate removal system (Figures 2-1 and 2-2). In theory,
the MTSA-3-9 CYTOCD Whirlex collector (Figure 2-2) removed parti-
cles by centrifugal action and change in air flow direction. The unit
was designed for primary removal of larger size particles generated
during the coal-fire phase and was not intended to meet the high
removal efficiencies required by stringent emission regulations.
Since the Key West tests (dealing with oil-fired flue gas) and the
Shawnee No. 10 phase (investigating limestone injection) did not require
particulate removal, the collector was bypassed by means of a built-in
damper. However, the particulate removal system was utilized during
a greater part of the Shawnee No. 9 phase of testing.

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*Although EPA policy is to use metric units in all of its documentations,
certain non-metric units are used in this report for clarity. Readers
more familiar with metric units may use the conversion factors in
Appendix E.
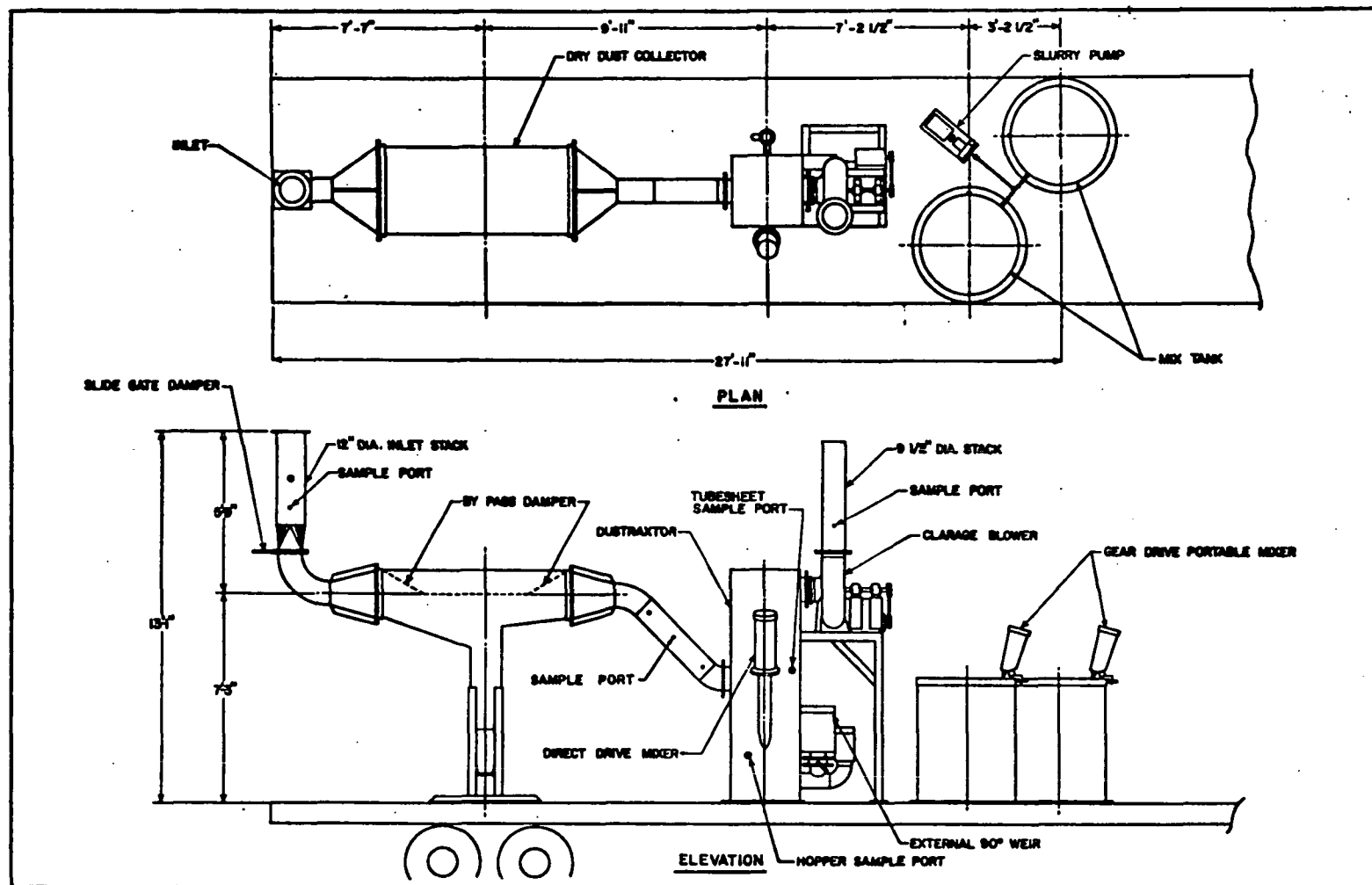
FIG 2-1 MOBILE PILOT PLANT EQUIPMENT ARRANGEMENT
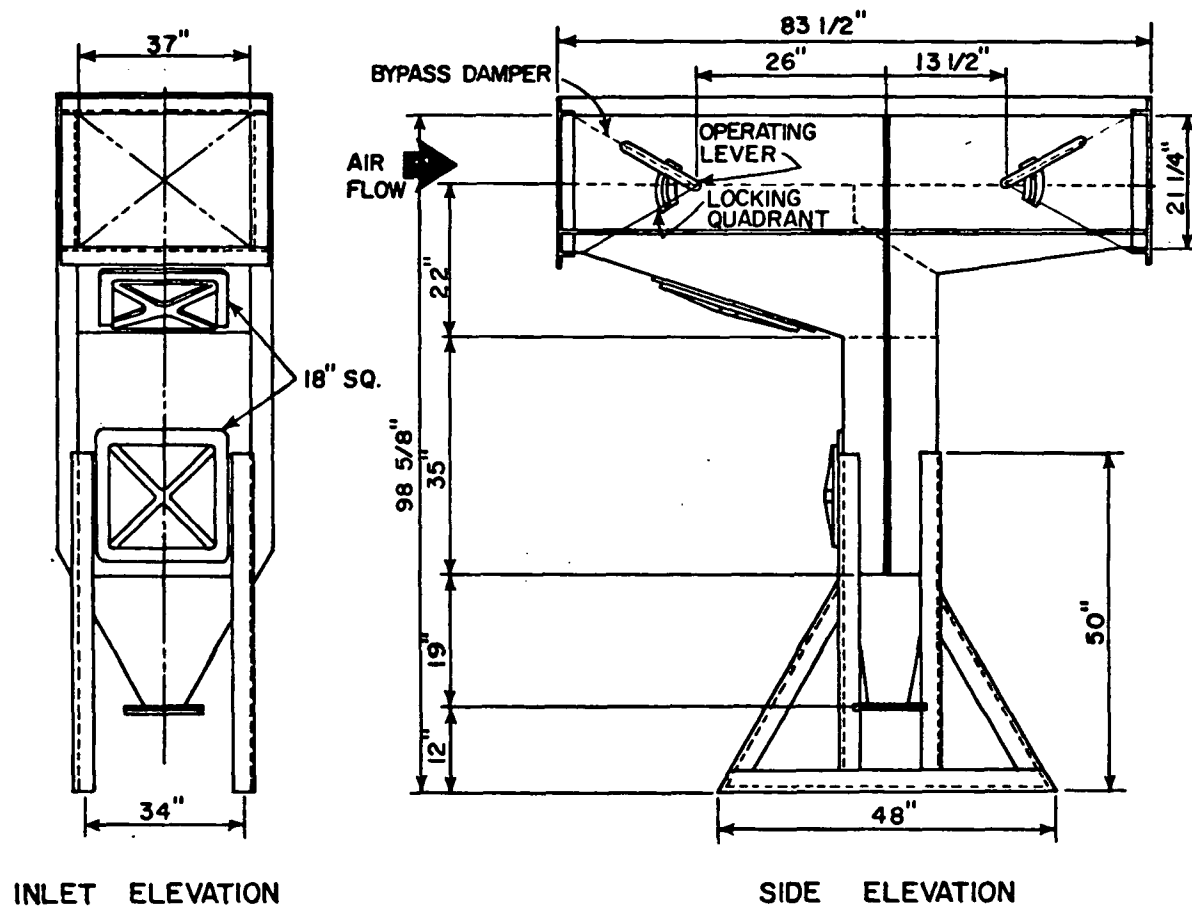
FIG. 2-2 PILOT PLANT DRY DUST COLLECTOR OUTSIDE DETAILS

The material of construction was carbon steel which appeared to be
satisfactory for this application. However, the bypass damper for the
scrubber system, located on the inlet side of the collector, was made
of 304 stainless steel. This damper served an on-off function only
and was not used to control the flue gas flow rate to the particulate
collector. Sample ports were provided in the connecting ductwork for
particulate, $SO_2$, and $NO_x$ sampling across the collector as well as
across the entire system.

Fly ash removal was accomplished by removing the bolted sealed blind
flange while the system was down. Because the collector and ductwork were
not insulated, condensate built up in the fly ash hopper. It was
necessary to drain this section daily, prior to start-up.

DUSTRAXTOR ABSORBER SYSTEM

The objective of scrubbing for $SO_2$ was to economically transfer maxi-
mum quantities of the contaminant from the flue gas to the scrubbing
liquid. Physical and chemical equilibrium and rate relationships
all limit the mass transfer of $SO_2$ in any system. However, the amount
of mass transfer depends not only upon the equilibrium relationships
but also upon the contacting scheme. The Dustraxtor employs many
contacting schemes.

Gas leaving the particulate collector passes into a modified single-
tube Dustraxtor. As shown in Figure 2-3, the design is essentially
a type of turbulent contact absorber (TCA). The unit consists of
a flooded collecting tube through which the flue gas passes. The
collecting tube is installed vertically in the inlet plenum chamber
directly above the recycle hopper so that the bottom of the tube is
a short distance above the liquid level in the hopper.

Flue gas enters the inlet plenum chamber, sweeps over the surface of
the scrubbing liquid, and is directed up the collecting tube.
The gas passing between the collecting tube inlet and the collecting
bonnet carries scrubbing slurry from the bonnet surface upward into

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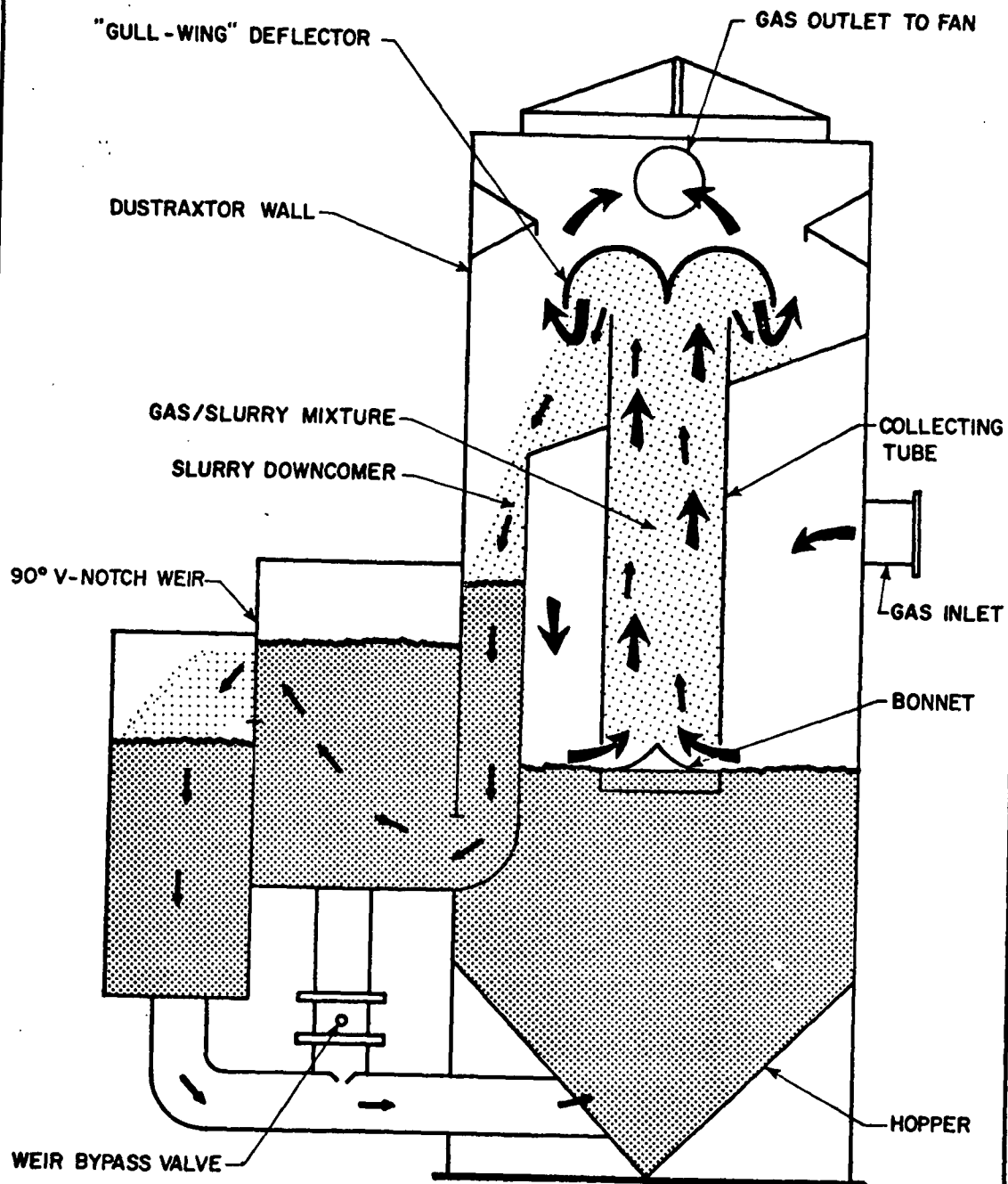
FIG. 2-3 TYPICAL CROSS SECTION OF DUSTRAXTOR SCUBBER

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the collecting tube. The shearing action of the gas atomizes the
scrubbing slurry into a dense spray as the gas slurry mixture con-
tinues up the collecting tube. The result of this action is a highly
turbulent mixing zone which provides the intimate contact necessary
for the chemical reaction to occur. As the gas is discharged from
the collecting tube, it is directed into a curved gull-wing deflector
which acts as a mechanical separator and forces the slurry downward
onto the tube sheet. This shower effect provides an additional mixing
zone in which absorption can occur. The cleaned gas is then discharged
via the flue gas exhaust system as the scrubbing solution is returned
by gravity to the recycle hopper. To summarize, the stages of gas-
liquid contact in this type of scrubber are:

1. The initial shearing action as the flue gas passes through
   the slot between the collecting bonnet and tube.
2. The highly turbulent mixing within the collecting tube
   where the gas is in intimate contact with slurry droplets.
3. The impingement of the gases and slurry upon the surface of
   the deflector.
4. The passage of gas through a highly turbulent curtain of
   slurry being discharged from the deflector.

The contacting schemes found in the Dustraxtor could be categorized
as countercurrent, co-current, and crosscurrent flow. Since there
were three contacting schemes occurring at the same time in this scrub-
ber, a theoretical analysis of the total mass transfer mechanism
would have been extremely difficult and only of academic interest.
Therefore, this type of an analysis was not conducted.

The Dustraxtor dimensions are shown in Figure 2-4. This unit differed
from the typical Dustraxtor design in the following ways:

1. An exterior weir system was added between the tube sheet
   downcomer and the hopper.
2. The capability was added to allow alteration of the tube
   diameter by substitution of different diameter prefabricated
   tubes.

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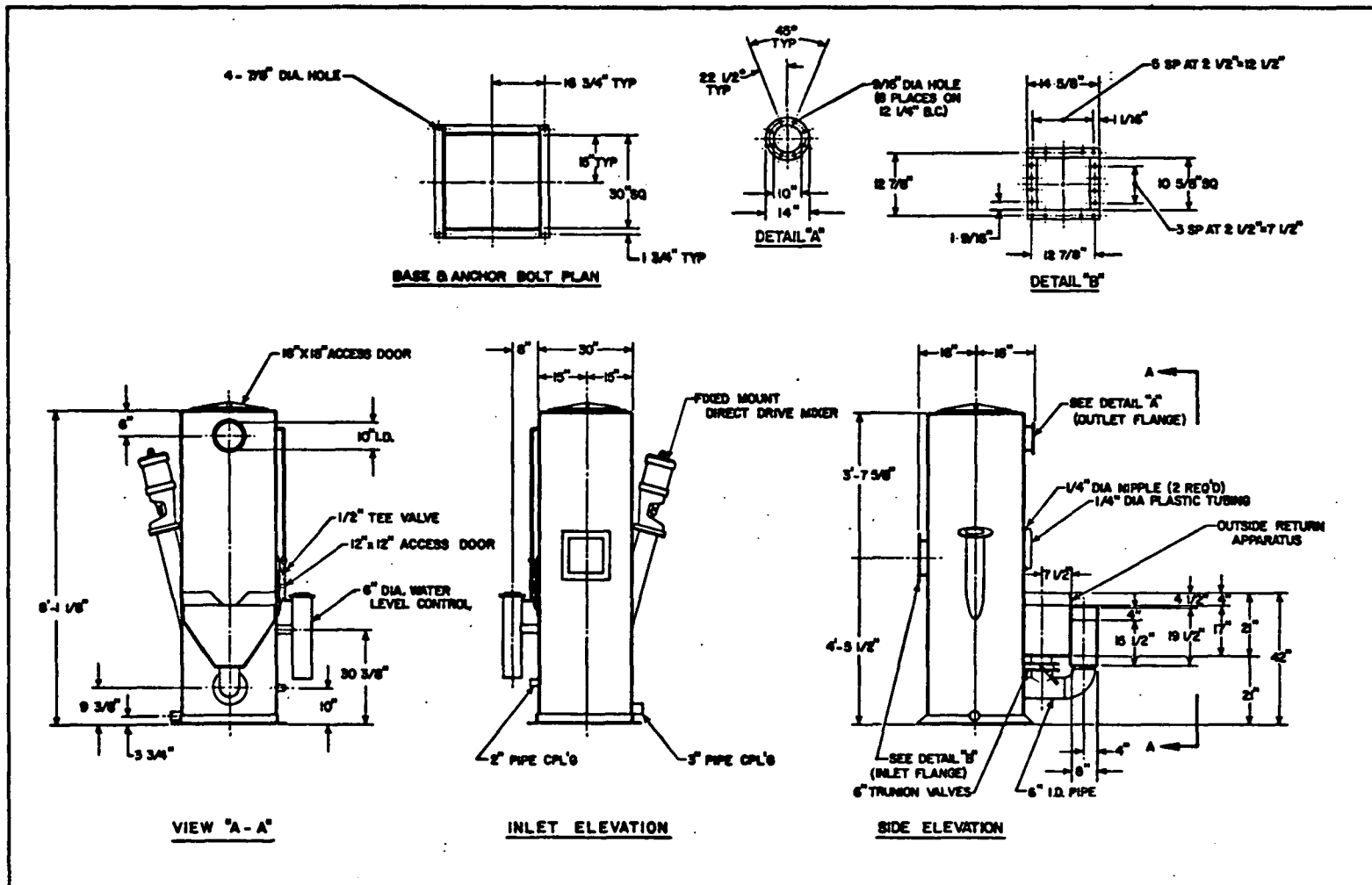
FIG 2-4 PILOT PLANT SCRUBBER (DUSTRAXTOR) DETAILS

The exterior weir provided a means of measuring the quantity of slurry taken up into the tube, which was later used to calculate the liquid/gas ratios. The details of the external return apparatus and the 90° "V-notch" weir are shown in Figure 2-5.

The liquid level in the scrubber was maintained by a level controller. The slurry composition was maintained indirectly by adjustment of the spent slurry flow rate. The level controller in turn maintained the desired liquid level by adjusting the fresh slurry feed rate.

In order to avoid problems with solids settling, a mechanical mixer was installed in the Dustraxtor to help keep solids in suspension. The mixer specifications are listed in Table 2-1. The sump had a 3 inch gravity-feed drain which was used to empty the scrubber after each test.

### Table 2-1. DUSTRAXTOR MIXER SPECIFICATIONS

| | |
|---|---|
| Trade Name: | Lightnin Mixer |
| Manufacturer: | Mixing Equipment Company, Inc.<br>138 Mt. Read Boulevard<br>Rochester, New York 14603 |
| Model: | N33-33, Fixed Mounted Propeller Type |
| Serial No.: | 7012653 |
| Design Specifications: | Motor – 1/3 HP/115V/60 Hz/1 phase/1750 rpm, totally enclosed |
| | Shaft – 304 SS, 3/4 inch diameter x 49 inches, 1750 rpm |
| | Propeller – 316 SS, 3.8 inch diameter |

The material of construction for the Dustraxtor and connecting ductwork to the particulate collector was 304 SS. All piping to and from the scrubber was galvanized steel. All sample ports on the scrubber were either stainless steel or polyvinyl chloride. A stainless steel butterfly valve, located in the bottom of the exterior weir, was used to bypass the measurement system.

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Dustraxtor Wall

Tube

Tubesheet

Downcomer

90° V-Notch Weir

Downcomer Exit

Weir Bypass Valve

Hopper
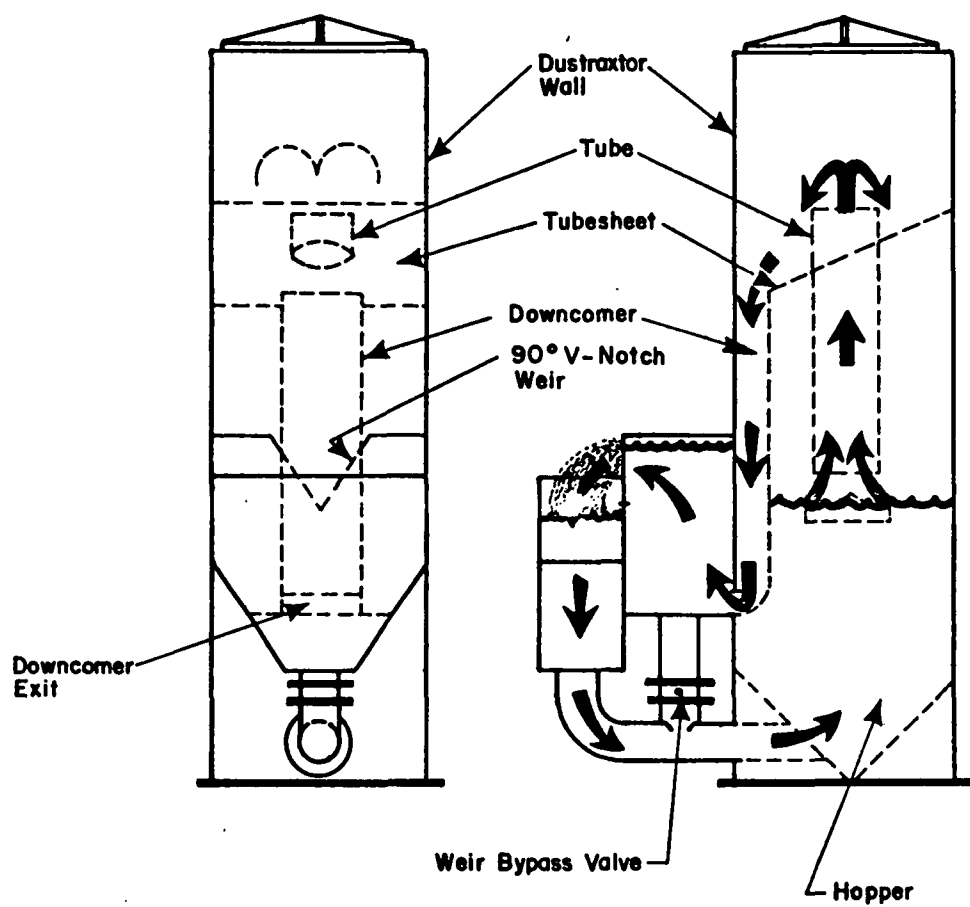
FIG. 2-5 DUSTRAXTOR OUTSIDE RETURN APPARATUS AND 90° V-NOTCH WEIR

A slide gate valve, installed on the 10-inch diameter discharge duct
was used to control the flue gas flow rate through the entire pilot
plant. The pressure drop across the Dustraxtor was controlled by
adjusting the balance vent line control valve. Sample ports were pro-
vided in the connecting ductwork for particulate, $SO_2$, and $NO_x$ sampling
across the Dustraxtor, as well as across the entire system. Liquid
sample ports were provided on the Dustraxtor body for tube sheet and
hopper liquor sampling. A set of spray nozzles for gas saturating pur-
poses was installed in the ductwork between the particulate collector
and the Dustraxtor.

## FLUE GAS EXHAUST SYSTEM

The scrubbed flue gas leaving the Zurn scrubber passed through an
induced-draft fan with an inlet damper control, to a vertical stack
containing sampling ports. The induced-draft fan was a No. 10 Clarage
Blower; the fan curve is shown in Figure 2-6. The I-D fan had a paddle-
blade impeller which, because of particulate carry-over and subsequent
"plating-out" on the blades, became unbalanced and failed twice during
the study. A field review of the I-D fan failures indicated that the
cast stainless steel spider, which secures the blade, fractured due
to fatigue caused by the fan imbalance.

## PILOT PLANT SCHEMATIC

Figure 2-7 shows the overall flow diagram of the pilot plant. The
location of thermometers and flow measuring devices are also shown
in this Figure. Additional information concerning the monitoring
system is included in Section 3: Test Instrumentation and Procedures.

## REACTANT HANDLING AND WASTE DISPOSAL SYSTEMS

The calcium based scrubbing slurry was prepared in mix tanks. The mix
tanks were equipped with steam coils and gear driven portable mixers.
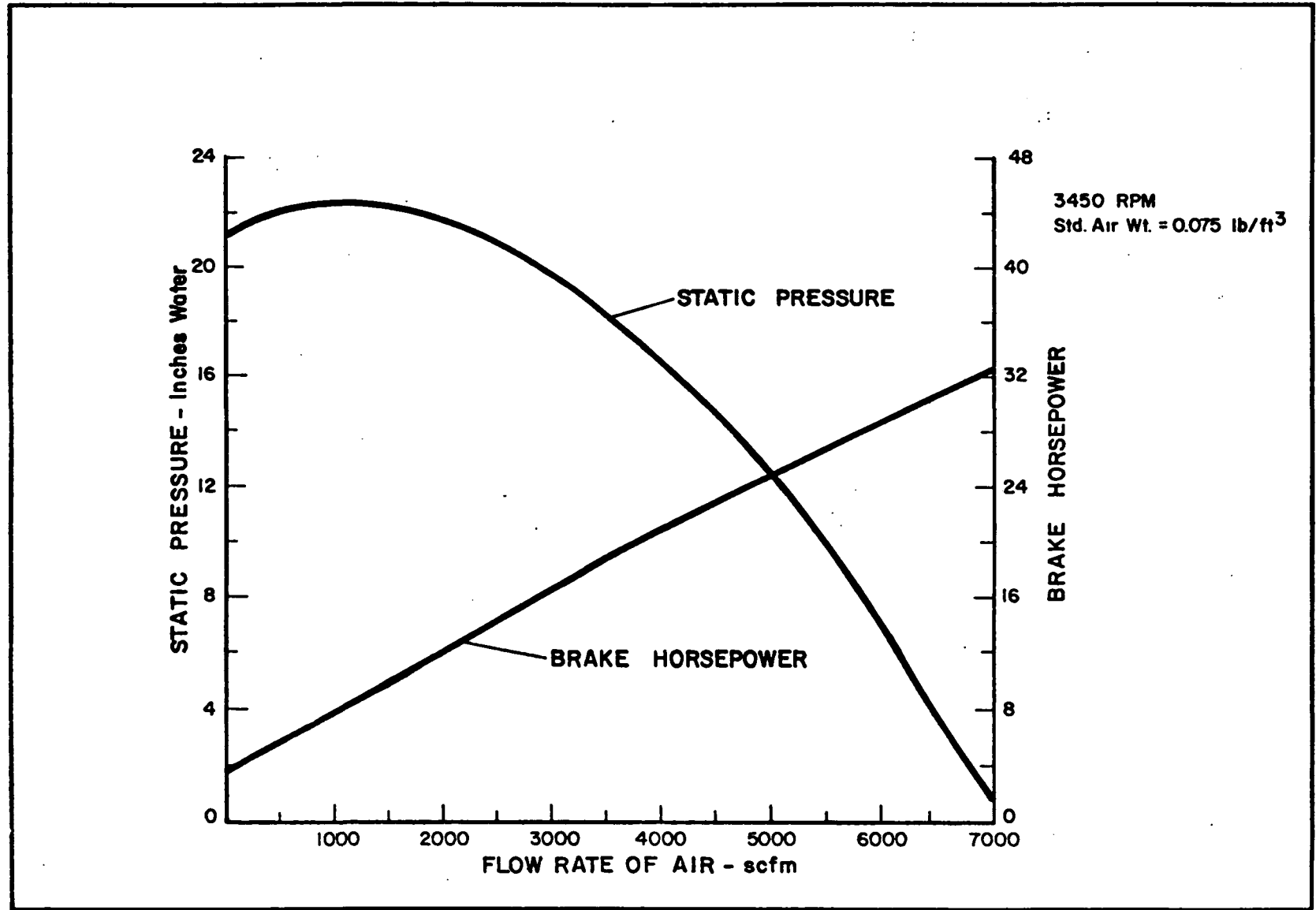
FIG. 2-6 NO. 10 CLARAGE BLOWER INDUCED DRAFT FAN CURVE

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The steam coils were not used during the study; however, they were available for use if desired. The mixers had a 304 stainless steel shaft, a 316 stainless steel 10 inch diameter propeller, and were driven by a 1/3 HP, 115 volt, 1750 rpm, totally enclosed electric motor. Detailed tank mixer specifications are shown in Table 2-2.

Table 2-2.  TANK MIXER SPECIFICATIONS

| | |
|---|---|
| Trade Name: | Lightnin Mixer |
| Manufacturer: | Mixing Equipment Company, Inc. <br> 138 Mt. Read Boulevard <br> Rochester, New York 14603 |
| Model: | ND-1, Portable Mixer |
| Serial No.: | None, Mixco Order No. M315836 |
| Design Specifications: | Motor - 1/3 HP/115V/60Hz/1 phase/1750 rpm, totally enclosed |
| | Shaft - 304 SS, 5/8 inch diameter x 48 inches, 1750 rpm |
| | Propeller - 316 SS, 10 inch diameter |

The scrubbing slurry from the mix tanks was fed by gravity to a high silicon iron Mark II Durcopump manufactured by the Duriron Company, Inc. The pump specifications are noted in Table 2-3.  The slurry feed rate from the pump to the scrubber was measured by a flowmeter located near the scrubber.  Excess slurry was returned to the mix tanks through a recirculation line shown in Figure 2-7.

Table 2-3.  SLURRY PUMP SPECIFICATIONS

| | |
|---|---|
| Manufacturer: | Duriron Company, Inc. <br> N. Findlay and Thomas Streets <br> Dayton, Ohio 45401 |
| Pump Design: | Series - 1-1/2 x 1 H - 6/60; Size - Mark II GPI <br> Packing - Standard; Alloy - Superchlor <br> Impeller Diameter - 6 inches; Shaft Wet End - Superchlor |
| Performance: | 20 gallons per minute <br> 36 feet of water total differential head <br> NPSH - 1.5 feet of water net positive suction head <br> 0.9 maximum brake horsepower |
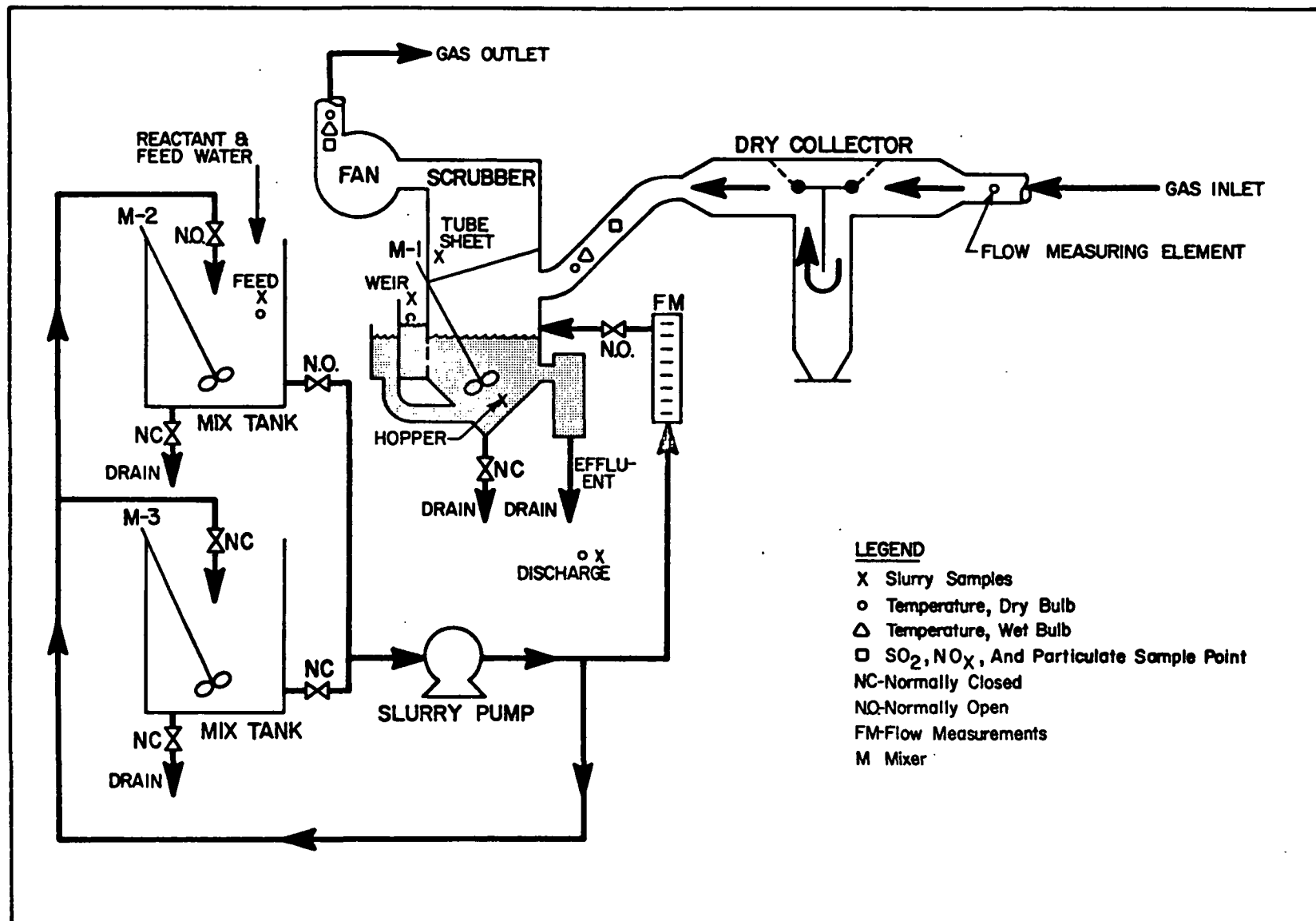
FIG. 2-7 SCHEMATIC FLOW DIAGRAM OF FLUE GAS AND SLURRY SOLUTIONS WITH LOCATIONS OF SAMPLING POINTS

LEGEND
X  Slurry Samples
o  Temperature, Dry Bulb
△  Temperature, Wet Bulb
□  $SO_2$, $NO_X$, And Particulate Sample Point
NC-Normally Closed
NO-Normally Open
FM-Flow Measurements
M  Mixer

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The required quantity of the calcium-based reactant was weighed out
and dumped into each mix tank containing fresh or salt water depending
upon the location of the pilot plant. The amount of reactant was set
by the required slurry concentration. Adequate time was allowed for
proper mixing of the calcium-based reactant and the water before
pumping into the scrubber system. Fresh slurry was fed to the scrubber
through the flowmeter while the spent slurry, from the scrubber system,
passed out the level controller.

During the Key West testing, the spent effluent was deposited in a
holding pond where the liquid was allowed to evaporate or permeate the
coral soil. During the Shawnee testing, the effluent was deposited
in a storm sewer, mixed with other plant waters, and pumped to the
Mississippi River. Each disposal technique was satisfactory for the
pilot scale system.

Several operating problems concerning the reactant handling system were
noted during the study. Due to infrequent maintenance checks, the feed
pump packing developed a leak (a marked reduction of pump pressure was
experienced) and became progressively worse as the project continued.
A more serious problem was encountered at the Shawnee site. Settleable
solids in the waste material often clogged the flexible hoses. This
necessitated frequent flushing with a fresh water stream to prevent
back-up into the scrubber.

## CHEMICAL ANALYSIS LABORATORY

During the Key West testing, the City Electric System power plant lab-
oratory was utilized for all chemical analyses. The laboratory was
equipped with instrumentation necessary for conducting the analyses
noted in Appendix A.

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# SECTION 3

## TEST INSTRUMENTATION AND PROCEDURES

In order to facilitate movement of the pilot plant, basic but highly
reliable instrumentation was utilized for this study. The $SO_2$ con-
centrations were determined with an electrochemical type sensor which
was calibrated daily with guaranteed-analysis calibration gas. All
temperatures were determined with properly calibrated thermometers,
and gas flow rates were determined with a calibrated sharp-edge orifice.
Standard sampling techniques were employed for particulates, $SO_2$, and
$NO_x$. Details of the analytical techniques are in Appendix A.

Test procedures were established based upon the experimental design
required for each phase of the test program. Day-to-day operation of
the pilot plant was held as constant as possible, with the only varia-
tion occurring in the level of the variable set for each test. The
test procedures employed at the two sites, Key West and Shawnee, were
varied only where necessary in order to comply with necessary conditions.

## $SO_2$ MONITORING

One of the most important analyses of the test program was the measure-
ment of the $SO_2$ concentration in the flue gas. $SO_2$ sampling probes,
fabricated from 6 inch lengths of 1/4 inch diameter SS tubing, were
located in the entrance and discharge ducts of the Dustraxtor. Analyses
were performed for the most part by a Dynasciences Model SS-330 monitor.
Selection of this monitor was based in part on the results of limited
test work conducted earlier.

The Dynasciences monitor operated on the principle of a fuel cell.
$SO_2$ was absorbed on a sensing electrode to form activated species capa-
ble of undergoing electro-oxidation. The resulting current was directly
proportional to the partial pressure of $SO_2$ in the gas mixture. The
current was amplified and the output recorded on a meter and a 10 mV
recorder.

The instrument specifications indicated linear response over the entire range of $SO_2$ concentration. Overall accuracy was specified at $\pm$ 1% full scale with the use of an external potentiometric recorder. Response time was specified as 90% of full scale in 1 minute. The instrument was to exhibit no response to $N_2$, $O_2$, $NO_x$, CO, $CO_2$, water vapor or hydrocarbons. In addition, the instrument was very portable and well suited to the field environment experienced in pilot plant operations.

In operation, the Dynasciences Model SS-330 did not meet all the specifications. Response time was not as rapid as claimed; the instrument was sensitive to changes in sampling gas flow rate (slight changes in operating pressure), and changes in ambient temperature. Also, the instrument stability was considerably less than specified. Electrochemical cell life was better than claimed by the manufacturer and once the initial operating problems were corrected, $SO_2$ monitoring operations were very reliable. In general, the instrument proved satisfactory for the conditions experienced during the pilot plant operation.

## $NO_x$ SAMPLING AND ANALYSIS

$NO_x$ samples were taken randomly during certain test periods. $NO_x$ probes were located at the entrance and discharge ducts of the Dustraxtor virtually in line with the $SO_2$ sampling probes. The phenoldisulfonic acid method was used for analysis.

A typical $NO_x$ sampling and analysis consisted of adding 25 ml of an absorbing solution (hydrogen peroxide and dilute sulfuric acid) to a 250 ml (nominal) evacuation flask. The flask was evacuated and attached to a purged sample line; the stop cock was opened; and the gas sample was drawn into the flask.

$NO_x$ was converted to nitric acid by the absorbent solution and reacted with phenoldisulfonic acid to produce a yellow compound which was measured colorimetrically. Color was measured with a photometer and compared with calibration curves from solutions containing a known quantity of nitrate.

A more complete and descriptive explanation of the phenoldisulfonic acid method used in these tests is given in the American Society for Testing and Materials (ASTM), Standard Method of Test for Oxides of Nitrogen in Gaseous Combustion Products (Phenoldisulfonic Acid Procedure), ASTM Designation: D1608-60 (1967). The analytical technique associated with this test procedure was very tedious and time consuming. However, since other procedures had not been adequately demonstrated on power plant flue gases, it was necessary to use this method to obtain reproducible data.

PARTICULATE SAMPLING

Particulate sampling was conducted at three points in the pilot plant: the entrance to the dry dust collector, the entrance duct to the Dustraxtor, and the Dustraxtor exit duct. The sampling train consisted of a stainless steel probe and nozzle, a glass fiber filter and a series of three Greenberg-Smith impingers. During the first attempts at particulate sampling, the glass fiber filter clogged as a result of the high moisture content present in the flue gas (the filter was not heated). The filter medium was therefore eliminated from the train during the remaining tests. The remainder of the particulate sampling system included a gas meter and vacuum pump.

Isokinetic sampling was performed by regulating the sample flow rate to correspond with the calculated velocity at the sampling point. This method was justified over the null balance procedure for this study to conform with suggested EPA test method. Uniform flow rates were demonstrated by observing the flue gas orifice over an extended period of time.

SLURRY SAMPLING AND ANALYSIS

During each test, representative slurry samples were taken at the following locations:
- Slurry feed
- Scrubber discharge

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- External weir
- Hopper sump
- Tube sheet

Figure 2-6 illustrates the various sampling points. During every test at least one 100 ml slurry sample was taken for analysis of the following parameters:

- pH
- Calcium
- Magnesium
- Chloride
- Nitrate
- Nitrite
- Sulfite
- Sulfate

Sampling was performed in a manner to avoid oxidation; the samples were placed in an ice water bath for transportation to the laboratory. pH was measured in the field as well as in the laboratory. Standard gravimetric, titrimetric, and colorimetric methods were used by the chemist following procedures outlined in American Society for Testing Materials (ASTM) 1970 Annual Book of ASTM Standards, Part 23, Water; Atmospheric Analysis, and the American Public Health Association, Standard Methods for the Examination of Water and Wastewater, 12th Edition. The slurry samples which contained solids and liquid were not separated prior to the analysis.

OTHER MEASUREMENTS

Field measurements for pH of the slurry samples were made with a Sargent-Welch Model PBX pH meter and laboratory ph measurements were made with a Sargent-Welch Model LSX pH meter.

Flue gas flow rate was measured by an Ellison Instrument Division, 12 inch "Annubar," type 740. The Annubar is a primary flow element utilizing a form of the classical Bernoulli energy balance equation to determine flow rate. The equation used was:

$$Q_n = 7.9 \ SND^2 \ \frac{\sqrt{\gamma_f}}{\gamma_1} \ \sqrt{h_n} \qquad\qquad (3\text{-}1)$$

A full description of the symbols of this equation, and other equations available for use with this flow element, were supplied by Ellison Instrument Division, Boulder, Colorado, and are reproduced in Appendix B. The Annubar included an interpolating tube with equal annuli segments, an equalizing element, and a downstream element for measuring the downstream pressure (static pressure less the impact pressure of the flow). The system had a non-clog design which was desirable for operation in the pilot plant. The unit was calibrated against standard pitot tube traverses prior to initial testing in Key West. Detailed drawings and specifications of the Annubar were supplied by Ellison Instrument Division and are also reproduced in Appendix B.

GENERALIZED TEST PROCEDURE

A typical testing day in which three tests were usually completed is described below. The experimental design established the operating levels for the variables under study. These variables were set during the test period.

In preparation for a run with a cold start (that is, the scrubber had been idle long enough to allow the ducts to accumulate condensation), the unit was first filled with salt or fresh water and allowed to run for a minimum of 30 minutes to attain operating temperatures and to flush the accumulated condensate out of the ductwork. Normal conditions for this warm-up and flushing were a gas flow rate of 1000-1450 scfm, liquid feed rate of 10-15 gpm and a $\Delta P$ of 9-12 in. $H_2O$.

While waiting for the system to reach operating conditions, the two mix tanks were flushed and cleaned; the proper quantity of reactant for

the test was calculated, weighed out, and mixed in one tank; and the liquid for the warm-up operation was pumped from the remaining tank. After warm-up, the system was shut-down (fan off, pump off, reactant feed valve off, inlet damper closed) and drained immediately. While the Dustraxtor was draining, the proper quantity of reactant was weighed out and mixed in the second feed tank forming the scrubbing slurry.

When the scrubber was drained, the drain valve and weir butterfly shut-off valves were closed. Slurry was then pumped into the scrubber at maximum flow rate until the Dustraxtor was full. The sequence of events concerning the controls were as follows:

1. Hopper mixer - on
2. Reactant flow - 2-5 gpm
3. Level control - 50% open
4. Inlet damper - open
5. Fan - on

Once the system was in operation, the levels were set for the various operating parameters. During the first hour of a test, the gas flow rate, slurry flow rate, and pressure drop were monitored to assure that the unit would approach equilibrium at the predetermined conditions. Based upon preliminary test results, steady state was assumed after the system had been in operation for 2 hours and the $SO_2$ concentration at the pilot plant exit remained constant.

Prior to final data acquisition, the $SO_2$ monitor was calibrated and the inlet $SO_2$ concentration was determined. During this time, the inlet gas conditions were recorded (temperature, flow rate, pressures and $SO_2$ concentration). The required stoichiometric ratio based on the inlet $SO_2$, was calculated and adjusted as necessary. The $SO_2$ monitor was then used to analyze the Dustraxtor outlet gas. When the effluent $SO_2$ concentration stabilized, outlet conditions were recorded (temperature, flow rate, pressure, and $SO_2$ concentration).

During a test, several slurry samples were collected and placed in an ice water bath for storage prior to laboratory analyses. The samples collected and stored in 8-ounce plastic bottles included the following: slurry feed, scrubber discharge, weir overflow, tube sheet, and Dust-raxtor hopper samples.

After a test was completed, operating conditions were changed for the next test. The unit was shut down, drained, and refilled with reactant for another test. There was usually a working period of about 1/2 hour before the system was ready for another test. Following this procedure, about three 2 1/2 hour tests were completed every day.

TEST PROCEDURE FOR EXTENDED OPERATION

The start-up for extended operation did not differ from that of a normal test day. Test conditions were specified to be held constant for approximately an 8 hour period. No variables were changed during this test period.

TEST PROCEDURE FOR ADDITIVE OPERATION

The start-up for additive experiments (catalyst--$FeCl_3$ or inhibitor--hydroquinone) did not differ from that of a normal test day. All experimental procedures outlined above were followed with the following additions and modifications:

1. Two identical reactant tanks were mixed: one contained the the test additive, the other did not.

2. The scrubber was filled and started up on reactant without the test additive.

3. Inlet and outlet conditions were recorded as outlined earlier. During some experiments, scrubber effluent samples were not taken at this time.

4. After stabilization of the outlet conditions, the correct amount of additive was added to the scrubber weir simultaneously with changing the reactant feed to the tank with additive. The feed rates remained constant.

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5. The outlet conditions were allowed to re-stabilize after additive addition; they were recorded again and scrubber effluent samples were collected.

# SECTION 4

## SUMMARY OF RESULTS

Results of both the short term and extended tests were consolidated
into one set of results for each test site. Because of the great
volume of data gathered during the test program, only a summary of the
results is presented in this report. An addendum, available through
EPA's Control Systems Laboratory, contains all test data taken during
the 10 months of field work. Appendices C and D contain scrubber
operating conditions and data summary tables, respectively.

## SYSTEM OPERATING CONDITIONS AND CHARACTERISTICS

A summary of the important system operating conditions and character-
istics including data important to future design and optimization of
the Dustraxtor absorber is given below.

### Liquid Entrainment Relationships

The relationships of the parameters governing liquid entrainment in the
Dustraxtor unit are presented in Figures 4-1 and 4-2. Approximately
170 data points are represented showing the association between the
liquid entrainment and gas flow rate at selected pressure drops ($\Delta P$)
from 6.5-14.0 in. $H_2O$.

Figure 4-1 applies to a single 12-inch diameter Dustraxtor tube. Each
curve, representing a constant pressure drop condition, exhibits a
point of maximum liquid entrainment which becomes more apparent as
pressure drop increases. Thus, at a $\Delta P$ of 6.5 inches, a $\pm$ 350 scfm
variation in gas flow rate about the maximum entrainment point results
in a 15 gpm reduction in liquid entrainment. Compared to this, at a
$\Delta P$ of 12.0 inches, a decrease in entrainment by 15 gpm is caused by a
gas flow variation of only $\pm$ 170 scfm. Another characteristic of this
maximum point is its tendency to occur at progressively lower gas flow
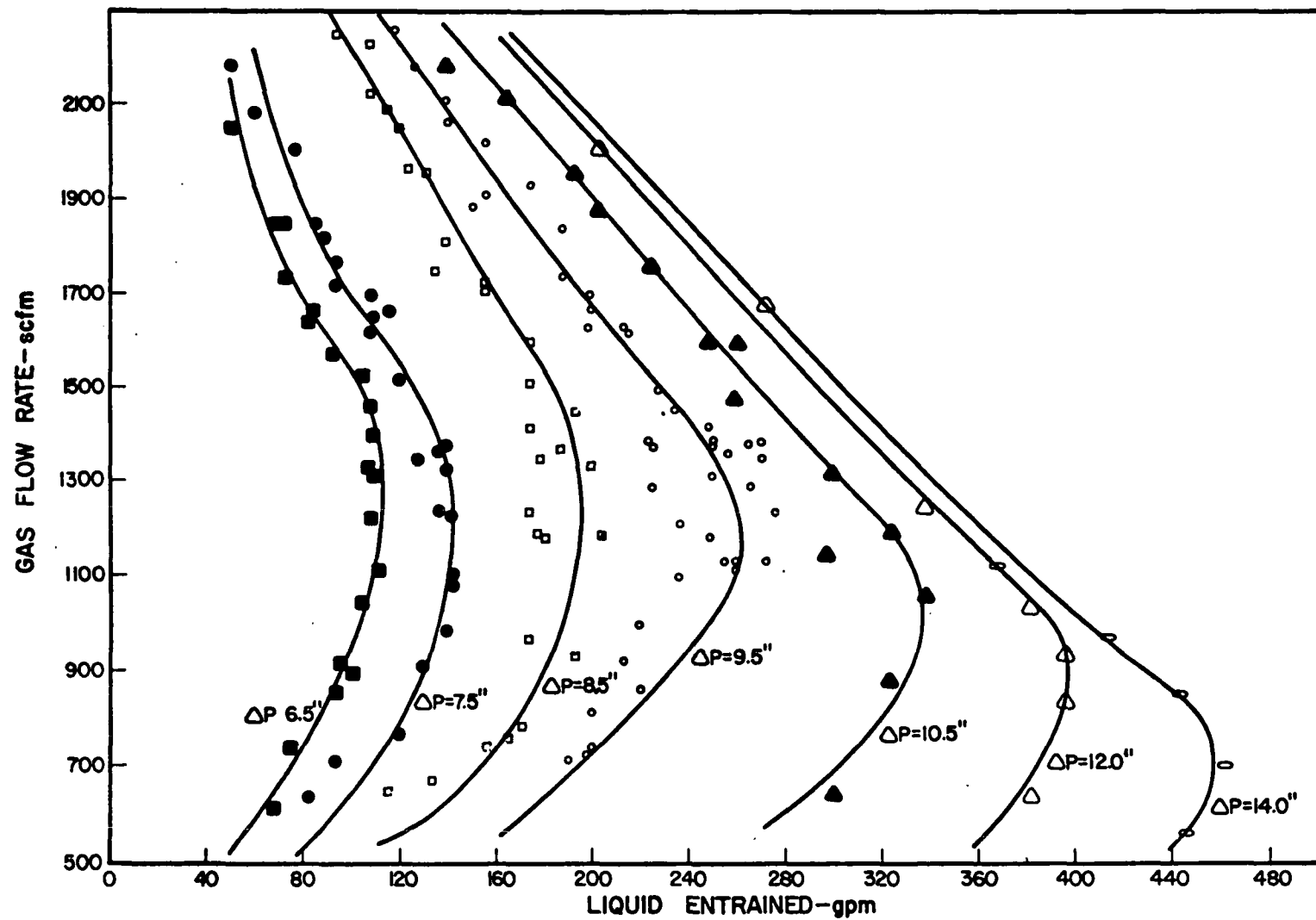
FIG. 4-1. SALT WATER ENTRAINED IN THE 12" TUBE AT SELECTED PRESSURE DROPS AND GAS FLOW RATES

31
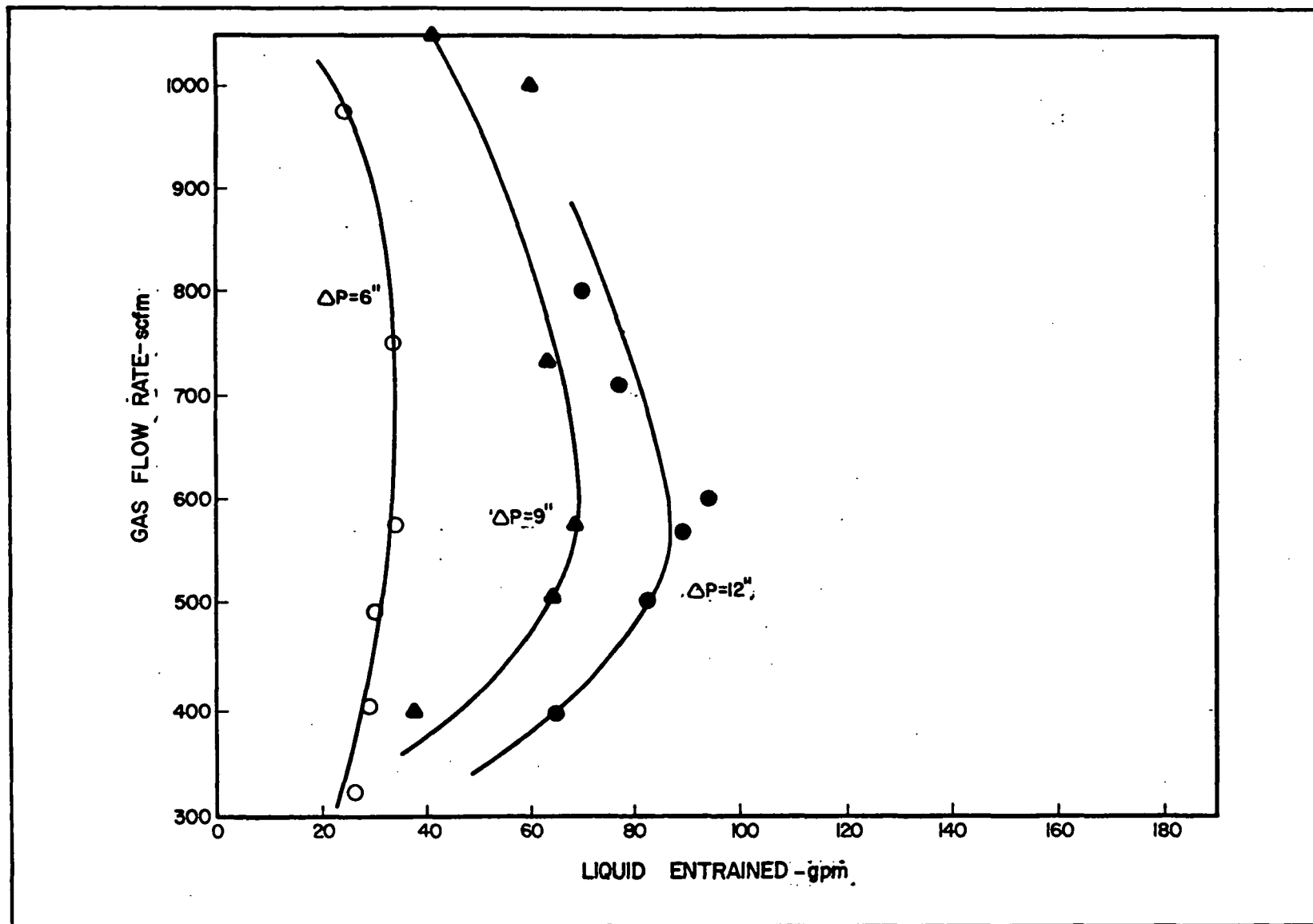
FIG. 4-2. RIVER WATER ENTRAINED IN THE 8" TUBE AT SELECTED PRESSURE DROPS AND GAS FLOW RATES

rates as pressure drop increases. As an illustration, a maximum
entrainment of 112 gpm is realized at about 1300 scfm for a 6.5 inch
ΔP. At a 12 inch ΔP the maximum entrainment (396 gpm) has dropped to
900 scfm and at a 14 inch pressure drop the maximum has fallen to
700 scfm, nearly half of the flow rate and velocity of the gas stream
for the 6.5 inch ΔP maximum.

As gas flow rate and corresponding gas velocity increase above the
maximum entrainment point, all of the curves converge upward toward
a greatly reduced range of entrainment volumes. This trend is so
pronounced that if assumed to continue at the same rate, extrapolation
of the data would indicate a minimal gain of 50 gpm in liquid entrain-
ment at a 2700 scfm flow rate when the ΔP changed from 6.5 to 14.5
in. $H_2O$.

Figure 4-2 is a corresponding plot of the scrubber characteristics
utilizing a single 8 inch diameter Dustraxtor tube. The same general
shape and trends appear for the 8 inch tube as were exhibited for the
12 inch tube. However, the maximum entrainment points occured at
lower gas flow rates and higher gas velocities and were 1/2 to 1/4
the order of magnitude found for the 12 inch Dustraxtor tube.

No attempt has been made to analyze the actual physical mechanism of
entraining and lifting the slurry from the surface within the hopper
or its transportation through the scrubber; hence, a complete under-
standing of the dynamic principles illustrated by the data of Figures
4-1 and 4-2 is not possible. The development of a model to establish
the analytical relationship of liquid entrainment as a function of
ΔP and gas flow was not attempted.

Liquid/Gas Ratios

Figure 4-3 is a plot of liquid/gas ratios versus gas flow rates for both
the 8 inch and 12 inch Dustraxtor tubes. Two corresponding pressure
drops are depicted for each size tube (9 and 12 inches for the 8 inch

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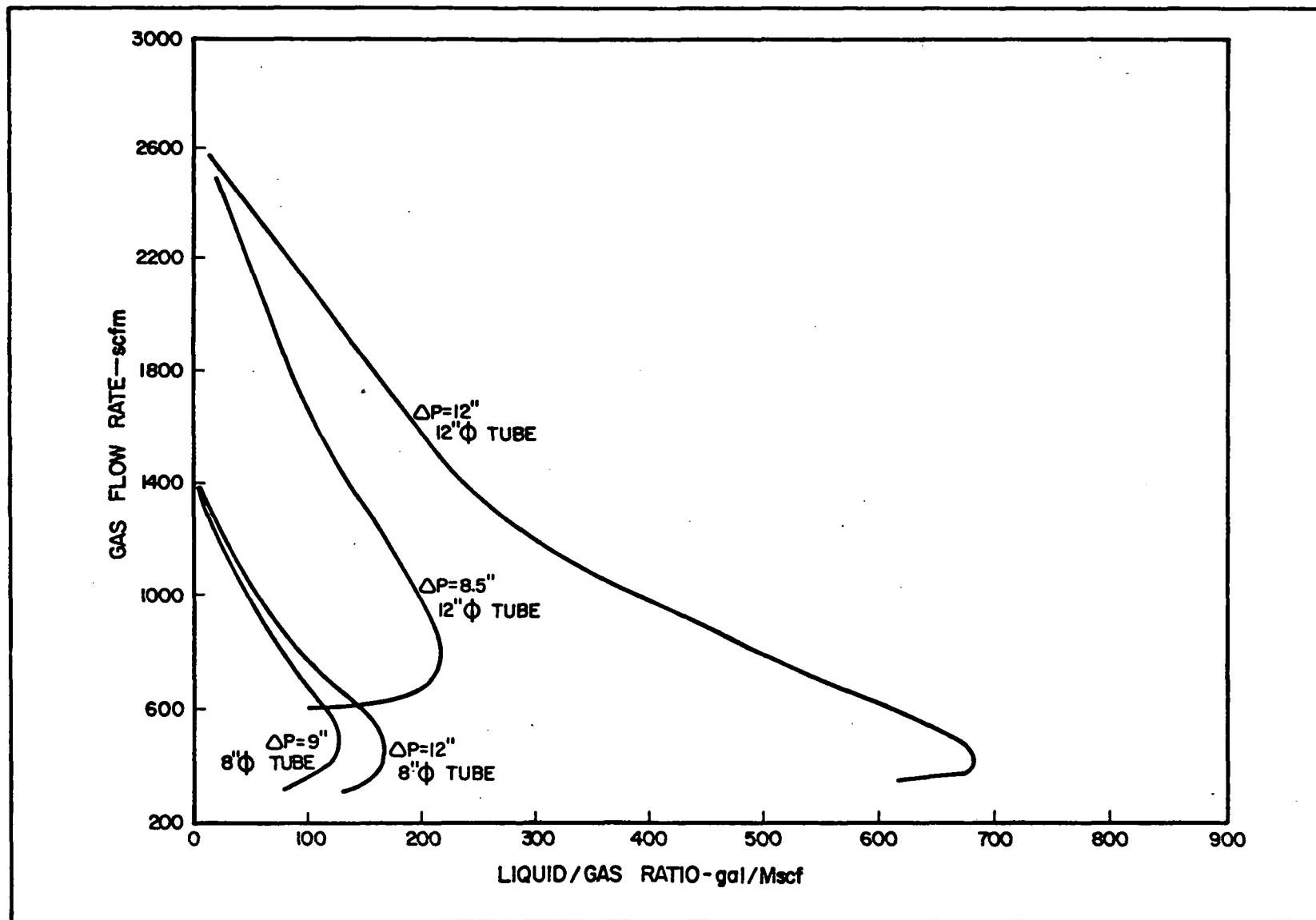
FIG. 4-3. LIQUID/GAS RATIOS FOR 8" & 12" DIA. DUSTRAXTOR TUBES AT SELECTED PRESSURE DROPS AND GAS FLOW RATES

diameter tube; 8.5 and 12 inches for the 12 inch diameter tube). These
curves were wholly derived from the data points shown in Figures 4-1
and 4-2. For the sake of clarity, the actual data points have been
eliminated. All of the curves show an expected maximum liquid/gas
ratio at some relatively low gas flow rate. The magnitude of this max-
imum increases with increasing values of $\Delta P$; however, the point of max-
imum liquid/gas ratio occurs at a slightly lower gas flow rate than
the maximum entrainment volume (Figure 4-1 and 4-2). As an example:
maximum entrainment volume for a 12 inch $\Delta P$ and a 12 inch Dustraxtor
tube occurs at about 850 scfm while the maximum liquid/gas ratio,
680 gallons per thousand cubic feet (gal./Mcf), occurs at a significantly
lower gas flow rate of about 420 scfm. Also at high flow rates the
liquid/gas ratio seems to fall off very rapidly, approaching zero
for the 12 inch tube at 2700 scfm and at 1400 scfm for the 8 inch tube.
Therefore, from Figure 4-3, it would appear that liquid/gas ratio is
independent of pressure drop at higher gas flow rates.

Finally, Figure 4-3 exhibits the same trend as Figures 4-1 and 4-2
regarding tube diameter; that is, increasing tube diameter results in
an increased liquid/gas ratio.

## Characteristics and Analysis of Feed Reactants and Discharge

While lack of sufficient instrumentation and funds prevented a detailed
study of the chemical reaction kinetics and mechanisms occurring during
the scrubbing process, analyses were made of the chemical constituents
important to the understanding of the chemical processes occurring in
the Dustraxtor absorber. These analyses were made for pH, $Ca^{++}$, $Mg^{++}$,
$Cl^-$, $NO_3^-$, $NO_2^-$, $SO_3^{--}$, and $SO_4^{--}$. A summary of the chemical analyses
results for the scrubber feed and discharge streams of each reactant
tested during the test program are shown in Tables 4-1 through 4-11.

## Characteristics and $SO_2$ Analysis of Influent Flue Gases

A summary of the influent flue gas characteristics for both the oil-
fired Key West unit No. 3 and coal-fired Shawnee units No. 9 and 10 is

Table 4-1.  SUMMARY OF SALT WATER TESTS

CHEMICAL ANALYSES

(Key West)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | $NO_3$ (mg/1) | $NO_2$ (mg/1) | $SO_3$ (mg/1) | $SO_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| Scrubber Feed | | | | | | | | |
| Average | 7.6 | 475 | 1385 | 23,207 | 0.40 | <0.01 | 1 | 2640 |
| Maximum | 7.8 | 1040 | 1510 | 25,000 | 0.60 | <0.01 | 1 | 2740 |
| Minimum | 7.4 | 410 | 1215 | 19,800 | 0.02 | <0.01 | 1 | 2125 |
| Scrubber Discharge | | | | | | | | |
| Average | 2.6 | 432 | 1375 | 21,667 | 0.20 | <0.01 | 32 | 3171 |
| Maximum | 2.9 | 530 | 1440 | 23,500 | 0.80 | <0.01 | 127 | 3840 |
| Minimum | 2.3 | 420 | 1360 | 20,000 | <0.01 | <0.01 | 3 | 2800 |


Table 4-2.  SUMMARY OF CORAL MARL

CHEMICAL ANALYSES

(Key West)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | $NO_3$ (mg/1) | $NO_2$ (mg/1) | $SO_3$ (mg/1) | $SO_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| Scrubber Feed | | | | | | | | |
| Average | 7.7 | 541 | 1431 | 22,400 | 0.9 | 0.14 | 2 | 2872 |
| Maximum | 8.0 | 2180 | 1920 | 30,000 | 16.0 | 0.40 | 7 | 3840 |
| Minimum | 7.5 | 400 | 1340 | 19,000 | 0 | 0 | 1 | 2220 |
| Scrubber Discharge | | | | | | | | |
| Average | 5.5 | 1614 | 1471 | 23,180 | 3.0 | 2.27 | 6419 | 4641 |
| Maximum | 6.4 | 2800 | 1875 | 30,000 | 15.2 | 10.40 | 40,000 | 6100 |
| Minimum | 4.7 | 880 | 584 | 12,500 | 0 | 0 | 1110 | 3500 |

Table 4-3.   SUMMARY OF FREDONIA LIMESTONE

CHEMICAL ANALYSES

(Key West)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | NO$_3$ (mg/1) | NO$_2$ (mg/1) | SO$_3$ (mg/1) | SO$_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| **Scrubber Feed** | | | | | | | | |
| Average | 7.6 | 492 | 1401 | 22,520 | 0.50 | 0.20 | 1 | 2810 |
| Maximum | 7.9 | 600 | 1460 | 26,500 | 2.80 | 0.60 | 2 | 3040 |
| Minimum | 7.1 | 400 | 1340 | 20,000 | 0 | 0 | 1 | 2750 |
| **Scrubber Discharge** | | | | | | | | |
| Average | 5.6 | 1551 | 1498 | 22,900 | 1.60 | 2.20 | 5601 | 5183 |
| Maximum | 6.1 | 1960 | 1940 | 31,500 | 5.80 | 7.92 | 23300 | 5400 |
| Minimum | 4.5 | 1120 | 875 | 15,000 | 0 | 0 | 900 | 3700 |

Table 4-4.   SUMMARY OF HYDRATED LIME

CHEMICAL ANALYSES

(Key West)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | NO$_3$ (mg/1) | NO$_2$ (mg/1) | SO$_3$ (mg/1) | SO$_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| **Scrubber Feed** | | | | | | | | |
| Average | 11.4 | 2800 | 158 | 20,900 | 0.70 | 0.08 | 2 | 2815 |
| Maximum | 11.6 | 2960 | 267 | 21,500 | 0.80 | 0.15 | 3 | 2840 |
| Minimum | 11.1 | 2680 | 97 | 20,500 | 0.60 | 0.01 | 1 | 2760 |
| **Scrubber Discharge** | | | | | | | | |
| Average | 8.3 | 80 | 2697 | 21,200 | 0.70 | 0.22 | 25,400 | 4203 |
| Maximum | 8.7 | 100 | 3340 | 22,000 | 1.20 | 0.35 | 37,300 | 4850 |
| Minimum | 7.7 | 56 | 2330 | 20,500 | 0.20 | 0.13 | 11,900 | 3660 |

Table 4-5. SUMMARY OF DOLOMITE

CHEMICAL ANALYSES

(Key West)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | NO$_3$ (mg/1) | NO$_2$ (mg/1) | SO$_3$ (mg/1) | SO$_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| Scrubber Feed | | | | | | | | |
| Average | 7.6 | 485 | 1386 | 21,500 | 1.20 | 0.50 | 2 | 2963 |
| Maximum | 7.7 | 560 | 1410 | 21,500 | 1.60 | 0.90 | 3 | 3000 |
| Minimum | 7.5 | 440 | 1340 | 21,500 | 0.80 | 0.10 | 1 | 2920 |
| Scrubber Discharge | | | | | | | | |
| Average | 5.2 | 599 | 1563 | 20,100 | 2.70 | 0.03 | 515 | 4740 |
| Maximum | 5.4 | 840 | 1850 | 21,500 | 3.20 | 0.09 | 600 | 6740 |
| Minimum | 4.9 | 116 | 1410 | 18,000 | 1.80 | 0.01 | 450 | 4050 |

Table 4-6. SUMMARY OF PRECIPITATED CALCIUM CARBONATE

CHEMICAL ANALYSES

(Key West)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | NO$_3$ (mg/1) | NO$_2$ (mg/1) | SO$_3$ (mg/1) | SO$_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| Scrubber Feed | | | | | | | | |
| Average | 7.6 | 467 | 1355 | 21,300 | 1.10 | 0.10 | 2 | 2800 |
| Maximum | 7.6 | 480 | 1385 | 22,500 | 1.20 | 0.14 | 2 | 2840 |
| Minimum | 7.5 | 440 | 1340 | 20,500 | 1.00 | 0.07 | 2 | 2760 |
| Scrubber Discharge | | | | | | | | |
| Average | 5.9 | 1133 | 1360 | 16,200 | 0.90 | 0.18 | 1919 | 3677 |
| Maximum | 6.2 | 1640 | 804 | 20,500 | 1.40 | 0.27 | 3500 | 41200 |
| Minimum | 6.0 | 880 | 655 | 13,000 | 0.40 | 0.09 | 1000 | 3250 |

Table 4-7.    SUMMARY OF SHAWNEE NO. 9 FREDONIA
LIMESTONE CHEMICAL ANALYSES
(Paducah)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | $NO_3$ (mg/1) | $NO_2$ (mg/1) | $SO_3$ (mg/1) | $SO_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| **Scrubber Feed** | | | | | | | | |
| Average | 8.2 | 24 | 4.9 | 14 | 3.30 | 0.27 | 4 | 43 |
| Maximum | 8.5 | 32 | 7.4 | 15 | 5.50 | 0.35 | 5 | 131 |
| Minimum | 8.0 | 12 | 3.5 | 13 | 1.50 | 0.16 | 2 | 0 |
| **Scrubber Discharge** | | | | | | | | |
| Average | 5.3 | 1063 | 61.9 | 373 | 7.50 | 0.10 | 1585 | 1654 |
| Maximum | 5.6 | 1440 | 97.0 | 800 | 15.50 | 0.16 | 2600 | 2479 |
| Minimum | 5.0 | 600 | 48.5 | 100 | 3.50 | 0.09 | 950 | 910 |

Table 4-8.    SUMMARY OF SHAWNEE NO. 9 ARAGONITE
CHEMICAL ANALYSES
(Paducah)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | $NO_3$ (mg/1) | $NO_2$ (mg/1) | $SO_3$ (mg/1) | $SO_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| **Scrubber Feed** | | | | | | | | |
| Average | 8.1 | 36 | 11.3 | 60 | 3.9 | 0.20 | 2 | 108 |
| Maximum | 8.1 | 38 | 12.0 | 90 | 5.0 | 0.22 | 2 | 156 |
| Minimum | 8.1 | 34 | 9.5 | 30 | 2.5 | 0.18 | 1 | 41 |
| **Scrubber Discharge** | | | | | | | | |
| Average | 6.1 | 570 | 48.6 | 211 | 3.8 | 0.34 | 478 | 1061 |
| Maximum | 6.3 | 1000 | 48.6 | 350 | 5.5 | 0.55 | 780 | 2060 |
| Minimum | 5.8 | 360 | 48.5 | 150 | 3.0 | 0.16 | 300 | 580 |

Table 4-9.　　SUMMARY OF SHAWNEE NO. 9 SALTWATER/FREDONIA
LIMESTONE CHEMICAL ANALYSES
(Paducah)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | $NO_3$ (mg/1) | $NO_2$ (mg/1) | $SO_3$ (mg/1) | $SO_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| **Scrubber Feed** | | | | | | | | |
| Average | 8.2 | 60 | 8.5 | 12,000 | 2.50 | 0.40 | 1 | 58 |
| Maximum | 8.2 | 60 | 8.5 | 12,000 | 2.50 | 0.40 | 1 | 58 |
| Minimum | 8.1 | 60 | 8.5 | 12,000 | 2.50 | 0.40 | 1 | 58 |
| **Scrubber Discharge** | | | | | | | | |
| Average | 5.6 | 1040 | 48.5 | 9,500 | 3.30 | 0.17 | 865 | 2120 |
| Maximum | 5.7 | 1280 | 48.5 | 10,000 | 3.50 | 0.17 | 1150 | 2880 |
| Minimum | 5.4 | 800 | 48.5 | 9,000 | 2.00 | 0.16 | 580 | 1360 |

Table 4-10.　　SUMMARY OF SHAWNEE NO. 10 ARAGONITE INJECTION
CHEMICAL ANALYSES
(Paducah)

| | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | $NO_3$ (mg/1) | $NO_2$ (mg/1) | $SO_3$ (mg/1) | $SO_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| **Scrubber Feed** | | | | | | | | |
| Average | 7.9 | 58 | 2.7 | 10.8 | 35.20 | 0.17 | 4 | 125 |
| Maximum | 8.1 | 92 | 3.5 | 13 | 52.00 | 0.18 | 8 | 205 |
| Minimum | 7.8 | 24 | 2.4 | 10 | 1.60 | 0.16 | 2 | 24 |
| **Scrubber Discharge** | | | | | | | | |
| Average | 7.8 | 520 | 60.7 | 200 | 3.90 | 4.20 | 37 | 1021 |
| Maximum | 7.9 | 600 | 72.9 | 250 | 8.00 | 6.00 | 80 | 1230 |
| Minimum | 7.4 | 440 | 48.5 | 150 | 1.60 | 3.00 | 15 | 740 |

Table 4-11.   SUMMARY OF SHAWNEE NO. 10 FREDONIA LIMESTONE
            INJECTION CHEMICAL ANALYSES
            (Paducah)

|  | pH | Ca (mg/1) | Mg (mg/1) | Cl (mg/1) | $NO_3$ (mg/1) | $NO_2$ (mg/1) | $SO_3$ (mg/1) | $SO_4$ (mg/1) |
|---|---|---|---|---|---|---|---|---|
| **Scrubber Feed** | | | | | | | | |
| Average | 7.9 | 37 | 5.7 | 15 | 2.00 | 0.39 | 2 | 61 |
| Maximum | 8.1 | 64 | 6.0 | 15 | 3.10 | 1.50 | 2 | 80 |
| Minimum | 7.4 | 28 | 5.0 | 15 | 0.20 | 0.20 | 1 | 24 |
| **Scrubber Discharge** | | | | | | | | |
| Average | 5.8 | 643 | 33.6 | 135 | 5.20 | 0.61 | 557 | 1200 |
| Maximum | 6.9 | 1320 | 48.6 | 200 | 7.50 | 3.60 | 1700 | 2080 |
| Minimum | 4.9 | 320 | 24.3 | 100 | 2.40 | 0.18 | 100 | 310 |

presented in Tables 4-12 and 4-13, respectively.  In addition, plots of
the variation in entering $SO_2$ concentration with time at both test
sites are shown in Figures 4-4 and 4-5.  The major variations in inlet
$SO_2$ concentration at the Key West site were attributed to a change in
sulfur content of the fuel oil.  This was either due to stratification
of different sulfur content fuels in the fuel storage tank or a change
in the total sulfur content in the tank, the latter resulting from
the mixing of fuel oil shipments in the tank.  Similarly, $SO_2$ variations
at the Shawnee test site were attributed to the wide variation of sulfur
present in the coal supplied to the plant.  In addition, during the
month of July, TVA was conducting precipitator efficiency tests on
Shawnee No. 10.  These tests frequently increased dilution air leakages
into the flue gas upstream of the pilot plant entrance.

Scale Deposition

Deposition of scale in piping, fans, pumps, tanks, sumps, and on the
absorber internals varied from nondetectable to moderately heavy during
the Key West and Shawnee No. 9 test programs.  The degree and rate of

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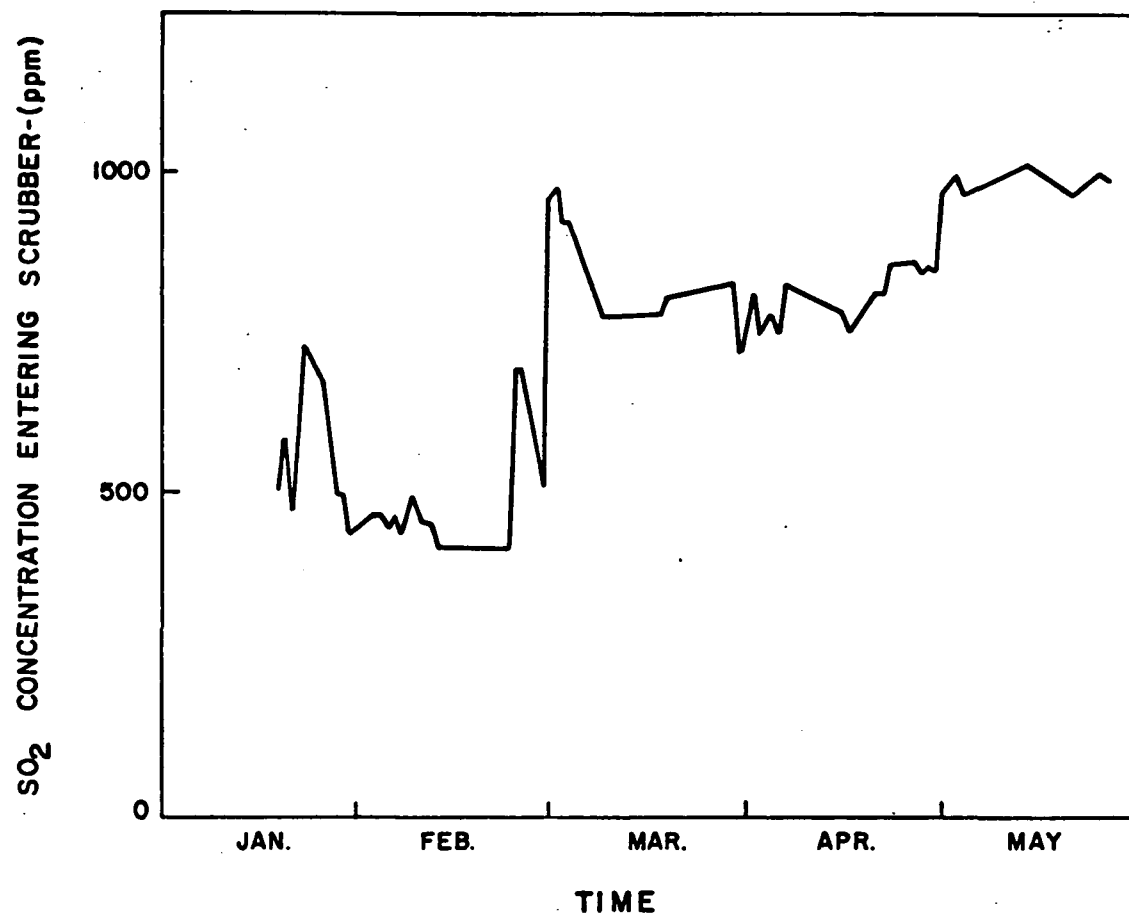
FIG. 4-4. VARIATION OF INLET SO$_2$ CONCENTRATION, KEY WEST - 1971
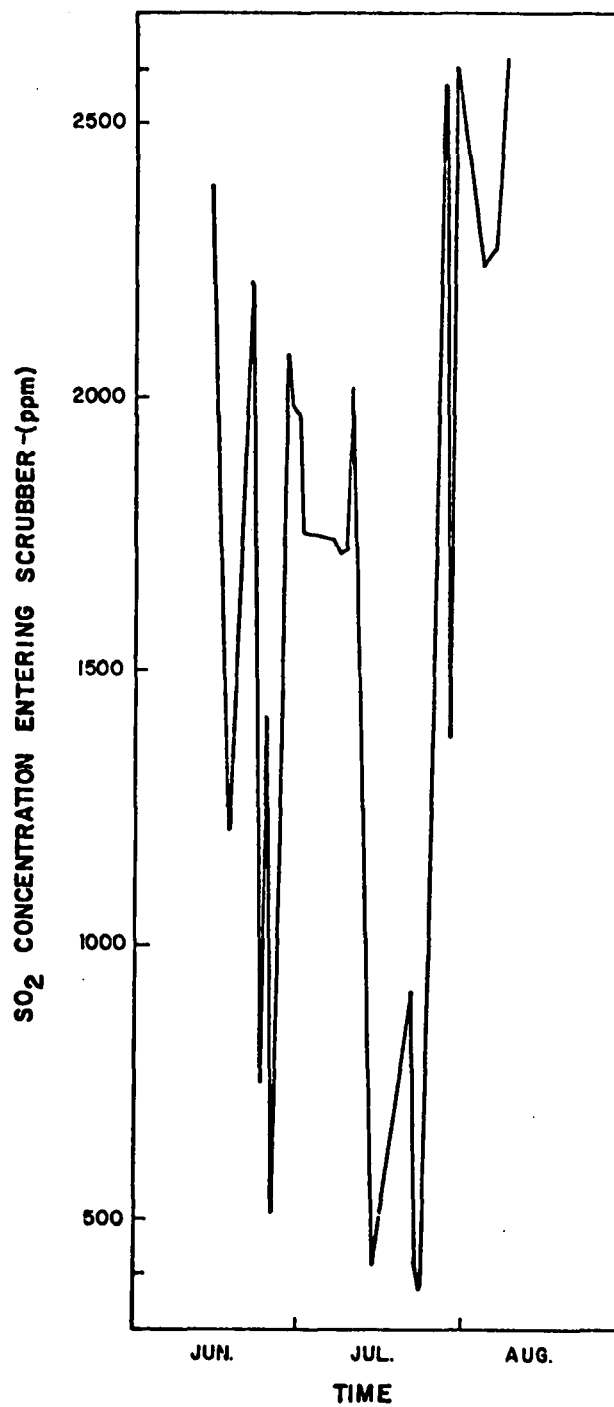
FIG. 4-5. VARIATION OF INLET SO$_2$ CONCENTRATION, PADUCAH - 1971

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Table 4-12.  SUMMARY OF INLET FLUE GAS CONDITIONS

(Key West Unit No. 3)

| | |
|---|---|
| Average Dry Bulb Temperature | 231°F |
| Average Wet Bulb Temperature | 130°F |
| Average $SO_2$ Concentration | 703 ppm |


Table 4-13.  SUMMARY OF INLET FLUE GAS CONDITIONS

(Shawnee Units No. 9 and 10)

| | |
|---|---|
| Average Dry Bulb Temperature | 191°F |
| Average Wet Bulb Temperature | 119°F |
| Average $SO_2$ Concentration | 1699 ppm |

deposition was not quantified except in terms of how rapidly the scrubbing system was affected. While scale deposits did occur, the only interference with the system operation was a fan failure caused by build-up on the blades.

The deposits resulted primarily from precipitation of calcium salts and deposition of the reactant material. The composition of the deposit on the tube was identified by x-ray diffraction and is presented in Table 4-14. Deposits were not found in the mix tank, pumps, or related piping. Deposits were found on the weir hopper and inside scrubber wall at the water line, the tube at the liquid/gas interface, the mist elimination section, and in the fan housing. It should be noted that all deposits except those found on the tube and in the fan were very minor and did not interfere with the system performance over a 6 month period. The deposits on the tube occurred moderately fast and the rate of formation appeared to increase with slurry concentration. The tube deposits took the form of stalactites which grew directly into the gas path. If allowed to grow for an extended time period, these deposits would interfere with system performance. Table 4-15 summarizes the degree of deposition at various locations in the pilot plant during both the Key West and TVA Shawnee Unit No. 9 tests.

Table 4-14.  X-RAY DIFFRACTION ANALYSES OF SCALE

FORMATION ON THE TUBE

(Key West)

| Compound | Quantity (wt%) |
|---|---|
| $CaSO_4 \cdot 2H_2O$ | 30.5 |
| $CaCO_3$ | 68.0 |
| $MgCO_3$ | 1.5 |

Table 4-15.   DEGREE OF DEPOSITION AT VARIOUS SYSTEM LOCATIONS

(Key West Unit No. 3 and Shawnee Unit No. 9)

| Location | Degree | Rate of Formation |
|---|---|---|
| Mix Tanks | negligible | - |
| Pumps & Related Piping | negligible | - |
| Weir Hopper (water line) | slight | slow |
| Absorber Body (water line) | slight | slow |
| Tube Before[a] | moderately heavy | moderate |
| After | negligible | - |
| Mist Eliminator | slight | slow |
| Fan | slight | very slow |

[a]Note the change when wash water was added to control scale formation at this location.

The deposits at the tube lip were controlled later in the test program by continually washing the tube with a small spray of fresh water in the vicinity of the tube lip. Fresh water was used because it was readily available at the pressure required. It is assumed that salt water would be entirely suitable for this purpose. The design requirements to control scale at the tube lip necessitated a ring attached to the tube approximately 6 inches above the bottom of the lip. The ring had a series of 1/16 inch diameter holes drilled in such a manner that the tube was continually wetted down to the lip. Once this modification was installed and adjusted, stalactite-type growth into the gas stream was eliminated. However, during the limestone injection testing on Unit No. 10 the scale deposition was so heavy that the spray ring proved ineffective. Therefore, operation in this manner for extended periods of time (16-24 hours) was not possible.

The deposits during testing on Unit No. 10 resulted primarily from impaction of calcined limestone on the exterior surface of the tube. This resulted from the heavy particulate loading to the absorber and an inadequately designed entrance for this heavy loading. This deposition interfered with the operation because calcined limestone impacted on the tube at the entrance, built up, and fell in large cakes into the hopper. Table 4-16 summarizes the scale and sludge deposition locations in the pilot plant while scrubbing flue gas from TVA Shawnee Unit No. 10.

Settling Characteristics

Table 4-17 summarizes the results of one test to determine the settling characteristics of the slurry effluent. This was done by measuring the time required for the turbid portion of a slurry sample (interface between slurry and clarified liquor) to settle in an undisturbed graduated cylinder. The exact location of the interface was defined by the graduations on the side of the cylinder. The majority of the settling appeared to occur during the first 10 minutes. These data were collected to aid in the design of a clarifier or other solid-waste handling equipment which might be required on a larger sized unit.

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Table 4-16. DEGREE OF DEPOSITION AT VARIOUS SYSTEM LOCATIONS

(TVA Shawnee Unit No. 10)

| Location | Degree | Rate of Formation |
|---|---|---|
| Mix Tanks | negligible | - |
| Pumps & Related Piping | negligible | - |
| Weir Hopper (water line) | slight | slow |
| Absorber Body (water line) | slight | slow |
| Tube[a] | severe | rapid |
| Mist Eliminator | slight | slow |
| Fan | slight | very slow |

[a]Scale at tube lip controlled by wash water. Major depositing occurred by impaction of calcined limestone carried in gas stream from Unit No. 10 during limestone injection test program.

Table 4-17. SETTLING RATE OF LIMESTONE SLURRY EFFLUENT

| Interface Location (ml in 500 ml graduated cylinder) | Time (Minutes) |
|---|---|
| 500 | 0 |
| 400 | 3.5 |
| 350 | 4.6 |
| 300 | 5.8 |
| 250 | 7.3 |
| 200 | 8.5 |
| 150 | 9.7 |
| 100 | 10.7 |
| 48 | 144.0 |

Note: sample taken from scrubber discharge during test P-32 which utilized 325 mesh Fredonia Valley limestone in a 3% slurry concentration.

## Dry Collector

No attempt was made at quantifying the operating parameters or the performance of the dry collector regarding $SO_2$ or $NO_x$ removal. While an attempt was made to quantify the particulate removal efficiency of the dry collector during the Shawnee No. 9 tests, procedural errors and equipment malfunctions caused the tests to be voided. Since sufficient data had been obtained concerning particulate removal across the entire pilot plant (dry collector and Dustraxtor scrubber) no further attempt was made to measure the removal in the dry collector separately.

The dry collector was bypassed, when not in use, by means of built-in dampers and gas ducts at both the Key West and Shawnee No. 10 test sites. The fly ash collected from Shawnee No. 9 flue gas had the characteristics expected of coal fly ash; however, the ash was not chemically analyzed.

## $SO_2$ ABSORPTION: KEY WEST PROGRAM

In this section some of the more general results of the Key West program are summarized. An addendum to this report, available through EPA's Control Systems Laboratory, contains all the data collected. Section 5 is a more complete analysis of the data collected during the factorial design experiments.

## Salt Water Tests

A total of forty three preliminary tests were conducted with no reactant in the salt water feed using a 12 inch diameter tube size. The purpose of this series was to determine the operating characteristics of the equipment, to establish base line data and to calibrate the instrument system. Thirty of the tests provided useful data from which $SO_2$ removal efficiencies could be calculated. Two levels of gas flow and pressure drop were used, these being the same as would later be utilized in the experimental design tests. The arithmetic average $SO_2$ removal efficiency was 39.6% with sea water alone. Figure 4-6 summarizes the effects of the two gas flow and pressure drop levels.
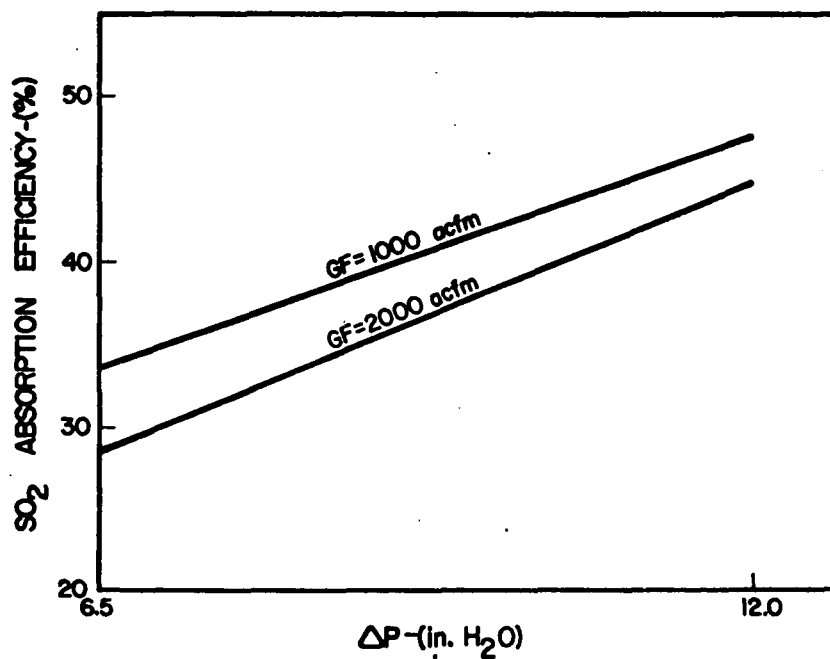
FIG. 4-6. ABSORPTION EFFICIENCY AS A FUNCTION OF GAS FLOW AND PRESSURE DROP: SALT WATER

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Three levels of salt water feed flow rate were tested during the pre-liminary shakedown period; these were 2, 5, and 10 gpm. Little change in absorption efficiency was measured between the two lower rates. Figure 4-7 summarizes the effects of the 2 and 10 gpm levels.

Coral Marl Tests

A total of thirty six tests were conducted with coral as the reactant of which thirty four provided useful data. All tests were conducted with a 12 inch diameter tube. Sixteen of these were the factorial experiment, ten were independent data for validating the derived prediction equation, and eight were centerpoint and additive tests. Except for the last eight tests, each of the five independent variable factors was tested at two levels. The average $SO_2$ removal efficiency using coral was 74.3%.

Figure 4-8 illustrates the absorption (expressed as $SO_2$ absorption efficiency) as a function of the independent variables studied during the experiments with the coral reactant. The independent variables were: gas flow rate, stoichiometry, reactant particle size, slurry concentration, and scrubber pressure drop. An increase in stoichiometric ratio or a decrease in gas flow rate at a fixed pressure drop, produced a signifi-cant increase in $SO_2$ absorption efficiency in the Dustraxtor. It should be noted that the pilot plant system was operated in a once-through con-figuration. These results should not be extrapolated to a closed-loop, recycle system with different ionic strength scrubbing slurries.

Four centerpoint experiments were conducted in which four of the variables were at the midpoint of the high and low level. The fifth variable, particle size, was not centered because of the unavailability of the proper size reactant. The average $SO_2$ removal efficiency for the centerpoint experiments was 71.1%. This compares closely with the 74.3% average $SO_2$ removal for all Key West coral tests and indicates there is a linear response to all variable factors within the range tested. Extrapolation beyond this range, however, is not recommended.
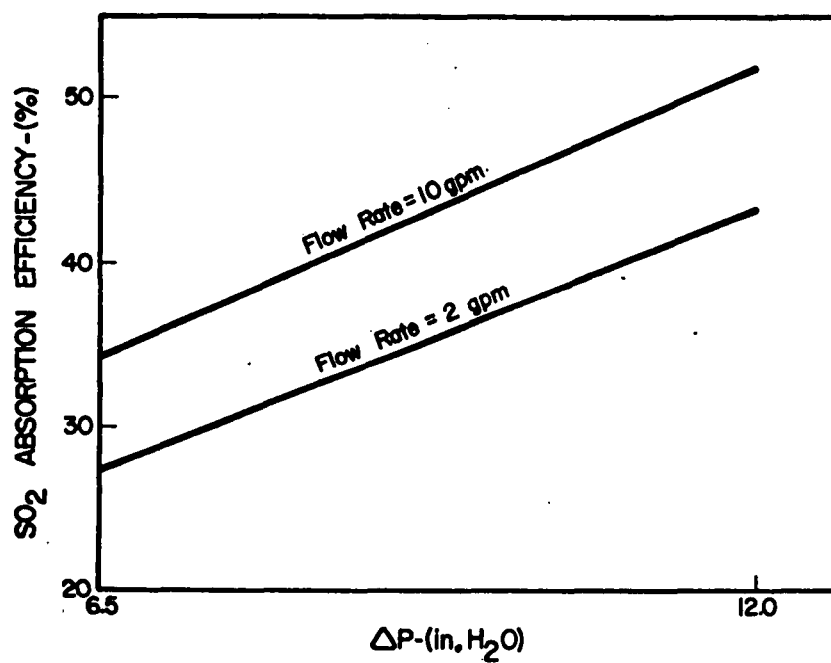
FIG. 4-7. ABSORPTION EFFICIENCY AS A FUNCTION OF FEED FLOW RATE AND PRESSURE DROP: SALT WATER

52
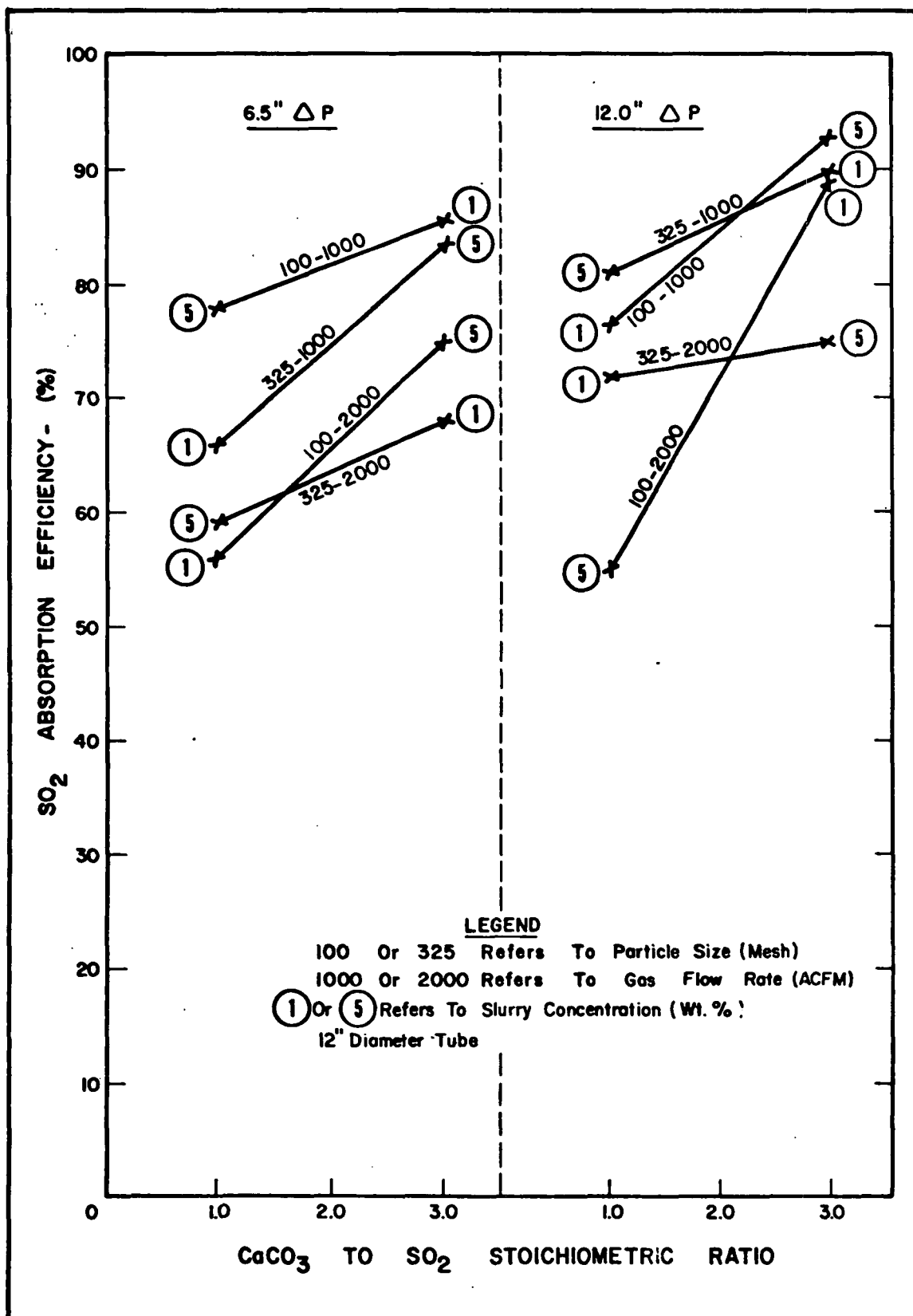
FIG. 4-8. SUMMARY OF CORAL SALT WATER EXPERIMENTAL DESIGN POINTS

Three tests were conducted in which additions were made to the slurry to test the effect of $FeCl_3$, as a catalyst, and hydroquinone, as an inhibitor. These compounds were recommended by EPA because they have been reported to affect $SO_2$ absorption by influencing the oxidation of sulfite to sulfate in the scrubber medium. Results were inconclusive concerning this claim since there did not appear to be a significant change in the $SO_2$ absorption capability with the additives tested. When the $FeCl_3$ was added directly to the mixture in the weir, an immediate decrease in $SO_2$ outlet concentration was observed on the $SO_2$ monitor. This response, however, was only temporary and the outlet concentration soon returned to its original level.

No noticeable results were detected in the case of the addition of hydroquinone nor in the case of the addition of both catalyst and inhibitor.

Fredonia Valley Limestone Tests

A total of forty three tests were conducted with limestone as the reactant of which forty one provided useful data. Sixteen of those were the factorial experiment, nine were independent data for validating the derived prediction equation, four were centerpoint tests, and twelve were comparative tests of the 8 inch and 12 inch scrubber tubes. The average $SO_2$ removal efficiency using Fredonia Valley limestone was 73.7%.

Figure 4-9 illustrates the absorption efficiency as a function of the five independent variables studied during the experiments with Fredonia Valley limestone. An increase in stoichiometry, a decrease in gas flow rate, or an increase in pressure drop each resulted in an increase in $SO_2$ absorption during the limestone tests. These same variables caused similar effects on $SO_2$ absorption during the coral reactant tests.

Four centerpoint experiments were conducted in which four of the variables were at the midpoint of the high and low level. As before, particle size was not centered. Three of the tests resulted in high $SO_2$
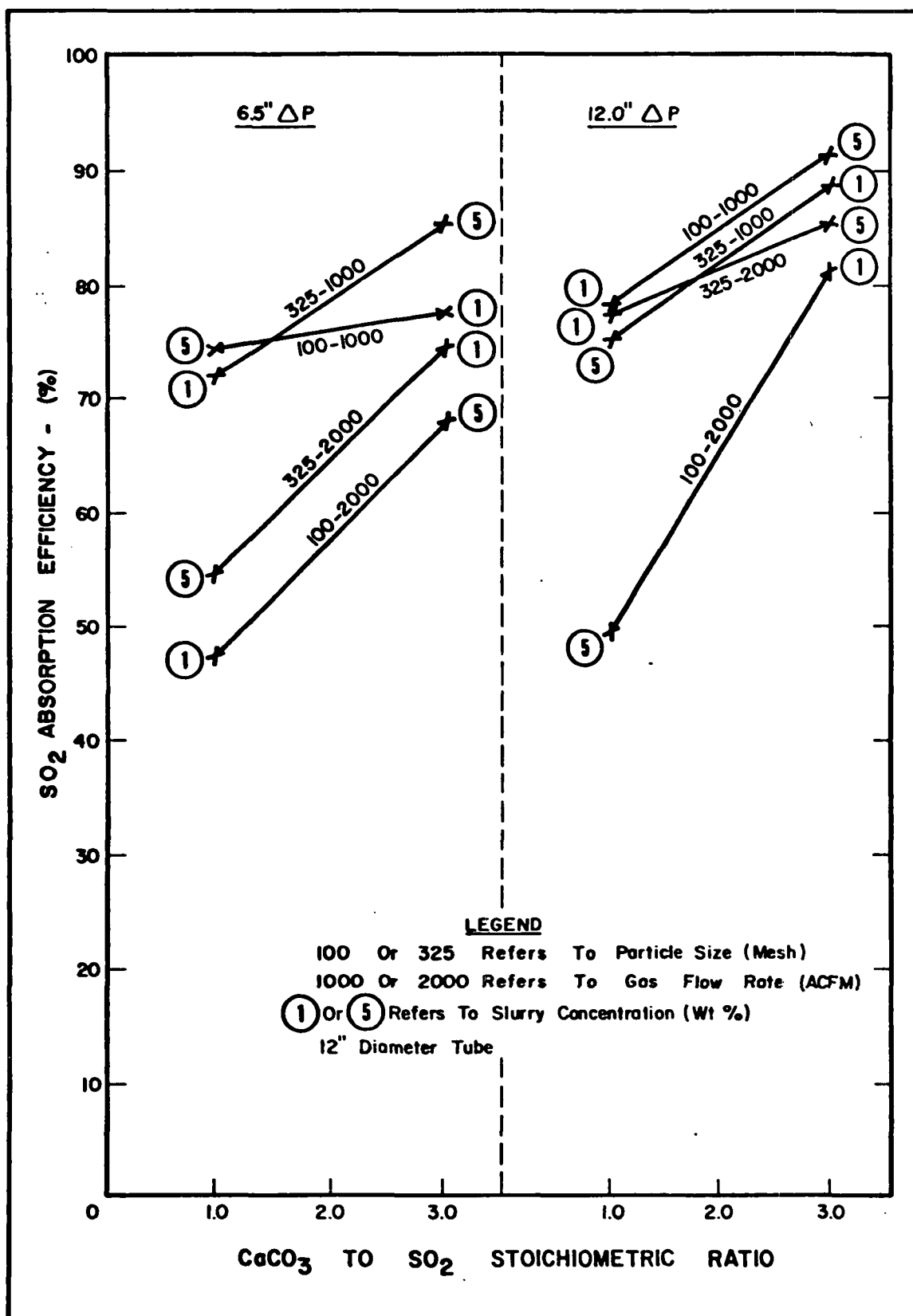
FIG. 4-9 SUMMARY OF FREDONIA VALLEY LIMESTONE
SALT WATER EXPERIMENTAL DESIGN POINTS

removal efficiencies, ranging between 84 to 86%. These values are considerably higher than expected results. It is suspected that a malfunction of the $SO_2$ monitor occurred. The fourth value was 70.6% which is much closer to the average value from all of the tests in this series.

Twelve tests with limestone demonstrated the increased absorption efficiency of the 12 inch scrubber tube. This series consisted of seven tests with the 12 inch tubes at various gas flow rates, all other variables held constant, and five similar tests with the 8 inch tube. The results of the experiment are shown in Figure 4-10.

Secondary Reactant Tests

Four tests with each of three secondary reactants were conducted. These were designed for factorial experiments, but one test for one reactant was voided due to carry-over into the sampling line rendering that test series inadequate for analysis. One final test was conducted with spent reactant. All tests were conducted with a 12 inch tube diameter. The average $SO_2$ removal efficiencies for the four reactants are shown in Table 4-18:

Table 4-18.   $SO_2$ REMOVAL EFFICIENCY FOR SECONDARY
REACTANT TESTS
(Key West No. 3)

| Reactant | Per Cent Removal (%) |
|---|---|
| Hydrated Lime | 93.0 |
| Dolomite | 46.8 |
| Precipitated Calcium Carbonate | 78.3 |
| Spent Reactant | 69.9 |

Figure 4-11 summarizes the results of the hydrated lime and dolomite for which adequate data were available.

56
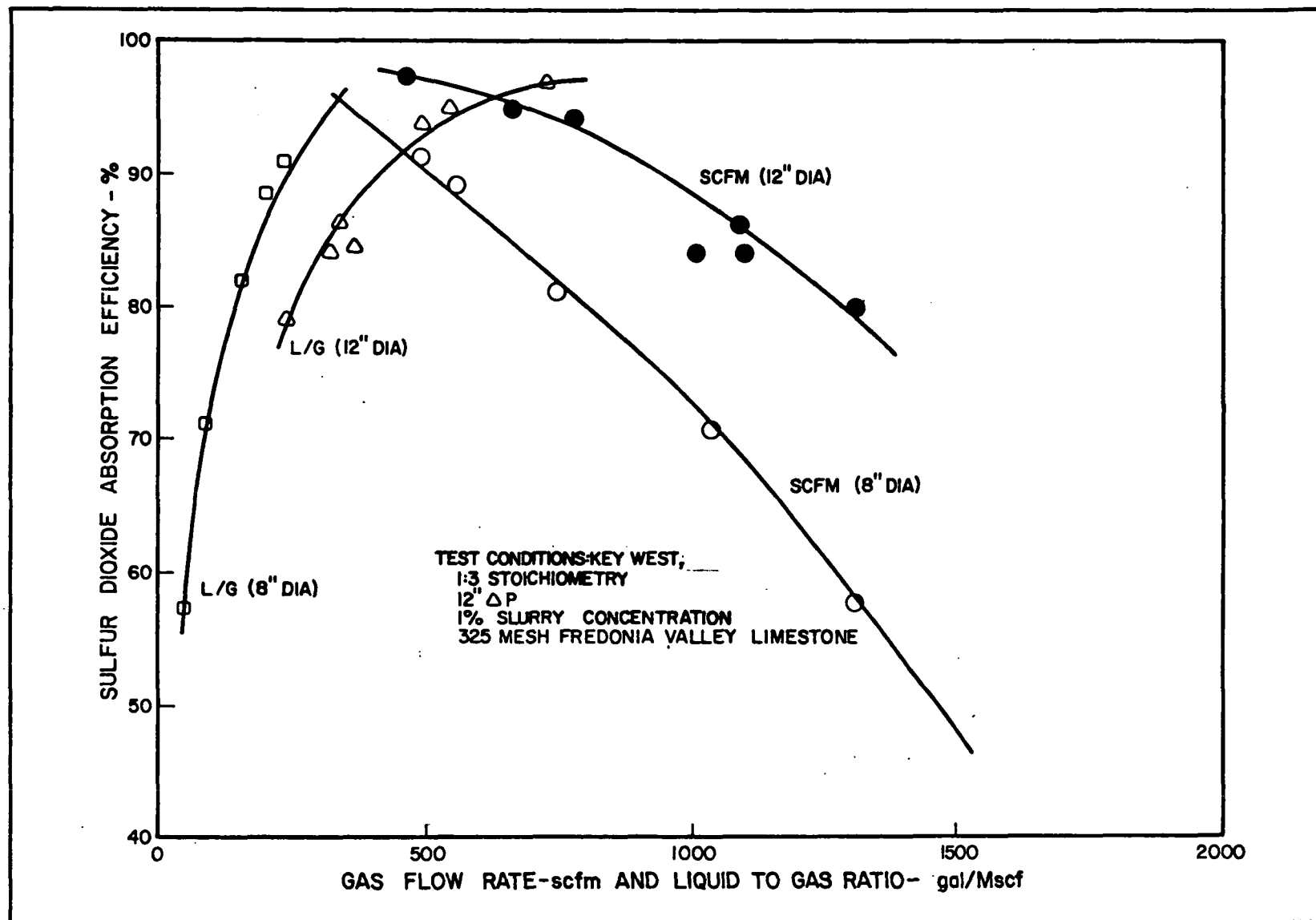
FIG. 4-10. SO$_2$ ABSORPTION EFFICIENCY AS A FUNCTION OF GAS FLOW RATE AND LIQUID/GAS RATIO

The figure shows SULFUR DIOXIDE ABSORPTION EFFICIENCY – % (vertical axis, 40 to 100) plotted against GAS FLOW RATE-scfm AND LIQUID TO GAS RATIO- gal/Mscf (horizontal axis, 0 to 2000). Curves are labeled: L/G (12" DIA), L/G (8" DIA), SCFM (12" DIA), SCFM (8" DIA).

TEST CONDITIONS: KEY WEST;
1:3 STOICHIOMETRY
12" ΔP
1% SLURRY CONCENTRATION
325 MESH FREDONIA VALLEY LIMESTONE

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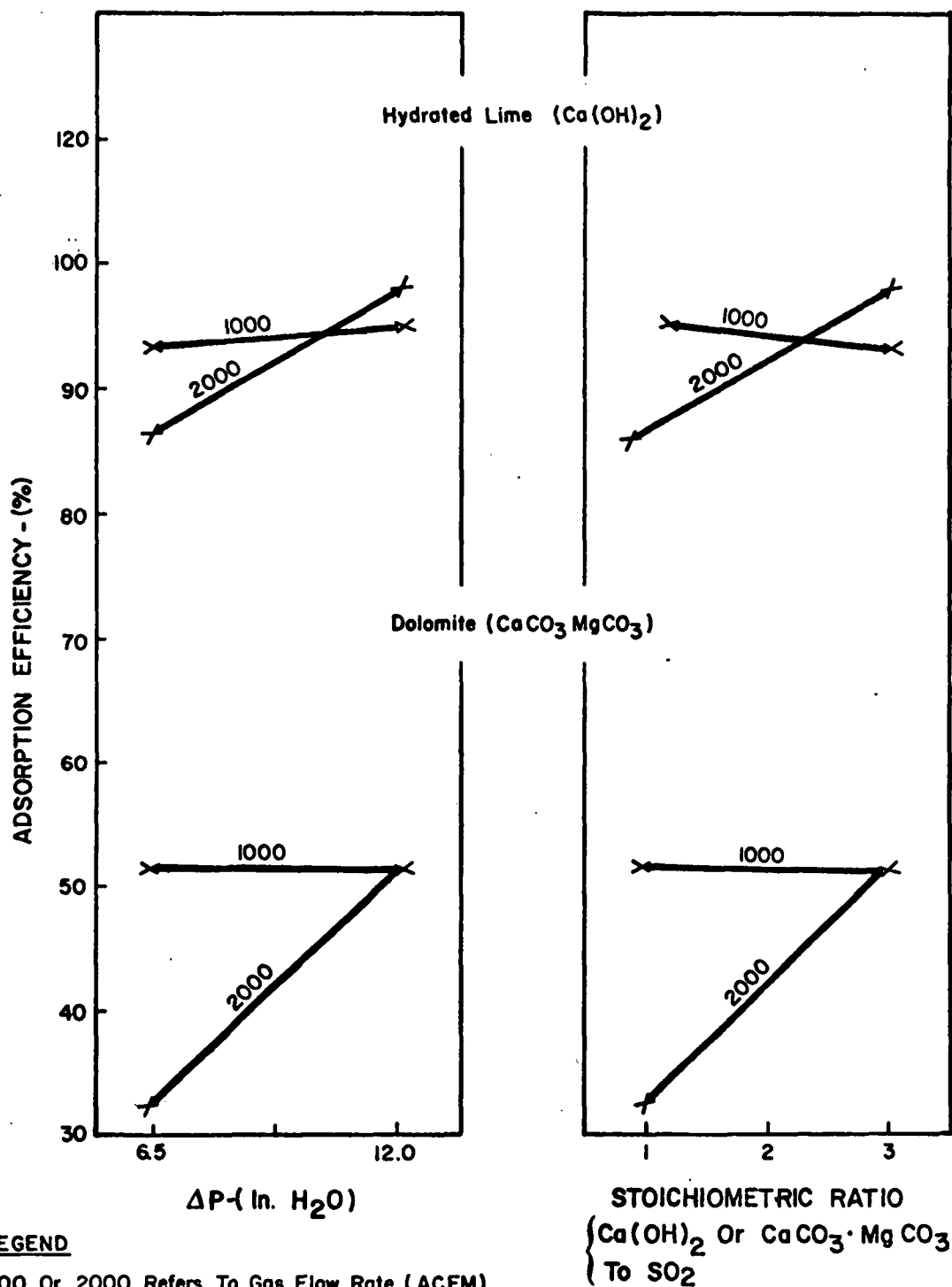
FIG. 4-11 SUMMARY OF SECONDARY REACTANTS SALT WATER EXPERIMENTAL DESIGN POINTS

SO$_2$.ABSORPTION:   PADUCAH PROGRAM

In this section some of the more general results of the Paducah program
are summarized.  An addendum to this report, available through EPA's
Control Systems Laboratory, contains all the data collected.  Section 5
is a more complete analysis of the data collected during the factorial
design experiments.

## Fredonia Valley Limestone Tests

A total of thirty five tests were conducted with limestone reactant in a
fresh water medium at the TVA Shawnee No. 9 unit.  Thirty three provided
useful data.  Of these, sixteen were the factorial experiment, eight
were centerpoint tests, five were additive tests, and four were tests with
the dry collector bypassed.  No tests were run for independent validating
purposes.

The average SO$_2$ removal efficiency for the sixteen factorial experiment
tests was 57.1%.  This compares badly with the 73.8% average removal
efficiency obtained in the sixteen factorial experimental tests conducted
at Key West using Fredonia Valley limestone with a salt water medium.
The variation in results is not entirely unexpected since there were many
differences in the two test series, namely: tube size, stoichiometric
ratio, slurry concentration, slurry medium and gas flow rate.

Figure 4-12 illustrates the absorption (expressed as SO$_2$ absorption
efficiency) as a function of some of the more important parameters studied
during the experiments on Unit No. 9.  An increase in stoichiometric ratio
or decrease in gas flow rate for each pressure drop produced a statistically
significant increase in SO$_2$ absorption efficiency in the Dustraxtor.  Again,
it should be noted that the pilot plant was operated in a one-through con-
figuration.  The results should not be extrapolated to a closed-loop, re-
cycle system with different ionic strength scrubbing slurries.

Five additive tests were conducted.  In three tests 200 ppm of FeCl$_3$ were
added at the weir to study the catalytic effects (see Coral Marl Tests
paragraph above).  There were none:  the average SO$_2$ removal efficiency
was 67.9% before the addition of the catalyst and 65.2% after.  Similarly.
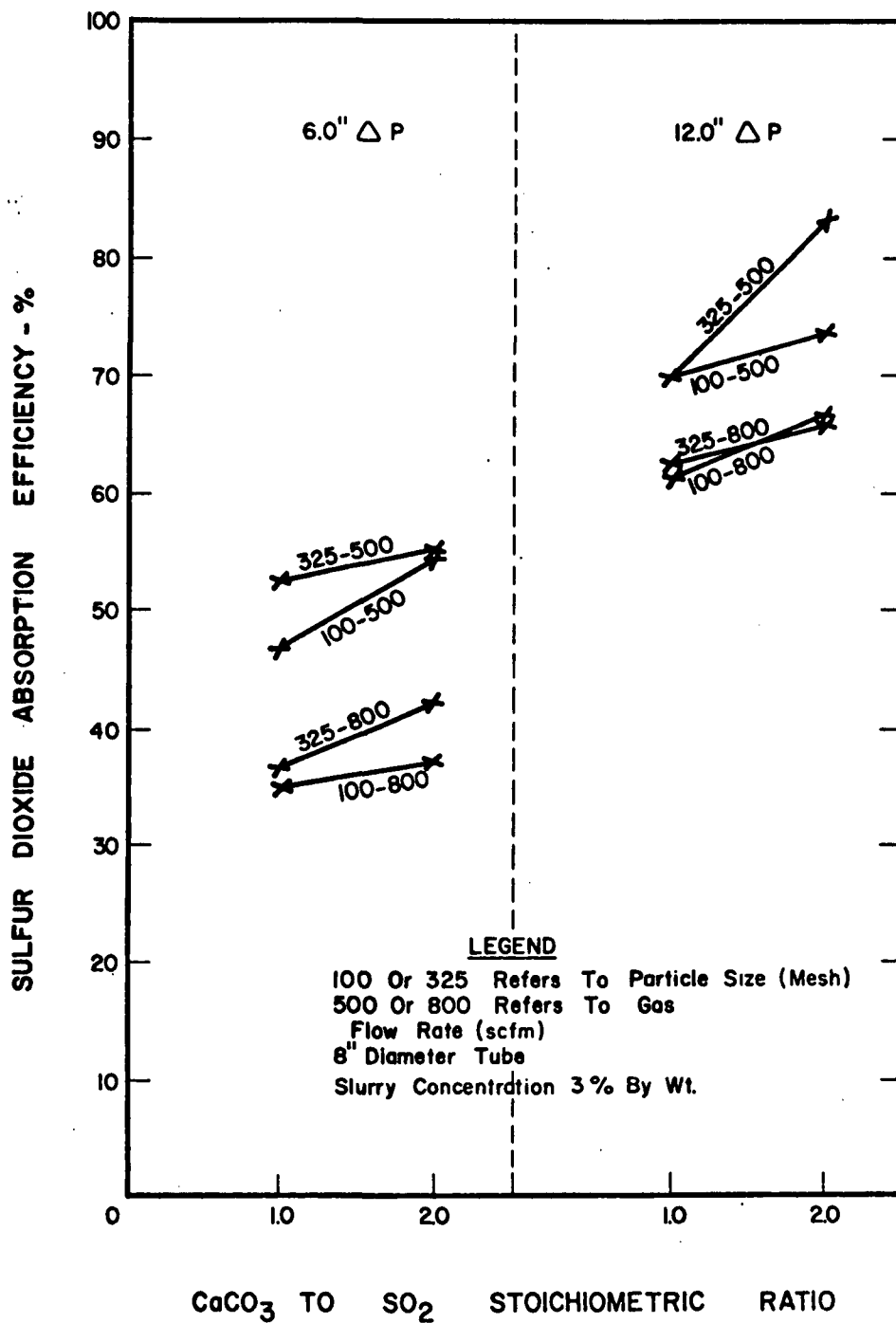
FIG. 4-12 SUMMARY OF FREDONIA VALLEY LIMESTONE
RIVER WATER EXPERIMENTAL DESIGN POINTS

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hydroquinone was tested in two cases as an inhibitor. Before addition the mean removal efficiency was 69.4%. After addition it was 66.4%. Based on knowledge of the $SO_2$ monitor's accuracy, drift characteristics, and response time, it was decided that effects on removal efficiencies amounting to less than 5% could not be separated from instrument and experimental error.

A total of twelve centerpoint tests were conducted. Four tests were performed at centerpoint conditions with the dry collector bypassed. This was done to evaluate the effects of coal fly ash on $SO_2$ absorption efficiencies. The average $SO_2$ removal efficiency for the four tests was 65.7%. The remaining eight centerpoint tests were conducted with the dry collector in line and resulted in an average $SO_2$ removal of 63.4%. The difference in average $SO_2$ removal for the two centerpoint test series is within instrument and experimental error. Therefore, no conclusion can be made concerning the effect of fly ash on $SO_2$ removal efficiencies.

## Aragonite Tests

Eight tests were conducted with aragonite using an 8 inch diameter tube. Four of these were the factorial experiment, two provided independent data at centerpoint, and two were dry collector bypass tests. All were at a 3% slurry concentration. The average $SO_2$ removal efficiency was 76.2%. The two tests with the dry collector bypassed, at centerpoint, showed an average of 67.7%.

## Simulated Key West Salt Water Tests

Three tests were conducted with Fredonia Valley Limestone in simulated salt water using an 8 inch tube diameter. An average $SO_2$ removal efficiency of 76.5% was obtained at centerpoint

## Injection Tests

In this test series conducted on TVA Shawnee Unit No. 10, the mobile pilot plant received flue gas laden with calcined limestone or aragonite,

as supplied from the boiler injection system. A total of seventeen injection tests were conducted; four with aragonite injection, thirteen with limestone injection. During all injection tests only river water was used as the scrubbing medium. The recorded stoichiometry is the injection stoichiometry of dry reactant to $SO_2$ as determined by TVA equipment operators. The tests conducted with aragonite injection resulted in an average $SO_2$ efficiency of 85.9%. The limestone tests gave an average $SO_2$ efficiency of 77.1%.

PARTICULATE COLLECTION IN THE SCRUBBER SYSTEM

Since the city of Key West was using fuel oil exclusively, no particulate testing was conducted at this site, and no quantitative results were available. From deposits observed above the scrubber mist eliminator section and in the fan and fan ductwork, it was concluded that particulates were generated during the scrubbing processes.

A number of tests utilizing the apparatus described in Section 3 Particulate Sampling paragraph, were conducted to quantify the particulate removal at the Paducah test site (Shawnee No.9). The results of the successful tests are presented in Table 4-19. The average result was dry collector and Dustraxtor. No attempt was made to determine the size range or composition of the particulates.

NO$_x$ ABSORPTION

Tables 4-20 through 4-23 present NO$_x$ absorption data. Tables 4-21 and 4-23 present individual test results. Tables 4-20 and 4-22 show the average inlet and outlet measurements. Although these averages show a reduction in NO$_x$ across the scrubber, the conclusion that significant absorption occurred is unwarranted because of the large standard deviations of the measured concentrations and of the experimental error associated with the analytical techniques.

SULFUR BALANCE

Table 4-24 shows sulfur balances from selected factorial design tests. These were selected as representative of both the Key West (coral and limestone) and the Paducah (limestone) tests. The consistently low exit

Table 4-19. PILOT PLANT PARTICULATE REMOVAL EFFICIENCY

(PADUCAH UNIT NO. 9)

| Test Number | $\Delta P$ (in $H_2O$) | Gas Flow (scfm) | Particulate Loading (gr/scf) Influent | Effluent | Particulate Removal Efficiency(%) |
|---|---|---|---|---|---|
| P-2 | 6.0 | 422 | 5.83 | 0.13 | 97.77 |
| P-5 | 12.0 | 620 | 4.77 | 0.08 | 98.32 |
| P-7 | 6.0 | 617 | 5.21 | 0.11 | 97.89 |
| P-12 | 12.0 | 417 | 5.16 | 0.05 | 99.03 |
| P-17 | 9.0 | 520 | 5.62 | 0.07 | 98.75 |
| PA-5 | 9.0 | 520 | 4.92 | 0.08 | 98.37 |
| PA-6 | 9.0 | 520 | 5.76 | 0.09 | 98.44 |

Average Efficiency.........98.37%

Table 4-20. AVERAGE OF $NO_x$ MEASUREMENTS

(KEY WEST UNIT NO. 3)

| | Average $NO_x$ (ppm) | Standard Deviation (ppm) |
|---|---|---|
| Key West | | |
| Pilot Plant Entrance | 440.9 | 97.0 |
| Pilot Plant Exit | 390.6 | 85.4 |

Table 4-21. TEST RESULTS OF $NO_x$ DURING THE KEY WEST TEST SERIES

| Test No. | Influent Concentration (ppm) | Effluent Concentration (ppm) | $NO_x$ Absorption (ppm) | Removal (%) |
|---|---|---|---|---|
| S-38 | 357 | 310 | 47 | 13.2 |
| C-19 | 425 | 401 | 24 | 5.6 |
| C-26 | 387 | 362 | 25 | 6.5 |
| C-27 | 195 | 404 | - | - |
| C-28 | 392 | 356 | 36 | 9.2 |
| C-29 | 645 | 596 | 49 | 7.6 |
| C-30 | 475 | 452 | 23 | 4.8 |
| F-3 | 392 | 307 | 85 | 23.2 |
| F-4 | 475 | 504 | - | - |
| F-5 | 417 | 398 | 19 | 4.6 |
| F-16 | 547 | 415 | 132 | 24.1 |
| F-17 | 388 | 300 | 88 | 22.7 |
| F-20 | 195 | 228 | 33 | - |
| F-21 | 310 | 247 | 63 | 20.3 |
| F-22 | 416 | 374 | 42 | 10.1 |
| F-23 | 407 | 408 | - | - |
| F-24 | 536 | 402 | 134 | 25.0 |
| F-25 | 512 | 400 | 112 | 21.9 |
| F-26 | 501 | 472 | 29 | 5.8 |
| F-27 | 187 | 325 | - | - |
| F-28 | 462 | 551 | - | - |
| HL-1 | 462 | 475 | - | - |
| HL-2 | 425 | 376 | 49 | 11.5 |
| D-3 | 510 | 472 | 38 | 7.5 |
| D-4 | 175 | 365 | - | - |
| PC-1 | 416 | 392 | 24 | 5.8 |
| PC-2 | 489 | 471 | 18 | 3.7 |

Average $NO_x$ Absorption (ppm) . . . 54

Table 4-22.  AVERAGE NO$_x$ MEASUREMENTS

(PADUCAH TEST SERIES)

|  | Average NO$_x$ (ppm) | Standard Deviation (ppm) |
|---|---|---|
| **Unit No. 9** | | |
| Pilot Plant Entrance | 710.8 | 176.6 |
| Pilot Plant Exit | 672.0 | 173.4 |
| **Unit No. 10** | | |
| Pilot Plant Entrance | 764.0 | 101.8 |
| Pilot Plant Exit | 723.5 | 108.2 |

Table 4-23.  TEST RESULTS OF NO$_x$ DURING THE PADUCAH TEST SERIES

| Test No. | Influent Concentration (ppm) | Effluent Concentration (ppm) | NO$_x$ Absorption (ppm) | Removal (%) |
|---|---|---|---|---|
| P-5 | 437 | 402 | 35 | 4.2 |
| P-7 | 178 | 811 | - | - |
| P-8 | 782 | 741 | 41 | 5.2 |
| P-16 | 645 | 608 | 37 | 5.7 |
| PA-5 | 892 | 846 | 46 | 5.2 |
| PA-6 | 798 | 763 | 35 | 4.4 |
| IP-6 | 836 | 800 | 36 | 4.3 |
| IP-7 | 700 | 845 | - | - |
| IP-8 | 692 | 647 | 45 | 6.5 |

Average NO$_x$ Absorption (ppm). . . . . 39

## Table 4-24.  SULFUR BALANCES FOR SELECTED TESTS AT

## KEY WEST AND PADUCAH

| Test Number | Liquid Stream Sulfur Flow (lbs/min) | | Gas Stream Sulfur Flow (lbs/min) | | Total Liquid & Gas Stream Sulfur Flow (lbs/min) | | Sulfur Accounted For (%) |
|---|---|---|---|---|---|---|---|
| | Feed | Disch | Influent | Effluent | Influent | Effluent | |
| C-20 | 0.0432 | 0.0600 | 0.0486 | 0.0071 | 0.0918 | 0.0671 | 73.1 |
| C-21 | 0.0140 | 0.0200 | 0.0486 | 0.0131 | 0.0626 | 0.0331 | 52.9 |
| C-22 | 0.0288 | 0.0445 | 0.0989 | 0.0431 | 0.1277 | 0.0876 | 68.6 |
| C-23 | 0.0173 | 0.0245 | 0.0988 | 0.0249 | 0.1161 | 0.0494 | 42.5 |
| C-34A | 0.0200 | 0.0242 | 0.0932 | 0.0247 | 0.1132 | 0.0489 | 43.2 |
| F-8 | 0.0080 | 0.0143 | 0.0267 | 0.0072 | 0.0347 | 0.0215 | 62.0 |
| F-18 | 0.0320 | 0.0489 | 0.1027 | 0.0532 | 0.1347 | 0.1021 | 75.8 |
| F-20 | 0.0064 | 0.0104 | 0.1004 | 0.0508 | 0.1068 | 0.0612 | 57.3 |
| F-26 | 0.0033 | 0.0053 | 0.0513 | 0.0128 | 0.0546 | 0.0181 | 33.2 |
| F-42 | 0.0189 | 0.0222 | 0.0912 | 0.0268 | 0.1101 | 0.4900 | 44.5 |
| P-1 | 0.0002 | 0.0055 | 0.0902 | 0.0432 | 0.0904 | 0.0487 | 53.9 |
| P-2 | 0.0004 | 0.0085 | 0.0826 | 0.0379 | 0.0830 | 0.4640 | 55.9 |
| P-3 | 0.0000 | 0.0065 | 0.0822 | 0.0245 | 0.0822 | 0.0310 | 37.7 |
| P-5 | 0.0001 | 0.0067 | 0.1030 | 0.0395 | 0.1031 | 0.0462 | 44.8 |
| P-8 | 0.0005 | 0.0084 | 0.0896 | 0.0558 | 0.0901 | 0.0642 | 71.3 |
| P-13 | 0.0002 | 0.0066 | 0.1146 | 0.0729 | 0.1148 | 0.0789 | 68.7 |
| P-20 | 0.0001 | 0.0074 | 0.0084 | 0.0345 | 0.0885 | 0.0419 | 47.3 |
| P-21 | 0.0001 | 0.0104 | 0.0861 | 0.0323 | 0.0861 | 0.0427 | 49.6 |
| P-22 | 0.0003 | 0.0198 | 0.0877 | 0.0303 | 0.0878 | 0.0413 | 47.0 |
| P-23 | 0.0003 | 0.0082 | 0.0812 | 0.0303 | 0.0813 | 0.0342 | 42.1 |

Key West:

    Average Sulfur Accounted for ....... 55.3%

    Maximum Sulfur Accounted for ....... 75.8%

Paducah:

    Average Sulfur Accounted for ....... 51.8%

    Maximum Sulfur Accounted for ....... 71.3%

Total Average Sulfur Accounted for ...... 53.57%

sulfur values might be attributed to the analytical technique used on the liquid discharge stream. Slurry samples were sometimes allowed to stand up to 24 hours before the total sulfur analysis (as $SO_4^{--}$) was performed.

This time period allowed sulfur to crystallize out of solution as the dihydrate, $CaSO_4 \cdot 2H_2O$. Although slurry samples were thoroughly mixed prior to aliquot removal, the rapid settling that occurred made representative sampling difficult. In addition, it is suspected that the $CaSO_4 \cdot 2H_2O$ may not have been completely digested in the time allotted. Either of these two situations could account for the low sulfur results shown in Table 4-24.

# SECTION 5

## DATA ANALYSIS

### INTRODUCTION AND SUMMARY

Five factorial experiments were conducted with the reactants to determine the effects of the several independent variables. The five factors investigated were: gas flow rate (GF); pressure drop ($\Delta P$); stoichiometric ratio (SR); particle size (PS); and slurry concentration (SC). These experiments are summarized in Table 5-1.

TABLE 5-1. SUMMARY OF FACTORIAL EXPERIMENTS

| | Key West | Key West | Paducah |
|---|---|---|---|
| Type of Design | Half Replicate of a $2^5$ = 16 Runs | Half Replicate of a $2^3$ = 4 runs | Full Replicate of a $2^4$ = 16 runs |
| Reactants Studied | Coral (C) and Fredonia Valley Lime-Stone (FVL) | Dolomite (D) and Hydrated Lime (HL) | Fredonia Valley Limestone (FVL) |
| Factors Studied and Their Levels | GF(scfm)     1450  775<br>$\Delta P$(in.$H_2O$)  12.5  6.5<br>SR(mole/mole) 1:3  1:1<br>PS(mesh)      325  100<br>SC(%)           5    1 | GF(acfm)  2000 1000<br>$\Delta P$         12.0  6.5<br>SR           1:3   1:1<br>PS     Uncontrolled<br>SC          1     1 | GF(scfm)600   400<br>$\Delta P$       12.0 6.0<br>SR         1:2  1:1<br>PS         325  200<br>SC          3    3 |
| Factors found Statistically Significant at 95% level | FG,$\Delta P$,SR )<br>GFSC, PSC) for C<br><br>GF,$\Delta P$,SR    for FVL | GF,$\Delta P$,SR  for D<br><br>$\Delta P$,SR      for HL | GF,$\Delta P$,SR for FVL |

A factorial experiment is designed to test the significance of a number of different operating factors simultaneously. The proper application of the method permits a rapid and inexpensive method for determining the effects of each of the factors over the specified range. The interpretation of the results is difficult, however, and sound engineering judgement must be used in assigning statistical significance to the conclusions. This judgement

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Table 5-2.  KEY WEST TEST PROGRAM EXPERIMENTAL DESIGN

REACTANTS:

        Coral (C)

        Fredonia Valley Limestone (FVL)

| Run No. | Factors | | | | | Responses (% $SO_2$ Removal) | |
|---------|---------|-----------|-----|-----|-----|--------|--------|
|         | GF      | $\Delta P$ | SR  | PS  | SC  | C      | FVL    |
| 1       | −       | −         | −   | +   | −   | 64.6   | 71.1   |
| 2       | +       | −         | −   | −   | −   | 56.5   | 48.3   |
| 3       | −       | +         | −   | −   | −   | 73.1   | 76.6   |
| 4       | +       | +         | −   | +   | −   | 70.6   | 76.4   |
| 5       | −       | −         | +   | −   | −   | 85.3   | 78.9   |
| 6       | +       | −         | +   | +   | −   | 67.6   | 74.4   |
| 7       | −       | +         | +   | +   | −   | 90.1   | 90.4   |
| 8       | +       | +         | +   | −   | −   | 88.8   | 82.6   |
| 9       | −       | −         | −   | −   | +   | 77.5   | 73.7   |
| 10      | +       | −         | −   | +   | +   | 58.2   | 50.0   |
| 11      | −       | +         | −   | +   | +   | 80.5   | 75.0   |
| 12      | +       | +         | −   | −   | +   | 55.6   | 49.4   |
| 13      | −       | −         | +   | +   | +   | 83.3   | 88.5   |
| 14      | +       | −         | +   | −   | +   | 74.7   | 68.7   |
| 15      | −       | +         | +   | −   | +   | 93.3   | 90.5   |
| 16      | +       | +         | +   | +   | +   | 75.0   | 86.0   |

                    Total Response. . . .  1195.2    1180.5

                    Average Response. . .   74.7      73.8

may be based on knowledge of and experience with the physical and chemical processes involved and the methods in which the factors act; comparison of results with other similar experiments; or conducting additional tests of factors whose significance is questionable.

In treatment of the data, classical analysis of the variance techniques are used, details of which may be found in any elementary statistics text. Important assumptions involved in the use of these techniques include:

- o Independence of the tests
- o Normal distribution of the experimental errors
- o Linearity of response (percent $SO_2$ removal) to each of the factors in the range tested.

In general the analysis showed that in these experiments the three factors GF, $\Delta P$ and SR were statistically significant at the 95% confidence level. This means that one can be 95% confident that $SO_2$ removal efficiency is different for the two levels tested for each factor. No conclusion can be reached concerning the effect of levels outside the range tested nor can it be concluded that one factor is more effective than another.

KEY WEST TESTS

The main test series at Key West consisted of half-replicate $2^5$ factorial experiments for each of two reactants, coral and Fredonia Valley limestone (FVL). The factors and levels are listed below:

| Factor | Design Levels | |
| --- | --- | --- |
| | High (+) | Low (−) |
| GF – Gas flow (scfm) | 1450 | 775 |
| $\Delta P$ – Pressure drop (in.$H_2O$) | 12.0 | 6.5 |
| SR – Stoichiometric ratio | 1:3 | 1:1 |
| PS – Particle size (mesh) | 325 | 100 |
| SC – Slurry concentration (%) | 5 | 1 |

Table 5-2 shows the experimental design and the response measured as percent $SO_2$ removal for the main Key West test program.

A half replicate $2^5$ factorial experiment permits determination of all main effects and two-factor interactions. Each main effect is aliased with a four-factor interaction and each two-factor interaction is aliased with a three-factor interaction. If all third order and above interactions are considered small (to be shown in the analysis of the Paducah tests, following), the design permits independent estimates of the main effects and two-factor interactions. However, if all two factor interactions are considered important, there remain no degrees of freedom to estimate the error. Thus, the investigator must estimate the error mean square by the engineering judgement mentioned above or by assuming, a priori, that some specific two factor interactions are negligible.

The means of the response from the two reactants, 74.7% for coral and 73.8% for Fredonia Valley limestone, were tested for significant difference. There was found to be no significant difference at the 99% confidence level. Furthermore, the correlation coefficient between the sixteen pairs of data points was calculated to be 0.89. These facts might indicate that the physical and chemical processes involved were similar for each of the two reactants and that any main effect or interaction that is assigned to experimental error in the one case should be so assigned in the other case. In view of the lack of substantiating information concerning the estimation of the error, an a priori judgement was made that differences in average effect of less than 2% are within the range of experimental error.

Tables 5-3 and 5-4 show the analysis of the variance for the Key West coral and limestone tests respectively. If the calculated effect is below this value in either test, the values are used for the estimate of the error. With this scheme only three main effects and two interactions would remain. An exception to this scheme is made in the main effect of particle size. It has been shown that coral undergoes certain physical changes in the presence of sea water in which the particles are retained in a colloidal suspension, regardless of the original particle size distribution. For this reason, particle size main effect is assigned to the error sum in the case of coral but not in the case of limestone.

## Table 5-3. CORAL REACTANT---ANALYSIS OF THE VARIANCE

## KEY WEST TEST PROGRAM

|  | Total Effects | Average Effects | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|---|
| Total | 1195.2 | 74.7 |  |  |  |
| GF | -101.2 | -12.7 | 640.1 | 640.1 | 37.7 |
| ΔP | 58.8 | 7.4 | 216.1 | 216.1 | 12.7 |
| SR | 122.0 | 15.3 | 930.2 | 930.2 | 54.7 |
| PS | -14.4 | -1.8 | 13.0 | Error |  |
| SC | 2.0 | 0.3 | 0.3 | Error |  |
| GFΔP | 7.2 | 0.9 | 3.2 | Error |  |
| GFSR | 8.4 | 1.1 | 4.4 | Error |  |
| GFPS | 6.0 | 0.8 | 2.3 | Error |  |
| GFSC | -42.0 | -5.3 | 110.3 | 110.3 | 6.5 |
| ΔPSR | 12.8 | 1.6 | 10.2 | Error |  |
| ΔPPS | 25.2 | 3.2 | 39.7 | Error |  |
| ΔPSC | -38.4 | -4.8 | 92.2 | 92.2 | 5.5 |
| SRPS | -36.8 | -4.6 | 84.6 | Error |  |
| SRSC | -12.0 | -1.5 | 9.0 | Error |  |
| PSSC | 7.2 | 0.9 | 3.2 | Error |  |

TOTAL .... 2158.8

Error sum of squares - 169.9

Error mean square     - 17.0

$F_{0.95}$ (1,10) - 4.96

$F_{0.99}$ (1,10) = 10.04

## Table 5-4. FVL REACTANT---ANALYSIS OF THE VARIANCE

## KEY WEST TEST PROGRAM

|  | Total Effects | Average Effects | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|---|
| Total | 1180.5 | 73.8 |  |  |  |
| GF | 108.9 | -13.6 | 741.2 | 741.2 | 21.2 |
| ΔP | 73.3 | 9.2 | 335.8 | 335.8 | 9.6 |
| SR | 139.5 | 17.4 | 1216.3 | 1216.3 | 34.8 |
| PS | 43.1 | 5.4 | 116.1 | 116.1 | 3.3 |
| SC | -16.9 | -2.1 | 17.8 | Error |  |
| GFΔP | 32.7 | 4.1 | 66.8 | Error |  |
| GFSR | 35.7 | 4.5 | 79.7 | Error |  |
| GFPS | 32.5 | 4.1 | 66.0 | Error |  |
| GFSC | -38.3 | -4.8 | 91.7 | 91.7 | 2.6 |
| ΔPSR | 4.7 | 0.6 | 1.4 | Error |  |
| ΔPPS | 14.3 | 1.8 | 12.8 | Error |  |
| ΔPSC | -33.3 | -4.2 | 69.3 | 69.3 | 2.0 |
| SRPS | -5.9 | -0.7 | 2.2 | Error |  |
| SRSC | 31.7 | 4.0 | 62.8 | Error |  |
| PSSC | -8.7 | -1.1 | 4.7 | Error |  |

TOTAL ..... 2884.6

Error sum of squares - 314.2

Error mean square  - 34.9

$F_{0.95}$ (1,9) = 5.12

$F_{0.99}$ (1,9) = 10.60

Some further justification for the 2% cut-off value is provided by tests conducted with limestone in Paducah. In this test series, where aliasing does not occur, all interaction effects are small. A comparison of the average effects for the two Key West and the one Paducah test series shows considerable stability from one test to another.

As can be noted in the case of coral, three main effects and two inter-actions are statistically significant at a confidence level of 95% or greater. In the case of limestone, only the three main effects are significant. This is determined by comparing the F ratio, defined as

$$F = \frac{\text{Factor Mean Square}}{\text{Error Mean Square}}$$

with the significance values in the tables. For instance in Table 5-3 the F ratio for GF is

$$F = \frac{640.1}{17.0} = 37.7$$

which is greater than $F_{0.99} = 10.04$. Therefore, gas flow rate has a statistically significant effect on percent $SO_2$ removal by coral.

Prediction equations have been developed for relating response to the significant factors:

$$Y_C = 74.7 + [-12.7GF + 7.4\Delta P + 15.3SR - 5.3(GF \cdot SC) - 4.8(P \cdot SC)] \quad (5-1)$$

$$Y_{FVL} = 73.8 + [-13.6GF + 9.2\Delta P + 17.4SR] \quad (5-2)$$

where $Y_C$ and $Y_{FVL}$ are percent $SO_2$ removal for coral reactant and limestone reactant, respectively.

$$GF = \frac{\text{gas flow (scfm)} - 1112}{675}$$

$$\Delta P = \frac{\text{pressure drop (H}_2\text{0)} - 9.25}{5.5}$$

$$SR = \frac{\text{stoichiometric ratio} - 2}{2}$$

$$SC = \frac{\text{slurry concentration} - 3}{4}$$

These equations are given in this way to show their deviation. As can be

Seen, the basic equations include the average total response, Table 5-2, and the average effects of each of the significant factors and interactions, Tables 5-3 and 5-4. The constants in the definitions of the variables are the average of the test design levels and the range of test design levels.

There were nineteen additional tests in the coral and limestone series at Key West which were not part of the factorial experiment. These tests provided independent data to examine the accuracy of the prediction equations. Figure 5-1 is a plot of predicted response versus actual response for these nineteen data points.

Figure 5-2 illustrates the response expected from the two significant interactions in the coral reactant series. It appears that high slurry concentration increases the change in response due to changes in gas flow rate and decreases the change in response due to pressure drop changes.

Two additional reactants, dolomite and hydrated lime were tested in half-replicate $2^3$ experimental design programs at Key West. Table 5-5 shows the design criteria and the results of the tests. In this experimental design each main factorial effect is aliased with a two-factor interaction. Further, the second order interaction cannot be estimated nor can the error mean square. A partial analysis of the variance is given in Table 5-6.
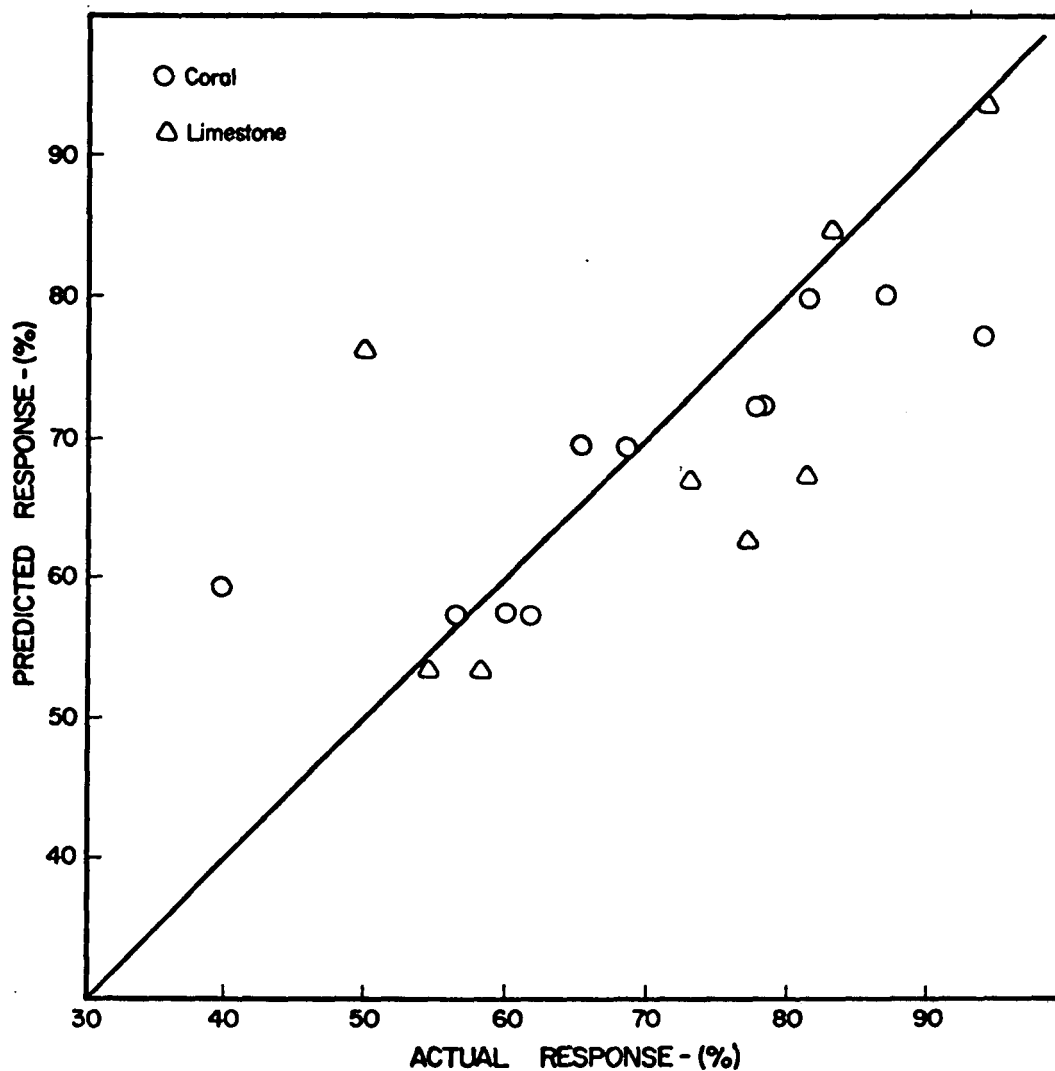
FIG. 5-I. PREDICTED RESPONSE VS. ACTUAL RESPONSE FOR INDEPENDENT DATA FROM THE
MULTIPLE LINEAR REGRESSION FORMULA
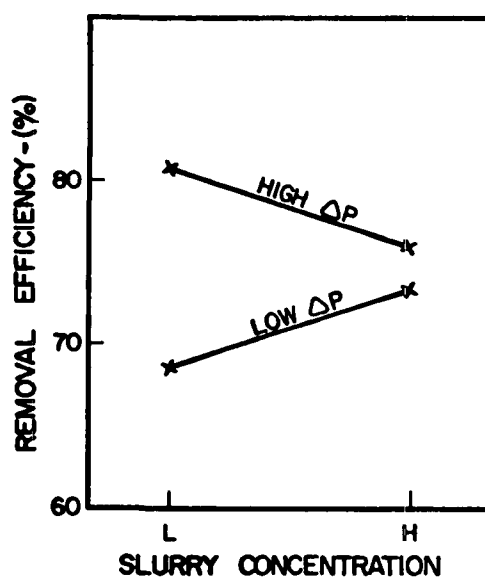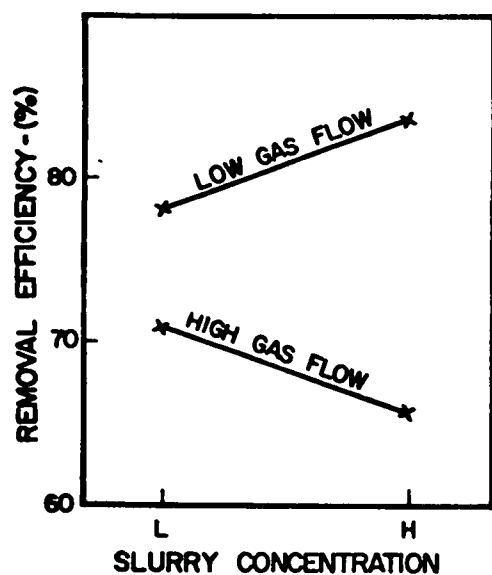
FIG. 5-2. SUMMARY OF SIGNIFICANT INTERACTIONS IN CORAL EXPERIMENTS

**Table 5-5. SECONDARY REACTANT TEST PROGRAM**

**AT KEY WEST TEST SITE**

SECONDARY REACTANTS:

        Dolomite (D)

        Hydrated Lime (HL)

| | | TEST PROGRAM | | Response (% $SO_2$ Removal) | |
|---|---|---|---|---|---|
| Test No. | $\Delta P$ | Stoichiometry | Gas Flow Rate | D | HL |
| 1 | 6.5" | 1:1 | 2000 acfm | 32.6 | 86.4 |
| 2 | 12.0" | 1:1 | 1000 acfm | 51.8 | 94.9 |
| 3 | 6.5" | 1:3 | 1000 acfm | 51.7 | 93.4 |
| 4 | 12.0" | 1:3 | 2000 acfm | 51.2 | 97.5 |

    Slurry concentration - 1% by wt.

    Particle size - no control due to use of commercially available materials.


**Table 5-6. SECONDARY REACTANTS— ANALYSIS OF THE VARIANCE**

**KEY WEST TEST PROGRAM**

| Effect | Dolomite | | | Hydrated Lime | | |
|---|---|---|---|---|---|---|
| | Total Effect | Mean Effect | Mean Square | Total Effect | Mean Effect | Mean Square |
| Total | 187.3 | 46.8 | | 372.2 | 93.0 | |
| Gas Flow (GF) | -19.7 | -9.8 | 97.0 | -4.4 | -2.2 | 4.8 |
| Pressure Drop ($\Delta P$) | 18.7 | 9.4 | 87.4 | 12.6 | 6.3 | 39.7 |
| Stoichiometric Ratio (SR) | 18.5 | 9.2 | 85.6 | 9.6 | 4.8 | 23.0 |
| Total | | | 270.0 | | | 67.5 |

Prediction equations for the secondary reactants are:

$$Y_D = 46.8 + [-9.8GF + 9.4\Delta P + 9.2SR] \qquad (5-3)$$
and

$$Y_{HL} = 93.0 + [-2.2GF + 6.3\Delta P + 4.8SR] \qquad (5-4)$$

where $Y_D$ and $Y_{HL}$ are percent $SO_2$ removal for dolomite reactant and hydrated lime reactant respectively.

$$GF = \frac{gas\ flow\ (acfm)\ -\ 1500}{1000}$$

$$\Delta P = \frac{pressure\ drop\ (in.H_2O)\ -\ 9.25}{5.5}$$

$$SR = \frac{stoichiometric\ ratio\ -\ 2}{2}$$

An analysis of the variance in response to the two different reactants showed a significant difference of the means at the 99.5% confidence level.

PADUCAH TEST PROGRAM

A full replicate $2^4$ factorial test program was conducted on the No. 9 unit at Paducah, using FVL as a reactant. The factors and levels are listed below. Slurry concentration was constant at 3 in this test series.

| Factor | Design Level | |
|---|---|---|
| | High (+) | Low (-) |
| GF – Gas Flow (scfm) | 600 | 400 |
| $\Delta P$ – Pressure drop (in.H_2O) | 12.0 | 6.0 |
| SR – Stoichiometric ratio | 1:2 | 1:1 |
| PS – Particle size (mesh) | 325 | 200 |

Table 5-7 shows the experimental design and the response measured as percent $SO_2$ removal. The full replicate design permits determination of all main effects and interactions. With the criteria established earlier, i.e. that effect values less than 2% in any test are considered error, all two-factor interactions would be used to estimate the error mean square. Further, if all two-factor interactions are so considered, certainly higher

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Table 5-7. PADUCAH TEST PROGRAM EXPERIMENTAL DESIGN

REACTANT: Fredonia Valley Limestone

SLURRY CONCENTRATION: 3% wt.

| Run No. | Factors | | | | Response (% $SO_2$ Removal) |
|---|---|---|---|---|---|
| | GF | ΔP | SR | PS | |
| 1 | − | − | − | + | 52.0 |
| 2 | − | − | + | + | 54.0 |
| 3 | − | + | − | + | 70.2 |
| 4 | − | + | + | + | 83.7 |
| 5 | + | + | − | + | 61.7 |
| 6 | + | + | + | + | 67.3 |
| 7 | + | − | − | + | 34.7 |
| 8 | + | − | + | + | 37.8 |
| 9 | − | − | + | − | 53.2 |
| 10 | − | − | − | − | 46.3 |
| 11 | − | + | + | − | 73.9 |
| 12 | − | + | − | − | 70.0 |
| 13 | + | − | − | − | 36.3 |
| 14 | + | − | + | − | 42.1 |
| 15 | + | + | − | − | 62.6 |
| 16 | + | + | + | − | 67.7 |

Total Response    913.5

Average Response   57.1

order interactions should be as well. Table 5-8 shows the analysis of the variance for the Paducah limestone test program. It is seen that the three main effects, gas flow, pressure drop, and stoichiometric ratio, are significant at the 95% confidence level. A prediction equation for this test series is given below:

$$Y_p = 57.1 + [-11.6GF + 25.1\Delta P + 5.7SR]$$

where $Y_p$ is percent $SO_2$ removal.

$$GF = \frac{\text{gas flow rate (scfm)} - 500}{200}$$

$$\Delta P = \frac{\text{pressure drop (in.H}_2\text{O)} - 9}{6}$$

$$SR = \text{stoichiometric ratio} - 1.5$$

No independent data are available for testing the accuracy of the prediction equation.


LIQUID/GAS RATIO

Some evidence has been seen that only three factors are significant in determining the $SO_2$ removal efficiency. Two of these factors, gas flow and pressure drop (for a given size scrubber tube), uniquely determine the liquid/gas ratio. Figure 5-3 is a plot of absorption efficiency versus liquid/gas ratio for five of the reactants. The efficiencies for high and low levels of stoichiometric ratios are shown as envelopes around the mean response for each reactant. As can be noted, the efficiency increases rapidly with liquid/gas ratio up to about 140 gal/Mcf. After that point, little additional increase is achieved. Furthermore, it would appear that increased efficiency is gained by increased reactivity of the slurry above that from increased stoichiometric ratio.

The three Paducah salt water simulation test points lie on the Key West Limestone curve indicating that the difference in this curve and the Paducah curve results from the different media (salt water and river water) rather than the different size tubes.

Table 5- 8.   FVL REACTANT - ANALYSIS OF THE VARIANCE
PADUCAH TEST PROGRAM

|          | Total Effects | Average Effects | Sum of Square | Mean Square | F Ratio |
|----------|--------------:|----------------:|--------------:|------------:|--------:|
| Total    | 913.5         | 57.1            |               |             |         |
| GF       | -93.1         | -11.6           | 541.7         | 541.7       | 62.3    |
| $\Delta$P | 200.7        | 25.1            | 2517.5        | 2517.5      | 289.4   |
| SR       | 45.9          | 5.7             | 131.7         | 131.7       | 15.1    |
| PS       | 9.3           | 1.2             | 5.4           | Error       |         |
| GF$\Delta$P | 16.1       | 2.0             | 16.2          | Error       |         |
| GFSR     | -6.7          | -0.8            | 2.8           | Error       |         |
| GFPS     | -23.7         | -3.0            | 35.1          | Error       |         |
| $\Delta$PSR | 10.3       | 1.3             | 6.6           | Error       |         |
| $\Delta$PPS | 9.1        | 1.0             | 4.1           | Error       |         |
| SRPS     | 2.5           | 0.3             | 0.4           | Error       |         |
| GF$\Delta$PSR | -6.7     | -0.8            | 2.8           | Error       |         |
| GF$\Delta$PPS | 1.1      | 0.1             | 0.1           | Error       |         |
| GFSRPS   | -6.9          | 0.9             | 3.0           | Error       |         |
| $\Delta$PSRPS | 17.7     | 2.2             | 19.6          | Error       |         |
| GF$\Delta$PSRPS | -11.3  | -1.4            | 8.0           | Error       |         |

TOTAL ...........3295.0

Error sum of squares - 104.1

Error mean square    -   8.7

$F_{0.95}$ (1,12) = 4.75

$F_{0.99}$ (1,12) = 9.33
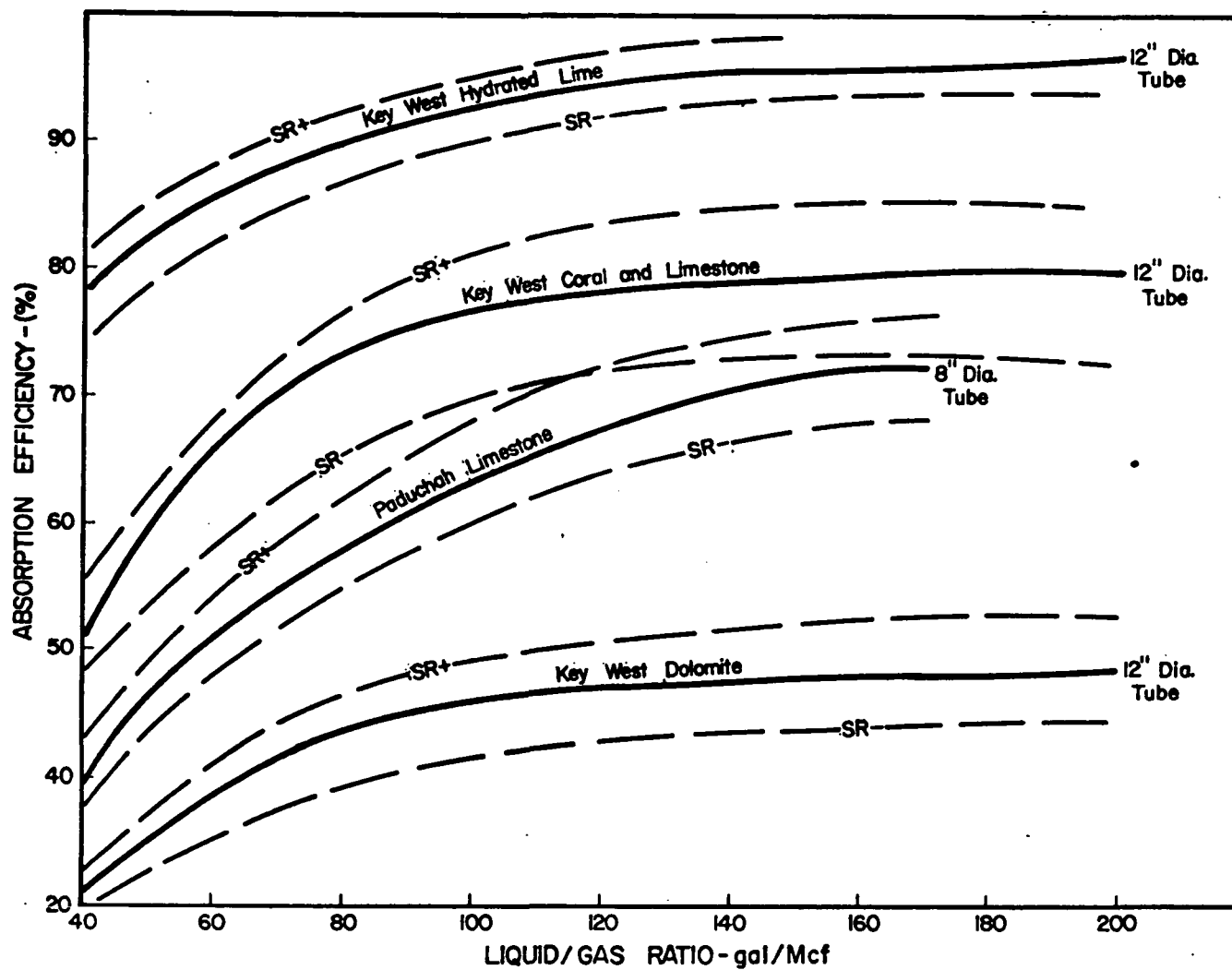
FIG. 5–3. ABSORPTION EFFICIENCY AS A FUNCTION OF LIQUID/GAS RATIO

Further, at a given liquid/gas ratio, residence time in the 8 inch tube is longer than in the 12 inch tube (Figures 4-1 and 4-2).

# SECTION 6

## CONCLUSIONS

The following conclusions are based upon field observations and analysis of the data.

### PILOT PLANT EQUIPMENT

(1) Locating the scrubber fan at the outlet of the system caused solids build up on the blades which ultimately resulted in fan failure due to imbalance.

(2) Corrosion and pitting were experienced on the interior walls of the 316-SS scrubber body and the non-PVC piping and valving. This corrosion and pitting appeared to be more severe, both in degree and rate, when using salt water. However, this corrosion and pitting did not result in failure of the scrubber body during the ten months of pilot plant operation.

(3) Condensation was experienced in the non-insulated dry collector and ductwork.

(4) The long hoses used to transport scrubber waste discharge frequently clogged due to low flow rates.

(5) The pilot plant spray nozzles, intended for precontacting the inlet flue gas, were rendered useless due to clogging and corrosion before an evaluation could be made.

### SAMPLING AND ANALYSIS

(1) An "ice-trap" condenser immediately following the $SO_2$ sampling probe operated in a satisfactory manner with the Dynasciences SS-330 monitor.

(2) The Dynasciences $SO_2$ monitor performed satisfactorily.

(3) The use of one $SO_2$ monitor to measure both inlet and outlet flue gas proved cumbersome and reduced the accuracy of the calculated scrubber efficiency.

(4) The phenoldisulfonic acid analysis for determining concentrations of $NO_x$ proved limited.

(5) The Annubar velocity measuring device performed very well, producing accurate readings in a minimal length of time.

(6) The use of a non-heated probe and filter in the particulate sampling train caused condensation and ultimate clogging of the filter.

## $SO_2$ ABSORPTION EFFICIENCY

(1) Absorption efficiency increased significantly with increased pressure drop across the scrubber.

(2) Absorption efficiency increased significantly with decreased gas flow rate through the tube.

(3) Absorption efficiency increased significantly with increased stoichiometric ratio.

(4) There was no significant change in absorption efficiency resulting from a change in reactant particle size.

(5) There was no significant change in absorption efficiency resulting from a change in slurry concentration.

(6) The analysis of the factorial experiments showed no significant interaction between or among the five factors listed above.

(7) Absorption efficiency is an increasing function of liquid to gas ratio.

(8) For a given tube size and gas flow rate, liquid to gas ratio increased with increasing pressure drop.

(9) For a given tube size and pressure drop, liquid to gas ratio was a function of gas flow rate with maximum value near 600 scfm.

(10) For a given pressure drop and gas flow rate, liquid to gas ratio increased with tube size.

(11)  Absorption efficiency was different with different reactants with
      decreasing efficiency as follows:

        Hydrated Lime
        Precipitated Calcium Carbonate
        Limestone
        Coral
        Spent Coral
        Dolomite

(12)  In the tests conducted, residence time within the tube had no
      apparent effect on absorption efficiency.

(13)  Addition of the catalyst ($FeCl_3$) and/or the inhibitor (hydroquinone) to
      the slurry produced no significant effect on absorption efficiency.

## $NO_x$ AND PARTICULATE REMOVAL

(1)  $NO_x$ removal in the Dustraxtor scrubber utilizing limestone type
     reactants was negligible.

(2)  Particulate removal by the total pilot plant system (dry collector
     and Dustraxtor) was excellent though evidence of re-entrainment
     of slurry solids was noted.

## SCALE FORMATION

(1)  Except during the injection tests, all scale formation that threatened
     the operation of the pilot plant was eliminated by the installation of
     an annular fresh water spray ring around the lower few inches of the
     Dustraxtor tube.

## FULL SCALE SYSTEM

As indicated by results of the pilot test program on a single-tube
open-loop Dustraxtor, scale-up to a full size unit (capable of handling
50,000 to 60,000 scfm) should not present any problems other than those
already encountered and discussed on the pilot scale level.  However, to
handle larger quantities of boiler stack gases, the designer should
consider the potential unequal gas distribution in the scrubber as the

number of tubes is increased.  One solution might be to investigate the possibility of using fewer tubes of larger diameter (e.g., 16 or 18 inch) to increase scrubber capacity.

# APPENDIX A

## DETAILS OF ANALYSIS TECHNIQUES

### $SO_2$ APPARATUS AND PROCEDURE

Sampling of flue gas for $SO_2$ determination was accomplished by passing the sample gas through a Dynasciences Model SS-330 $SO_2$ monitor, the output of which was continuously recorded on a strip chart recorder. Once the instrumentation was "debugged", operation of the equipment was simple and required little operator time. Based upon wet chemical analyses, it was found to be very accurate.

The complete sampling train is shown in Figure A-1. The sampling probe used at all three sample locations consisted of stainless steel tubing 6 inches long x 1/4 inch O.D. A 500 ml flask was placed after the sampling probe to trap any moisture which may have condensed in the sampling tube. The dry trap was completely immersed in an ice bath to cool the sample gas to approximately 32°F. A single acting diaphragm pump drew the gas sample through approximately 15 feet of Tygon tubing. A tee located in the sample line was fitted with a 1/4 inch needle valve. Excess gas, pumped by the diaphragm pump, which did not flow through the monitor was vented.

The Dynasciences $SO_2$ monitor is an electrochemical gas analyzer. The sample gas is passed over a selective permeable membrane, where the $SO_2$ is absorbed on a sensing electrode to form activated species capable of undergoing electro-oxidation. The resulting current is directly proportional to the partial pressure of $SO_2$ in the gas mixture. The current is amplified and the output of the amplifier recorded.

The sampling procedure is as follows:
1. Connect the sampling train to zero gas (nitrogen) and zero the $SO_2$ monitor.
2. Connect the sampling train to the calibration gas (guaranteed analysis gas – sulfur dioxide and nitrogen) and calibrate the $SO_2$ monitor.
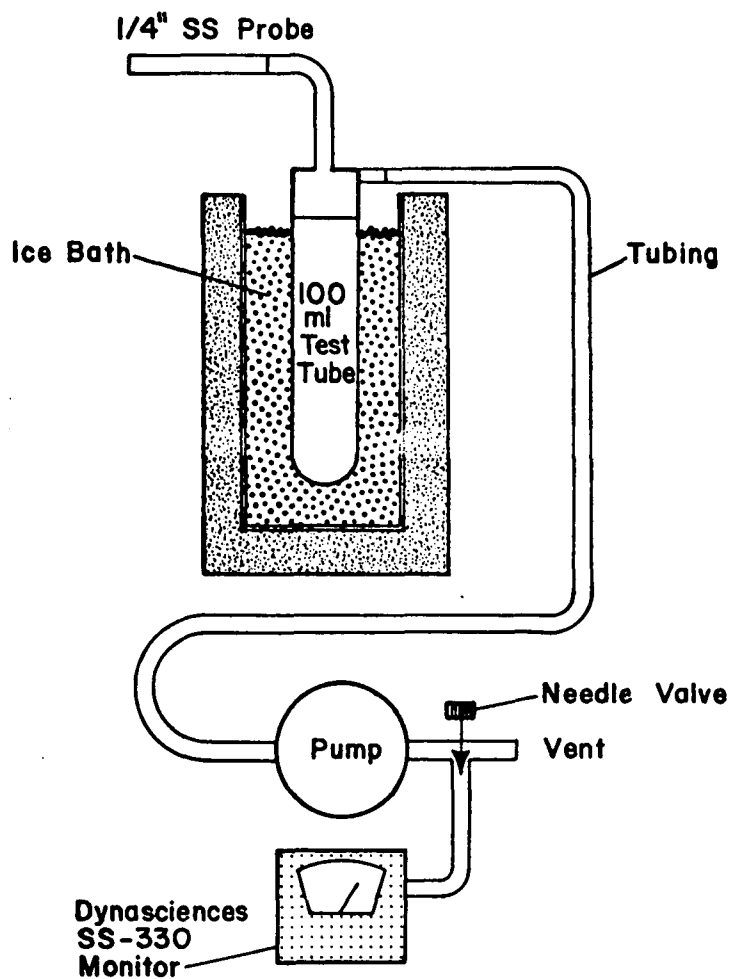
FIG. A-I. SO₂ SAMPLING APPARATUS

3. Connect the sampling train to the pilot plant making sure that all joints are gas-tight. Make sure the appropriate sampling line is open and connected with the sampling train.

4. Turn on the pump and adjust the gas flow rate through the $SO_2$ monitor (approximately 1 scfm).

## DUST LOADING APPARATUS AND PROCEDURE

The particulate sampling train is shown in Figure A-2. The probe, consisting of 1/4 inch stainless steel tubing, was connected to the first Greenberg-Smith impinger by a 4 foot length of Tygon tubing. Impingers No. 1 and No. 2 were each filled with 200 ml of distilled water. Impinger No. 3 was dry and used as a water trap.

In operation, the gas velocity through the duct was calculated before the start of the particulate sampling by means of the Annubar flow measuring element. The apparatus was assembled and the probe inserted into the center of the duct, open end upstream. Initial dry gas meter readings were recorded and the vacuum pump started. The flow rate through the dry gas meter was determined with a stop watch by measuring the time required for 0.1 $ft^3$ of gas to be pulled through the meter. The flow was then regulated by means of a gas control valve until the flow rate through the probe equalled the flow rate through the duct and an isokinetic condition existed. Between 10 and 20 standard cubic feet of gas was drawn through the train. The temperature and pressure inside the dry gas meter were recorded from the attached thermometer and vacuum gauge; the vacuum pump was shut off and the final dry gas meter reading was recorded.

## NITROGEN OXIDE APPARATUS AND PROCEDURE

### Principle

Stack gas samples are collected in evacuated flasks containing an absorbent consisting of hydrogen perioxide in dilute sulfuric acid. The nitric acid formed by the oxidation and absorption of nitrogen oxides is used to nitrate phenoldisulfonic acid which, when

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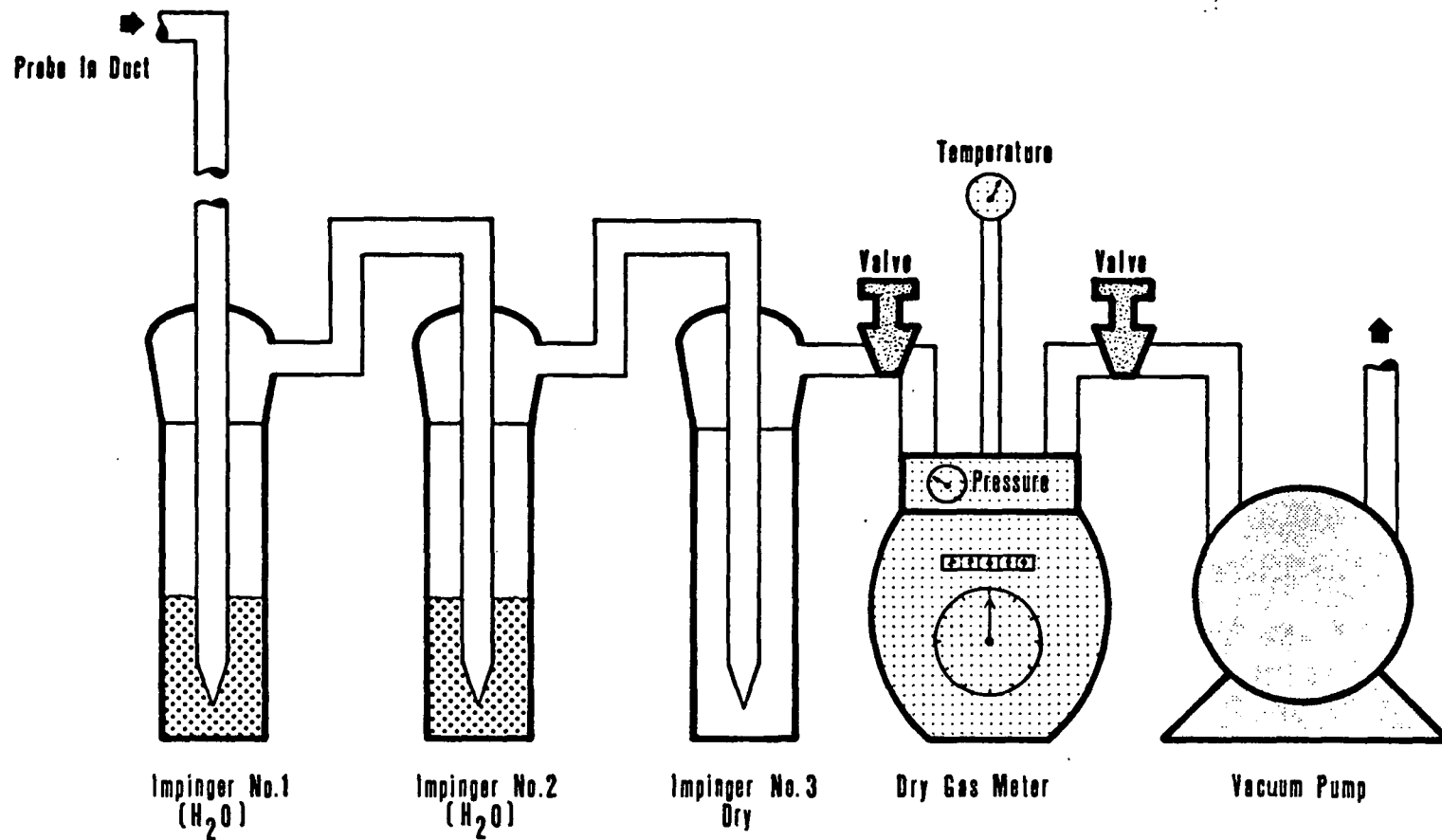
FIG. A-2. PARTICULATE SAMPLING TRAIN

reacted with ammonium hydroxide, forms a yellow compound (5-nitro, 6 hydroxy, 1, 3-benzenedisulfonic acid, triammonium salt). The intensity of the color produced is proportional to the concentration of nitrogen oxides in the sample and is measured spectrophotometrically at 420 m$\mu$.

## Interference

Inorganic nitrates, nitrites, or organic bearing compounds easily oxidized to nitrates and interfere with this method. Reducing agents, such as $SO_2$, when present in high concentrations, may interfere by reacting with the hydrogen peroxide in the absorbing reagent to leave an insufficient amount for reaction with the nitrogen oxides. Halides tend to interfere, if present, and give lower results.

## Reagents

Hydrogen peroxide solution - Dilute 10 ml of 30 percent $H_2O_2$ to 100 ml in a 100 ml volumetric flask with water.

Sulfuric acid (0.1 N) - Dilute 2.8 ml of concentrated $H_2SO_4$ to 1 liter with water.

Absorbing reagent - Dilute 6 ml of 3 percent $H_2O_2$ to 1 liter with 0.1 N $H_2SO_4$. This solution is stable and may be used for at least 30 days. Analyses in this laboratory have shown that the percent $H_2O_2$ in the absorbing reagent remained constant over a 49 day period.

Sodium hydroxide (1 N) - Dissolve 40 gm of NaOH pellets in water and dilute to 1 liter.

Ammonium hydroxide (concentrated)

Sulfuric acid (fuming)

Phenoldisulfonic acid solution - Dissolve 25 grams of pure
   white phenol in 150 ml of concentrated $H_2SO_4$ on a steam bath.
   Cool and add 75 ml fuming sulfuric acid. Heat to $100^{\circ}C$ for 2
   hours. Store in a dark stoppered reagent bottle.

Potassium nitrate solution (standard) - Dissolve 0.5495 grams
   of $KNO_3$ in 1 liter of water in a volumetric flask. Dilute
   100 ml of this solution to 1 liter in a volumetric flask.
   One ml of the final solution is equivalent to 0.025 mg $NO_2$.

## Collection of Samples

Emission sources containing oxides of nitrogen are sampled by a grab
sampling technique using an evacuated 250 ml flask.

The following procedure is used for the collection of samples: Add
25 ml of absorbing solution to the sample flask. Evacuate the flask
to the vapor pressure of the absorbing solution (approximately 20 mm
Hg). Disconnect the vacuum pump line and accurately measure the
vacuum in the flask. Connect the flask to the sample line and allow
the flask to fill with a sample of stack gas until there is very little
or no vacuum left. Measure precisely the final vacuum in the flask
and record the flask temperature. Shake the flask for 15 minutes and
allow to stand overnight to ensure complete reaction and absorption
of the nitrogen oxides.

## Analysis

Transfer the contents of the collection flask to a 250 ml beaker.
Wash the flask three times with 10 ml of water and add to the beaker.
For a blank, add 25 ml of absorbing solution and 30 ml of water to a
250 ml beaker. Proceed as follows for both the sample and blank:

Add 1 N NaOH dropwise to the beaker until the solution is alkaline to
litmus paper. Evaporate to dryness on a steam bath and allow to cool.
Add 2 ml of phenoldisulfonic acid solution to the residue and triturate
thoroughly with a glass stirring rod. Make sure all the residue comes in

contact with the solution. Add 1 ml $H_2O$ and 4 drops of concentrated $H_2SO_4$. Heat the solution on the steam bath for 3 minutes with occasional stirring.

Allow the solution to cool, add 20 ml $H_2O$, mix well, and add 10 ml of concentrated $NH_4OH$, dropwise, with constant stirring. Transfer the solution to a 50 ml volumetric flask. Wash the beaker three times with 5 ml portions of water. Dilute to 50 ml and mix thoroughly. Transfer a portion of the solution to a centrifuge tube and centrifuge for several minutes. If no centrifuge is available, filter the solution.

Determine the absorbency of each sample at 420 mμ. If the absorbency is outside the range of the calibration curve (e.g., absorbency >0.6), make a suitable dilution of the sample and blank and determine the absorbency. Obtain the number of milligrams of $NO_2$ present in the sample from a previously prepared calibration curve, where absorbency was plotted versus concentration.

## Calculations

Calculate the concentration of oxides of nitrogen as $NO_2$ in parts per million by volume as follows:

$$\text{ppm } NO_2 = \frac{(5.24 \times 10^2)(C)}{V_S}$$

where  $C$  = concentration of $NO_2$, mg

$V_S$ = gas sample volume at 70°F and 29.92 in. Hg, liters

Calculate the volume of gas sampled at standard conditions of 70°F, 29.92 in. Hg.

$$\text{Volume of gas sampled} = \frac{V_f(P_f - P_i) \times 530°R}{T_f \times 29.92 \text{ in. Hg}}$$

where  $V_f$ = flask volume, liters

$P_f$ = final flask pressure, in. Hg

$P_i$ = initial flask pressure, in. Hg

$T_f$ = flask temperature, °R

## CALCIUM--EDTA TITRIMETRIC METHOD

### Principle

When EDTA (ethylenediamine tetraacetic acid or its salts) is added to
water containing both calcium and magnesium, it combines first with the
calcium that is present.  Calcium can be determined directly using EDTA
when the pH is made sufficiently high so that the magnesium is largely
precipitated as the hydroxide and an indicator is used which combines
with the calcium only.  Several indicators are available that will give
a color change at the point where all of the calcium has been complexed
by the EDTA at a pH of 12-13.

### Interference

Under conditions of this test, the following concentrations of ions
cause no interference with the calcium hardness determination: copper,
2 mg/l; ferrous iron, 20 mg/l; ferric iron, 20 mg/l; manganese, 10 mg/l;
zinc, 5 mg/l; lead, 5 mg/l; aluminum, 5 mg/l; tin, 5 mg/l.  Ortho-
phosphate will precipitate calcium at the pH of the test.  Strontium
and barium interfere with the calcium determination and alkalinity
in excess of 30 mg/l may cause an indistinct endpoint with hard waters.

### Reagents

Sodium hydroxide, 1 N - Dissolve 40 g NaOH and dilute to 1 liter
with distilled water.

Murexide (ammonium purpurate) was prepared by mixing it with NaCl.

a.  Analytical reagent grade disodium ethylenediamine tetraacetate
dihydrate, also called (ethylenedinitrilo) tetraacetic acid disodium
salt (EDTA), $Na_2H_2C_{10}H_{12}O_8N_2 \cdot 2H_2O$, is commercially available.  Weigh
3.723 g of the dry reagent, dissolve in distilled water, and dilute
to 1,000 ml.  Check the titer by standardizing against standard calcium
solution.

b. The technical grade of the disodium salt of EDTA dihydrate may also be used if the titrant is allowed to stand for several days and is then filtered. Dissolve 4.0 g of such material in 800 ml distilled water. Standardize against standard calcium solution. Adjust the titrant so that 1.00 ml = 1.00 mg $CaCO_3$.

Because the titrant extracts hardness-producing cations from soft glass containers, store preferably in polyethylene and secondarily in Pyrex bottles. Compensate for gradual deterioration by periodic restandardization and a suitable correction factor.

## Procedure

Because of the high pH used in this procedure, the titration should be performed immediately after the addition of the alkali.

Use 1 ml of sample diluted to 50 ml with water.

Add 2.0 ml NaOH solution, or a volume sufficient to produce a pH of 12-13. Stir. Add 0.1-0.2 g of the indicator mixture selected (or 1-2 drops if a solution is used). Add EDTA titrant slowly with continuous stirring to the proper endpoint. When using murexide, the endpoint may be checked by adding 1 or 2 drops of titrant in excess to make certain that no further color change occurs.

Calculation: 1 ml EDTA = 0.4008 mg $Ca^{++}$

$Ca^{++}$ mg/l or ppm = Vol. EDTA x 0.4008 x 1000

MAGNESIUM--EDTA TITRIMETRIC METHOD

## Principle

EDTA and its soidum salts form a chelated soluble complex when added to a solution of certain metal cations. If a small amount of a dye such as Eriochrome Black T is added to an aqueous solution containing calcium and magnesium ions at a pH of 10.0 $\pm$ 0.1, the solution will become wine red.

If EDTA is then added as a titrant, the calcium and magnesium will be complexed. After sufficient EDTA has been added to complex all the magnesium and calcium, the solution will turn from wine red to blue. This is the endpoint of the titration. Magnesium ion must be present to yield a satisfactory endpoint in the titration. A small amount of complexometrically neutral magnesium salt of EDTA is therefore added to the buffer, a step which automatically introduces sufficient magnesium and at the same time obviates a blank correction.

The sharpness of the endpoint increases with increasing pH. The pH, however, cannot be increased indefinitely because of the danger of precipitating $CaCO_3$ or $Mg(OH)_2$, and because the dye changes color at high pH values. The pH value of $10.0 \pm 0.1$ recommended in this procedure is a satisfactory compromise. A limit of 5 minutes is set for the duration of the titration in order to minimize the tendency toward $CaCO_3$ precipitation.

## Interference

Some metal ions interfere with this procedure by causing fading or indistinct endpoints. This interference is reduced by the addition of certain inhibitors to the water sample prior to titration with EDTA.

Suspended or colloidal organic matter in the sample may also interfere with the endpoint but may be overcome by evaporating the aliquot to dryness on a steam bath, followed by heating in a muffle furnace at 600°C until the organic matter is completely oxidized. Dissolve the residue in 20 ml 1 N HCl, neutralize to pH 7 with 1 N NaOH, and make up to 50 ml with distilled water; cool to room temperature and continue according to the general procedure.

## Titration Precautions

Titrations are best conducted at or near normal room temperatures. The color change becomes impractically slow as the sample approaches freezing temperature. Indicator decomposition presents a problem in hot water.

The. pH specified in the recommended procedure may result in an environment conducive to $CaCO_3$ precipitation. Although the titrant can slowly redissolve such precipitates, a drifting endpoint will often yield low results. A time limit of 5 minutes for the overall procedure minimizes the tendency for $CaCO_3$ to precipitate. The following three methods also combat precipitation loss:

a. The samples can be diluted with distilled water to reduce the $CaCO_3$ concentration. The simple expedient of diluting a 25 ml aliquot to 50 ml has been incorporated in the recommended procedure. If precipitation occurs at this dilution, modification b or c can be followed. Reliance upon too small an aliquot contributes a systematic error originating from the buret-reading error.

b. If the approximate hardness of a sample is known or is ascertained by a preliminary titration, 90 per cent or more of the titrant can be added to the sample before the pH is adjusted with the buffer.

c. The sample can be acidified and stirred for 2 minutes to expel $CO_2$ before pH adjustment with the buffer. A prior alkalinity determination can indicate the amount of acid to be added to the sample for this purpose.

## Reagents

Buffer solution - Dissolve 1.179 g disodium salt of EDTA dihydrate and 0.644 g $MgCl_2 \cdot 6H_2O$ in 50 ml distilled water. Add this solution to 16.9 g $NH_4Cl$ and 143 ml conc. $NH_4OH$ with mixing and dilute to 250 ml with distilled water.

Eriochrome Black T is mixed with NaCl and used as an indicator.

Standard EDTA titrant, 0.01M. Analytical reagent grade disodium ethylenediamine tetraacetate dihydrate, also called (ethylenedinitrilo) tetraacetic acid disodium salt (EDTA), $Na_2H_2C_{10}H_{12}O_8H_2 \cdot 2H_2O$, is commercially available. Weigh 3.723 g of the dry reagent, dissolve in distilled water, and dilute to 1,000 ml. Check the titer by standardizing against standard calcium solution.

## Procedure

The aliquot of sample taken for the titration should require less than 15 ml of EDTA titrant.  The duration of titration should not exceed 5 minutes measured from the time of the buffer addition.

Dilute 1 ml of the sample to 50 ml with distilled water.  Add 1-2 ml of buffer solution.  Add an appropriate amount of dry-powder indicator. Add EDTA to the endpoint.

## Calculation

1 ml EDTA = 0.2431 mg $Mg^{++}$ (The calcium concentration, determination by the EDTA method, is required for this calculation since the volume of EDTA used in the above titration is consumed by both $Ca^{++}$ and $Mg^{++}$ ions.)

Vol. EDTA $Mg^{++}$ = Total EDTA Vol. - Vol. EDTA $Ca^{++}$ (from prior $Ca^{++}$ titration)

mg $Mg^{++}$/1 = Vol. EDTA $Mg^{++}$ x 0.2431 x 1000

CHLORIDE--ARGENTOMETRIC METHOD

## Principle

In a neutral or slighly alkaline solution, potassium chromate can be used to indicate the endpoint of the silver nitrate titration of chloride. Silver chloride is quantitatively precipitated before red silver chromate is formed.

## Interference

Substances in amounts normally found in potable waters will not interfere. Bromide, iodide, and cyanide register as equivalent chloride concentrations. Sulfide, thiosulfate, and sulfite ions interfere.  However, sulfite can be removed by treatment with hydrogen peroxide in a neutral solution, while sulfite and thiosulfate can be removed by treatment with hydrogen peroxide in alkaline solution.  Orthophosphate in excess of 25 mg/1

interferes by precipitation as silver phosphate.  Iron in excess of
10 mg/l will interfere by masking the endpoint.

## Reagents

Chloride-free water - If necessary, remove any chloride
impurity from distilled water by redistillation from
an all-pyrex apparatus or passage through a mixed bed
of ion-exchange resins.

Potassium chromate indicator solution - Dissolve 50 g
$K_2CrO_4$ in a little distilled water.  Add silver nitrate
solution until a definite red precipitate is formed.
Allow to stand 12 hrs , filter, and dilute filtrate
to 1 liter with distilled water.

Standard silver nitrate titrant, 0.0141 N - Dissolve 2.396 g
$AgNO_3$ in distilled water and dilute to 1,000 ml.  Stan-
dardize against 0.0141 N NaCl.  Store in a brown bottle.
Standard silver nitrate solution, exactly 0.0141 N, is
equivalent to 0.500 mg Cl per 1.00 ml.

## NITRITE

### Principle

Diazotized sulfanilic acid, formed by the reaction between sulfanilic
acid and $NO_2$, forms a reddish-purple azo dye by coupling with napthy-
lamine hydrochloride at pH 2 to 2.5.  The nitrite concentration is
determined by spectrophotometrically measuring this dye at 520 m .

### Interference

This method is not interfered with by relatively large amounts, up to
1,000 times, of the alkaline earths, zinc, nickel, arsenate, benzoate,
borate, bromide, chloride, fluoride, iodate, molybdate, nitrate, phosphate,

sulfate, and thiocyanate. Numerous heavy metals such as gold, lead, bismuth, iron, or mercury interfere by precipitation and others because of colored salts. Aliphatic amines react with nitrites to liberate gaseous nitrogen. Ammonia does not interfere in the small concentrations usually encountered. Strong reducing or oxidizing agents should be absent.

## Reagents

Sulfanilic acid solution - Dissolve 0.60 g sulfanilic acid
in 70 ml hot distilled water, cool, add 20 ml conc. HCl,
dilute to 100 ml with distilled water, and mix thoroughly.

Naphthylamine hydrochloride solution - Dissolve 0.60 g 1-
naphthylamine hydrochloride and 1 ml conc. HCl in
distilled water and dilute to 100 ml.

Sodium acetate solution, 2M - Dissolve 16.4 g $NaC_2H_3O_2$ or
27.2 g $NaC_2H_3O_2 \cdot 3H_2O$ in distilled water and dilute
to 100 ml. Filter if the solution is not clear.

Stock sodium nitrite solution - Dissolve 0.492 g $NaNO_2$ in
1,000 ml nitrite-free distilled water.

Standard sodium nitrite solution - Dilute 100.0 ml stock
sodium nitrite solution to 1,000 ml; then dilute 50.0
ml of this solution to 1,000 ml with sterilized nitrite-
free distilled water, add 1 ml chloroform, and preserve
in a sterilized bottle; 1.0 ml = 0.5 µg [N] or 1.6 µg
$NO_2^-$.

Manganese sulfate solution - Dissolve 480 g $MnSO_4 \cdot 4 H_2O$ or
400 g $MnSO_4 \cdot 2 H_2O$ or 364 g $MnSO_4 \cdot H_2O$ in distilled water,
filter, and dilute to 1 liter.

Potassium permanganate solution - Dissolve 0.4 g $KMnO_4$ in 1
liter distilled water.

Ammonium oxalate solution - Dissolve 0.9 g $(NH_4)_2C_2O_4 \cdot H_2O$
in 1 liter distilled water.

Nitrite-free water - Add 1 ml conc. $H_2SO_4$ and 0.2 ml man-
ganous sulfate solution to 1 liter distilled water and
make pink with 1 to 3 ml potassium permanganate solution.
After 15 minutes decolorize with ammonium oxalate solution.

## Procedure

Using appropriate dilutions of standard sodium nitrite solution,
prepare a curve for various $NO_2^-$ concentrations ranging from 0.05 to
1.4 mg $NO_2^-/l$ and plot against absorption at 320 m on a spectrophotometer
using a light path of 2 cm.

Place a 10 ml sample in the tube. Measure 1.0 ml sulfanilic acid
solution into the diluted sample, mix, and allow to stand at least 3
minutes and not more than 10 minutes for diazotization. The pH of
this solution should be about 1.4

Add 1.0 ml napthylamine hydrochloride solution and 1 ml sodium acetate
solution. This should buffer the system to a pH of 2.5. Dilute to
50 ml and mix well. After 10 minutes, but before 20 minutes, measure
the intensity of the reddish-purple color in a spectrophotometer, a
filter photometer, or by comparison in Nessler tubes.

## Calculation

Read $NO_2^-$ mg/l directly from the calibration curve.

NITRATE--BRUCINE METHOD

## Principle

The reaction between nitrate and brucine yields a sulfur yellow color
employed for colorimetric estimation. The color system does not obey
Beer's law, although in plotting transmittance against nitrate concentration

a smooth curve is produced.  It is necessary to develop color simulta-
neously in a series of standards and samples.  The intensity of the
color is measured at 410 m .

The intensity of the maximum color produced varies more or less inverse-
ly with the temperature, while the rate of color development varies
more or less directly with the temperature.  The temperature generated
upon mixing sulfuric acid with water can be controlled by adjusting
the acid concentration.  Both the acid concentration and the reaction
time have been selected to yield optimum results and to compensate for
any normal variations in room temperature.

## Interference

All strong oxidizing or reducing agents interfere.  The presence of
oxidizing agents may be determined by the addition of orthotolidine
reagent as in the measurement of residual chlorine.  The interference
by residual chlorine may be eliminated by the addition of sodium arsenite,
provided that the residual chlorine does not exceed 5 mg/l.  A slight
excess of sodium arsenite will affect the determination.  Ferrous and
ferric iron and quadrivalent manganese give slight positive interferences,
but in concentrations less than 1 mg/l these interferences are minimized
by the use of sulfanilic acid.  Chlorides do not interfere.

## Reagents

Stock nitrate solution - Dissolve 0.7218 g anhydrous potas-
sium nitrate, $KNO_3$, and dilute to 1,000 ml with distilled
water.  This solution contains 100 mg/l N.

Standard nitrate solution - Dilute 100.0 ml stock nitrate
solution to 1,000 ml with distilled water; 1.00 ml =
10.0 µg N.

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Sodium arsenite solution - Dissolve 5.0 g NaAsO$_2$ and dilute
   to 1 liter with distilled water. (CAUTION: Toxic; take
   care to avoid ingestion.)

Brucine-sulfanilic acid - Dissolve 1 g brucine sulfate and
   0.1 g sulfanilic acid in approximately 70 ml hot distilled
   water. Add 3 ml conc. HCl, cool and make up to 100 ml.
   This solution is stable for several months. The pink
   color that develops slowly does not affect its usefulness.
   (CAUTION: Brucine is toxic; take care to avoid ingestion.)

Sulfuric acid solution - Carefully add 500 ml of conc. H$_2$SO$_4$
   to 74 ml distilled water. Cool to room temperature before
   use. Keep tightly stoppered to prevent absorption of
   atmospheric moisture.

## Procedure

Prepare a calibration curve by plotting concentrations from 0.1 to
2.6 mg/l NO$_3^-$ against absorption at 410 m on a spectrophotometer using
a light path of 2 cm.

## Color Development

Carefully pipet 2.00 ml of sample containing not more than 10 mg/l
nitrogen into a 50 ml beaker. Add 1.0 ml brucine-sulfanilic acid reagent,
using a safety pipet. Into a second 50 ml meaker measure 10 ml H$_2$SO$_4$.
(An automatic buret is convenient for this purpose. The intensity of
color is affected slightly by the heat capacity of the containers. The
concentration of H$_2$SO$_4$ has been chosen so that normal variations in
heat capacities of beakers will not affect the result. It is important,
however, that only 50 ml beakers be used.) Mix the contents of the two
beakers by carefully adding the sample with brucine-sulfanilic acid
reagent to the beaker containing acid. Pour from one beaker to the other
four to six times to ensure mixing. Allow the treated sample to remain
in the dark for 10 ± 1 minutes. (The beaker may conveniently be covered

with a cardboard carton during this period.) While the sample is
standing for color development, measure 10 ml distilled water into the
empty beaker. After 10 minutes, add the water to the sample and mix as
before. Allow to cool in the dark for 20-30 minutes. Set the blank at
100 per cent transmittance at a wave-length of 410 m$\mu$. It is advisable
to run a series of standards with each set of samples. With a proper
arrangement of work, as many as twelve samples may be determined in a
batch along with eight standards.

## Calculation

Read $NO_3^-$mg/l directly from the calibration curve.

## SULFITE

## Principle

An acidified water sample containing sulfite is titrated with a
standardized potassium iodide-iodate titrant. Free iodine is released
when the sulfite has been completely oxidized, resulting in the
formation of a blue color in the presence of starch indicator.

## Interference

The presence of other oxidizable substances in the water such as organic
matter and sulfide will result in higher titration values for sulfite
than are actually present. Nitrite, on the other hand, will combine with
sulfite in the acid medium to destroy both, leading to low results. No
interference occurs with the Dual-Purpose Dry Starch Indicator Powder
because the sulfonic acid in this proprietary compound destroys the
nitrite. Copper ion rapidly accelerates the oxidation of sulfite solution.
Certain heavy metals may also react in a manner similar to coppper. Proper
sampling and immediate fixing by acid addition should minimize those
difficulties.

## Reagents

Sulfuric acid, 1 + 1.

Starch solution - To 5 g starch (potato, arrowroot, or
  soluble) in a mortar, add a little cold distilled water and
  grind to a paste. Pour into 1 liter of boiling distilled
  water, stir, and allow to settle overnight. Use the clear
  supernant. Preserve by adding either 1.3 g salicylic acid,
  4 g zinc chloride, or a combination of 4 g sodium propionate
  and 2 g sodium azide to 1 liter of starch solution.

Standard potassium iodide-iodate titrant, 0.0125 N - Dissolve
  0.4458 g anhydrous potassium iodate, $KIO_3$ (primary stan-
  dard grade dried for several hours at 120°C), 4.35 g
  potassium iodide, KI, and 0.31 g sodium bicarbonate,
  $NaHCO_3$, in distilled water, and dilute to 1,000 ml.
  This titrant is equivalent to 0.500 mg $SO_3^{=}$ per 1.00 ml.

## Procedure

Collect a fresh water sample with as little contact with air as possible.
Cool hot samples to 50°C or below in the cooling apparatus. Do not
filter the samples.

Add 1 ml $H_2SO_4$ (or 1 g dual-purpose starch indicator) to a 250 ml
Erlenmeyer flask or other titrating vessel, then measure 50 ml water
sample in a graduated cylinder, and transfer to the flask. Add 1 ml
starch indicator solution or 0.1 g starch powder. Titrate with potassium
iodide-iodate titrant until a faint permanent blue color develops in the
sampel, signaling the end of the titration. View the color changes against
a white background.

## Calculation

$$\text{mg/l } SO_3^= \text{ equals } \frac{A \times N \times 40{,}000}{\text{ml sample}}$$

where:  A = ml of titrant used for sample

N = normality of KI-KIO$_3$.


## SULFATE -- GRAVIMETRIC METHOD

### Principle

Sulfate is precipitated in a hydrochloric acid medium as barium sulfate
by the addition of barium chloride. The precipitation is carried out
near the boiling temperature and, after a period of digestion, the
precipitate is filtered, washed with water until free of chlorides,
ignited or dried, and weighed as $BaSO_4$.

### Interference

The gravimetric determination of sulfate is subject to many errors, both
positive and negative. In potable waters where the mineral concentration
is low, these may be of minor importance. The analyst should be familiar
with the more common interferences, however, so that he may apply
corrective measures when necessary.

### Reagents

Methyl red indicator solution - Dissolve 0.1 g methyl red
sodium salt in distilled water and dilute to 100 ml.

Hydrochloric acid- 1 + 1.

Barium chloride solution - Dissolve 100 g $BaCl_2 \cdot 2H_2O$ in
1 liter distilled water. Filter through a membrane filter
or hard-finish filter paper before use; 1 ml of this
reagent is capable of precipitating approximately 40 mg
$SO_4^=$.

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Asbestos cream - Add 15 g acid-washed medium-fiber asbestos, which is prepared especially for Gooch crucible determinations, to 1 liter distilled water. Remove the fine material from the asbestos before use by repeated decantations.

Silver nitrate-nitric acid - Dissolve 8.5 g $AgNO_3$ and 0.5 ml conc. $HNO_3$ in 500 ml distilled water.

## Procedure

Adjust the clarified sample -- treated if necessary to remove interfering agents -- to contain approximately 50 mg of sulfate ion in a 250 ml volume. Adjust the acidity with HCl to pH 4.5-5.0 using a pH meter or the orange color of methyl red indicator. Then add on additional 1 to 2 ml HCl. Lower concentrations of sulfate ion may be tolerated if it is impractical to concentrate the sample to the optimum level, but in such cases it is better to fix the total volume at 150 ml. Heat the solution to boiling and, while stirring gently, add warm barium chloride solution slowly until precipitation appears to be complete; then add about 2 ml in excess. If the amount of precipitate is small, add a total of 5 ml barium chloride solution. Digest the precipitate at $80°-90°C$, preferably overnight but for not less than 2 hours.

Prepare an asbestos filter mat in a Gooch crucible by using suitable suction apparatus. Wash with several portions of hot distilled water, dry, and ignite at 800°C for 1 hour. Cool the crucible in a desiccator and weigh.

Mix a small amount of ashless filter paper pulp with the barium sulfate, and filter at room temperature. The pulp aids filtration and reduces the tendency of the precipitate to creep. Wash the precipitate with small portions of warm distilled water until the washings are free of chlorides, as indicated by testing with silver nitrate-

nitric acid reagent.  Dry the filter and precipitate and ignite at
800°C for 1 hour.  Do not allow the filter paper to flame.  Cool in a
desiccator and weight.

Calculation

$$\text{mg/l } SO_4^- \text{ equals } \frac{\text{mgBaSO}_4 \times 411.5}{\text{ml sample}}$$

APPENDIX B

ANNUBAR FLOW ELEMENT, CALCULATION EQUATIONS,

AND ENGINEERING SPECIFICATIONS

Supplied by

Ellison Instrument Division
Boulder, Colorado

# ELLISON

TTERICH STANDARD CORP · DRAWER M · BOULDER COLORADO 80302 USA · TEL 303/449-8000 · TLX 45-903 · CABLE DIESTAN BDR

Annubar Primary Elements, like other differential mea- suring flow elements, utilize a form of the classical Bernoulli energy balance equation to determine flow rate. But, unlike most other flow elements, Annubar's differential pressure signal is consistent and uniform for a given pipe size and flow condition. Since it is uniform, only the operating range of the instrument or control system needs to be sized. This feature reduces calculations and also allows future changes to a sys- tem's flow rate without the necessity of resizing and changing primary elements.

Sizing the operating range of the instrument to be used with an Annubar element is made easy with the charts and formulas shown below. If you prefer to have Elli- son compute your instrument's operating range there is a small charge for this engineering service.

## HELPFUL HINTS FOR SIZING

1. Select one of the calculation methods shown below according to your accuracy requirements.
2. When flow is liquid, check your result against the "Quick-Size" chart in the Annubar catalogue, E-100. This is a fast way to double check calculations.
3. If your system's flow rates are extremely high or ex- tremely low, it may be desirable to change the pipe size for the metered section. Changing diameters of

the metered section will not affect accuracy providing sufficient upstream and downstream lengths of pipe are provided .... see Table II.
4. Contact your local Ellison Engineering Representative or our factory if you need any further information or help in sizing your instrument's operating range .... we are here to serve you.

## EASY INSTRUMENT SIZING

Select the calculation method that meets your needs:

A. **QUICK-SIZE CHART** — fastest sizing for water flows — see chart on the fold-out section of the Annubar catalogue, E-100.

B. **STANDARD "PLANT" EQUATIONS** — for general industrial metering needs .... see "B" below.

C. **PRECISE "THEORETICAL" EQUATIONS** — for highest accuracy requirements and laboratory work .... see "C" on next page.

D. **SLIDE RULE CALCULATOR** — convenient for fast sizing of gases, liquids, and steam. Request form E-87 from your Ellison Representative.

## "B" STANDARD "PLANT" EQUATIONS

1b. Liquid volume flow rate,

$$Q_a = SND^2 \frac{\sqrt{G_t}}{G_1} \sqrt{h_a} \quad , \text{or} \quad h_a = \left( \frac{Q_a G_1}{SND^2 \sqrt{G_t}} \right)^2$$

2b. Liquid weight flow rate,

$$W_a = SND^2 \sqrt{G_t} \sqrt{h_a} \quad , \text{or} \quad h_a = \left( \frac{W_a}{SND^2 \sqrt{G_t}} \right)^2$$

3b. Gas volume flow rate at standard condition,

$$Q_a = 7.9 \, SND^2 \frac{\sqrt{\gamma_t}}{\gamma_1} \sqrt{h_a} \quad , \text{or} \quad h_n = \left( \frac{Q_a \gamma_1}{7.9 \, SND^2 \sqrt{\gamma_t}} \right)^2$$

4b. Gas or steam weight flow rate,

$$W_a = .127 \, SND^2 \sqrt{\gamma_t} \sqrt{h_a} \quad , \text{or} \quad h_a = \left( \frac{W_n}{.127 \, SND^2 \sqrt{\gamma_t}} \right)^2$$

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# "C" PRECISE "THEORETICAL" EQUATIONS

1c. Liquid volume flow rate,

$$Q_a = SND^2 F_a F_m F_p \frac{\sqrt{G_t}}{G_t} \sqrt{h_a} \quad , \text{or} \quad h_a = \left( \frac{Q_a G_t}{SND^2 F_a F_m F_p \sqrt{G_t}} \right)^2$$

2c. Liquid weight flow rate,

$$W_a = SND^2 F_a F_m F_p \sqrt{G_t} \sqrt{h_a} \quad , \text{or} \quad h_a = \left( \frac{W_a}{SND^2 F_a F_m F_p \sqrt{G_t}} \right)^2 \quad ;$$

3c. Gas volume flow rate at standard condition,*

$$Q_a = 7.897 \, SND^2 \, F_a F_m V_a \, \frac{\sqrt{\gamma_t}}{\gamma_t} \sqrt{h_a} \quad , \text{or} \quad h_a = \left( \frac{Q_a \gamma_t}{7.897 \, SND^2 \, F_a F_m V_a \sqrt{\gamma_t}} \right)^2$$

4c. Gas or steam weight flow rate,

$$W_a = .1266 \, SND^2 \, F_a F_m V_a \, \sqrt{\gamma_t} \sqrt{h_a} \quad , \text{or} \quad h_a = \left( \frac{W_a}{.1266 \, SND^2 \, F_a F_m V_a \sqrt{\gamma_t}} \right)^2$$

*To determine flow at flowing conditions set $\gamma_t = \gamma_t$

# EQUATION SYMBOLS

For convenience the symbols shown below are of equal value to those listed in leading handbooks. Page reference numbers are provided after most of the symbol definitions. These numbers refer to the reference pages in "Principles and Practices of Flow Meter Engineering", handbook by L. K. Spink which is available from the Foxboro Company, Foxboro, Massachusetts.

$D$ = Inside diameter of pipe in inches (exact).  (p. 155)

$F_a$ = Expansion - contraction factor for inside area of pipe at flowing temperature to that at 68°F. Although "$F_a$" in this definition is not the same as found in handbooks, its numerical value is the same. $F_a$ = 1.000 between +31 and +106°F. on steel pipe.  (p. 156)

$F_m$ = Manometer correction factor. The value to correct for effect of density of the fluid that displaces the float or the manometer liquid in the measuring instrument. Do not use this factor if instrument's scale has correction factor included.  (p. 157)

$F_p$ = Correction for compressibility of flowing liquid. When negligible use 1.00.  (p. 271)

$G_t$ = Specific gravity of liquid at flowing temperature as compared to water at 60°F. which is 1.00. See Figure 2.  (p. 158, 162, 163, 165, 262, 267)

$G_t$ = Specific gravity of liquid at 60°F. as compared to water at 60°F. which is 1.00.  (p. 162, 264, 269)

$h_a$ = Differential pressure output of Annubar element in convenient units. ... see Table I.

$N$ = Grouped constant including $\sqrt{2g}$ (gravity acceleration), $\pi/4$ (circular area), and conversion constants which depend on units chosen for $Q_a$, $W_a$, and $h_a$ .... see Table I.  (p. 154)

$Q_a$ = Volume flow rate in convenient units. See Table I.  (p. 148)

$S$ = Constant factor for element at specific flow, $S = K_g F_v$. If $K_g$ or $F_v$ factors are other than those shown below, they will be supplied with individual Annubar elements or are available on request.

$K_g$ = Geometrical constant:

| Element Types 710 & 720 | Element Types 730 & 740 |
|---|---|
| ½" Pipe — Kg = 0.722 | 2" to 2½" Pipe — Kg = 0.876 |
| ¾" Pipe — Kg = 0.732 | 3" to 4" Pipe — Kg = 0.877 |
| 1 " Pipe — Kg = 0.755 | 5" to 6" Pipe — Kg = 0.878 |
| 1¼" Pipe — Kg = 0.776 | 8" Pipe — Kg = 0.887 |
| 1½" Pipe — Kg = 0.812 | 10" Pipe — Kg = 0.896 |
| 2 " Pipe — Kg = 0.846 | 12" Pipe — Kg = 0.903 |
| 2½" Pipe — Kg = 0.863 | 14" Pipe — Kg = 0.917 |
| | 16" Pipe — Kg = 0.928 |
| | 18" Pipe — Kg = 0.938 |
| | 20" Pipe — Kg = 0.949 |
| | 24" Pipe — Kg = 0.969 |

$F_v$ = Velocity distribution factor:
  $F_v$ = 0.63 for transition and turbulent flow.

$V_a$ = Gas adiabatic compression factor. Velocities below 12,000 ft./min. use 1.00.

$$V_a = \sqrt{ \frac{k}{k-1} \, \frac{P_t}{P_t - P_a} \left( \left[ \frac{P_t}{P_a} \right]^{\frac{k-1}{k}} - 1 \right) }$$

$k$ = Ratio of specific heats, or isentropic exponent. Gases which follow the perfect gas law (Diatomic gases such as Oxygen, Hydrogen, Nitrogen, Air and etc.) have $k$ = 1.40 under normal conditions.  (264)

$P_a$ = Upstream static pressure in consistent absolute units.

$P_t$ = Total or impact pressure at element in consistent absolute units.

* Solving with digital equipment is recommended.

$W_a$ = Weight flow rate in convenient units. See Table I.  (p. 148)

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$\gamma_f$ =Specific weight at flowing conditions in pounds per cubic foot including compressibility.

$$\gamma_f = \frac{14.7 + \text{PSIG of line}}{14.7} \times \frac{520}{460 + \text{line temp (°F)}} \times \gamma_1$$

Also, $\gamma_f$ = specific gravity of gas at flowing conditions times the weight of air (#/ft.³) at conditions equal to

flowing conditions. See Figure 1 and 3.   (p. 333,372)

$\gamma_1$ = Specific weight of gas at base conditions in pounds per cubic foot. $\gamma_1$ = Specific Gravity of gas at base conditions times the weight of air (#/ft.³) at base conditions. Air = .0765#/ft.³ at standard (60°F./ 14.73 psia) base conditions.   (p. 78)

### TABLE I — Factor "N" Values for Various "n" Units

| Q$_n$, Volume | "h$_n$" Units of Differential Pressure, Dry Calibration | | | |
|---|---|---|---|---|
| | IN. of H$_2$O * | IN. of Hg. * | Kg/cm | P.S.I. |
| GPM | 5.667 | 20.88 | 112.5 | 29.84 |
| GPH | 340.0 | 1252.0 | 6750. | 1790. |
| CFM | 0.7576 | 2.791 | 15.04 | 3.990 |
| CFH | 45.46 | 167.5 | 902.5 | 239.4 |
| LPM | 21.45 | 79.02 | 425.8 | 113.0 |

| W$_n$, Weight | | | | |
|---|---|---|---|---|
| PPM | 47.25 | 174.1 | 938.0 | 248.8 |
| PPH | 2835. | 10440. | 56280. | 14930. |

*Column readings corrected to 68° F.

## FIGURE 1. VALUES OF $\sqrt{\gamma_f}$ FOR AIR



TEMPERATURE, °F.

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"C" - SENSING PORTS ARE LOCATED IN APPROPRIATE CENTERS OF CONCENTRIC ANNULI.

ASME PAR UW - 16 DRILL OR BURN TWO 1" DIAMETER HOLES AND PROVIDE 1/4" MINIMUM WELD BEAD - ALIGN TO PIPE AXIS. (TYPICAL)

2 - ASTM SPEC. A106 GRADE NO. 2 2/3000 LBS. 1/2" NPT FORGED STEEL WELD COUPLINGS ARE SUPPLIED.

HIGH PRESSURE

"B" - PORT

TOP FLAT ON HEX TO BE SET PARALLEL TO PIPE AXIS

VIEW "F - F"
FULL SIZE

1/2" N.P.T.

2500 P.S.I RATED METAL COMPRESSION FERRULE.

7/16 - 24 THREAD

SECTION DETAIL
FULL SIZE

LOCATED 3/16" UPSTREAM FROM WELD COUPLING ON OPPOSITE SIDE

5/16" DIA.

FLOW STREAM

"A"

REFER TO SECTION DETAIL

4 7/8

PERMANENT METAL TAG WITH 3" CHAIN.

LOW PRESSURE

55°   15°

SECTION "G - G"
FULL SIZE

PROJECT_____
LOCATION_____
MATERIAL_____
APPROVED BY_____

Ⓓ 3 TO 4 PIPE DIAMETERS IS RECOMMENDED FOR DOWNSTREAM SIDE.
Ⓤ 8 OR MORE PIPE DIAMETERS IS RECOMMENDED FOR UPSTREAM SIDE AFTER VALVES, ELBOWS & ETC. - SEE FORM E-79.
Ⓦ PERMANENT TAG SHOWING MIN., NORM. & MAX. DESIGNED FLOWS, METER READINGS FOR DESIGNED FLOWS, TAG NO., LINE SIZE, SER. NO. & METERED FLUID.

| A NOM. PIPE SIZE * | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B HOLE DIA. - ALL | 5/32 | 5/32 | 5/32 | 5/32 | 5/32 | 5/32 | 5/32 | 5/32 | 5/32 | 5/32 | 1/8 |
| C NO. OF PORTS | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |

* SPECIFY PIPE SCHEDULE OR I.D. & O.D.

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DIETERICH STANDARD CORPORATION
ELLISON INSTRUMENT DIVISION
DRAWER M BOULDER COLORADO 80302 USA

741 TO 744 ANNUBAR FLOW ELEMENTS

| Date Revision | | | Date Revision | | | Part No. |
|---|---|---|---|---|---|---|
| 2-5-69 | | | | | | |
| Drawn HRH | Ch'k'd | | Date 6-4-68 | Scale 3/8"=1" | | |

E-68 876

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SECTION D

# APPENDIX C

## SUMMARY OF SCRUBBER OPERATING CONDITIONS

TABLE C-1.  SCRUBBER OPERATING CONDITIONS—SERIES S-XX—KEY WEST INITIAL SALT WATER TESTS

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| S1 | Preliminary | 12 | 2000 | 8.5 | – | – | – |
| S2 | Preliminary | 12 | 1013 | 6.5 | – | – | – |
| S3 | Preliminary | 12 | 1013 | 6.5 | – | – | – |
| S4 | Preliminary | 12 | 935 | 6.5 | 1:1 | 325 | 3 |
| S5 | – | – | – | – | V O I D  – | – | – |
| S6 | – | – | – | – | V O I D  – | – | – |
| S7 | – | – | – | – | V O I D  – | – | – |
| S8 | – | – | – | – | V O I D  – | – | – |
| S9 | – | – | – | – | V O I D  – | – | – |
| S10 | – | – | – | – | V O I D  – | – | – |
| S11 | Break in | 12 | 1572 | 12.0 | – | – | – |
| S12 | Break in | 12 | 788 | 6.5 | – | – | – |
| S13 | Break in | 12 | 783 | 6.5 | – | – | – |
| S14 | Break in | 12 | 789 | 6.5 | – | – | – |
| S15 | Break in | 12 | 1538 | 12.0 | – | – | – |
| S16 | Break in | 12 | 1538 | 12.0 | – | – | – |
| S17 | Break in | 12 | 1652 | 12.0 | – | – | – |
| S18 | – | – | – | – | V O I D  – | – | – |
| S19 | Break in | 12 | 784 | 6.5 | – | – | – |

TABLE C-1 (contd). SCRUBBER OPERATING CONDITIONS--SERIES S-XX--KEY WEST INITIAL SALT
WATER TESTS

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| S20 | Break in | 12 | 778 | 6.5 | - | - | - |
| S21 | - | - | - | - V O I D | - | - | - |
| S22 | - | - | - | - V O I D | - | - | - |
| S23 | Break in | 12 | 795 | 12.0 | - | - | - |
| S24 | Break in | 12 | 795 | 12.0 | - | - | - |
| S25 | Break in | 12 | 1496 | 6.5 | - | - | - |
| S26 | Break in | 12 | 1478 | 6.5 | - | - | - |
| S27 | Break in | 12 | 1483 | 6.5 | - | - | - |
| S28 | Break in | 12 | 1495 | 6.5 | - | - | - |
| S29 | Break in | 12 | 1488 | 6.5 | - | - | - |
| S30 | Break in | 12 | 1480 | 6.5 | - | - | - |
| S31 | Break in | 12 | 1492 | 12.0 | - | - | - |
| S32 | Break in | 12 | 1507 | 12.0 | - | - | - |
| S33 | Break in | 12 | 1486 | 12.0 | - | - | - |
| S34 | Break in | 12 | 810 | 12.0 | - | - | - |
| S35 | Break in | 12 | 776 | 12.0 | - | - | - |
| S36 | Break in | 12 | 776 | 12.0 | - | - | - |
| S37 | Break in | 12 | 1500 | 12.0 | - | - | - |

TABLE C-1 (contd).  SCRUBBER OPERATING CONDITIONS--SERIES S-XX--KEY WEST INITIAL SALT

WATER TESTS

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{lb\text{-}mole\ reactant}{lb\text{-}mole\ entering\ SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| S38 | Break in | 12 | 1468 | 6.5 | - | - | - |
| S39 | Break in | 12 | 784 | 12.0 | - | - | - |
| S40 | Break in | 12 | 782 | 12.0 | - | - | - |
| S41 | Break in | 12 | 781 | 12.0 | - | - | - |
| S42 | Break in | 12 | 780 | 12.0 | - | - | - |
| S43 | Break in | 12 | 778 | 6.5 | - | - | - |

TABLE C-2. SCRUBBER OPERATING CONDITIONS--SERIES C-XX--KEY WEST CORAL

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| C1 | - | - | - | - V O I D | - | - | - |
| C2 | Shakedown | 12 | 781 | 6.5 | 1:1.9 | 325 | 1 |
| C3 | Shakedown | 12 | 779 | 6.5 | 1:1.8 | 325 | 1 |
| C4 | Shakedown | 12 | 1468 | 6.5 | 1:1 | 325 | 1 |
| C5 | Shakedown | 12 | 1467 | 6.5 | 1:1 | 325 | 1 |
| C6 | Statistical | 12 | 1463 | 12.0 | 1:0.9 | 325 | 1 |
| C7 | Duplicate C6 | 12 | 1478 | 12.0 | 1:1 | 325 | 1 |
| C8 | Statistical | 12 | 775 | 6.5 | 1:1 | 325 | 1 |
| C9 | Extra | 12 | 779 | 6.5 | 1:3 | 325 | 1 |
| C10 | Extra | 12 | 1477 | 6.5 | 1:1 | 325 | 1 |
| C11 | - | - | - | - V O I D | - | - | - |
| C12 | Duplicate C6 | 12 | 1370 | 12.0 | 1:1 | 325 | 1 |
| C13 | Statistical | 12 | 721 | 12.0 | 1:3 | 325 | 1 |
| C14 | Statistical | 12 | 1470 | 12.0 | 1:3 | 325 | 5 |
| C15 | Statistical | 12 | 771 | 6.5 | 1:3 | 325 | 5 |
| C16 | Statistical | 12 | 1452 | 6.5 | 1:1 | 325 | 5 |
| C17 | Statistical | 12 | 772 | 12.0 | 1:1 | 325 | 5 |
| C18 | Statistical | 12 | 1498 | 6.5 | 1:3 | 325 | 1 |
| C19 | Statistical | 12 | 1460 | 12.0 | 1:3 | 100 | 1 |

TABLE C-2 (Cont.)   SCRUBBER OPERATING CONDITIONS--SERIES C-XX--KEY WEST CORAL

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| C20 | Statistical | 12 | 794 | 6.5 | 1:3 | 100 | 1 |
| C21 | Statistical | 12 | 794 | 12.0 | 1:1 | 100 | 1 |
| C22 | Statistical | 12 | 1457 | 6.5 | 1:1 | 100 | 1 |
| C23 | Statistical | 12 | 1483 | 6.5 | 1:3 | 100 | 1 |
| C24 | Statistical | 12 | 788 | 12.0 | 1:3 | 100 | 5 |
| C25 | Statistical | 12 | 1482 | 12.0 | 1:1 | 100 | 5 |
| C26 | Centerpoint | 12 | 1146 | 9.0 | 1:2 | 325 | 3 |
| C27 | Centerpoint | 12 | 1152 | 9.0 | 1:2 | 325 | 5 |
| C28 | Statistical | 12 | 788 | 6.5 | 1:1 | 100 | 5 |
| C29 | - | - | - | - V O I D | - | - | - |
| C30 | Duplicate C17 | 12 | 782 | 12.0 | 1:1 | 325 | 5 |
| C31 | Centerpoint | 12 | 1120 | 9.0 | 1:2 | 325 | 3 |
| C32 | Catalyst | 12 | 1120 | 9.0 | 1:2 | 325 | 3 |
| C33A | Centerpoint | 12 | 1120 | 9.0 | 1:2 | 325 | 3 |
| C33B | Inhibitor | 12 | 1120 | 9.0 | 1:2 | 325 | 3 |
| C34A | Inhibitor | 12 | 1120 | 9.0 | 1:2 | 325 | 3 |
| C34B | Inhibitor + Catalyst | 12 | 1120 | 9.0 | 1:2 | 325 | 3 |

TABLE C-3.  SCRUBBER OPERATING CONDITIONS--SERIES F-XX--KEY WEST FREDONIA VALLEY LIMESTONE

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| F1 | - | - | - | - V O I D | - | - | - |
| F2 | - | - | - | - V O I D | - | - | - |
| F3 | Statistical | 12 | 776 | 6.5 | 1:1 | 325 | 1 |
| F4 | Extra | 12 | 766 | 6.5 | 1:3 | 325 | 1 |
| F5 | Extra | 12 | 1462 | 6.5 | 1:1 | 325 | 1 |
| F6 | Extra | 12 | 1476 | 6.5 | 1:1 | 325 | 1 |
| F7 | Statistical | 12 | 1475 | 12.0 | 1:1 | 325 | 1 |
| F8 | Duplicate F3 | 12 | 777 | 6.5 | 1:1 | 325 | 1 |
| F9 | Statistical | 12 | 1468 | 12.0 | 1:3 | 325 | 5 |
| F10 | Statistical | 12 | 769 | 6.5 | 1:3 | 325 | 5 |
| F11 | Statistical | 12 | 1497 | 6.5 | 1:1 | 325 | 5 |
| F12 | Statistical | 12 | 1469 | 6.5 | 1:3 | 325 | 1 |
| F13 | Statistical | 12 | 694 | 12.0 | 1:3.3 | 325 | 1 |
| F14 | Extra | 12 | 781 | 12.0 | 1:1 | 325 | 5 |
| F15 | Statistical | 12 | 1480 | 12.0 | 1:3 | 100 | 1 |
| F16 | Statistical | 12 | 798 | 6.5 | 1:3 | 100 | 1 |
| F17 | Statistical | 12 | 796 | 12.0 | 1:1 | 100 | 1 |
| F18 | Statistical | 12 | 1468 | 6.5 | 1:1 | 100 | 1 |

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| F19 | Statistical | 12 | .800 | 6.5 | 1:1 | 100 | 5 |
| F20 | Statistical | 12 | 1453 | 12.0 | 1:1 | 100 | 5 |
| F21 | Statistical | 12 | 1460 | 6.5 | 1:3 | 100 | 5 |
| F22 | Statistical | 12 | 765 | 12.0 | 1:3 | 100 | 5 |
| F23 | Centerpoint | 12 | 1107 | 9.0 | 1:2 | 100 | 3 |
| F24 | Centerpoint | 12 | 1140 | 9.0 | 1:2 | 325 | 3 |
| F25 | Centerpoint | 12 | 1152 | 9.0 | 1:2 | 325 | 3 |
| F26 | Statistical | 12 | 790 | 12.0 | 1:1 | 325 | 5 |
| F27 | Duplicate F7 | 12 | 1440 | 12.0 | 1:1 | 325 | 1 |
| F28 | Duplicate F9 | 12 | 1445 | 12.0 | 1:3 | 325 | 5 |
| F29 | Duplicate F22 | 12 | 778 | 12.0 | 1:3 | 100 | 5 |
| F30 | Duplicate F19 | 12 | 778 | 6.5 | 1:1 | 100 | 5 |
| F31 | Special | 12 | 1317 | 12.0 | 1:3 | 325 | 1 |
| F32 | Special | 12 | 1110 | 12.0 | 1:3 | 325 | 1 |
| F33 | Special | 12 | 678 | 12.0 | 1:3 | 325 | 1 |
| F34 | Special | 12 | 784 | 12.0 | 1:3 | 325 | 1 |
| F35 | Special | 12 | 455 | 12.0 | 1:3 | 325 | 1 |
| F35A | Special | 12 | 1452 | 12.0 | 1:3 | 325 | 1 |

TABLE C-3 (Cont.). SCRUBBER OPERATING CONDITIONS--SERIES F-XX--KEY WEST FREDONIA VALLEY LIMESTONE

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| F36 | Special | 12 | 1093 | 12.0 | 1:3 | 325 | 1 |
| F37 | Special | 8 | 1052 | 12.0 | 1:3 | 325 | 1 |
| F38 | Special | 8 | 755 | 12.0 | 1:3 | 325 | 1 |
| F39 | Special | 8 | 557 | 12.0 | 1:3 | 325 | 1 |
| F40 | Special | 8 | 486 | 12.0 | 1:3 | 325 | 1 |
| F41 | Special | 8 | 1320 | 12.0 | 1:3 | 325 | 1 |
| F42 | Centerpoint | 12 | 1129 | 9.0 | 1:2 | 100 | 3 |

TABLE C-4. SCRUBBER OPERATING CONDITIONS--SERIES HL-XX--KEY WEST LIME, DOLOMITE, PRECIPITATED CaCO$_3$, AND RECYCLED LIMESTONE

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches H$_2$O) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering SO}_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| HL1 | Statistical | 12 | 1445 | 6.5 | 1:1 | - | 1 |
| HL2 | Statistical | 12 | 790 | 12.0 | 1:1 | - | 1 |
| HL3 | Statistical | 12 | 782 | 6.5 | 1:3 | - | 1 |
| HL4 | Statistical | 12 | 1455 | 12.0 | 1:3 | - | 1 |
| D1 | Statistical | 12 | 1430 | 6.5 | 1:1 | - | 1 |
| D2 | Statistical | 12 | 1430 | 12.0 | 1:3 | - | 1 |
| D3 | Statistical | 12 | 772 | 6.5 | 1:3 | - | 1 |
| D4 | Statistical | 12 | 772 | 12.0 | 1:1 | - | 1 |
| PC1 | Statistical | 12 | 1431 | 6.5 | 1:1 | - | 1 |
| PC2 | Statistical | 12 | 778 | 12.0 | 1:1 | - | 1 |
| PC3 | Statistical | 12 | 773 | 6.5 | 1:3 | - | 1 |
| PC4 | - | - | - | - V O I D | - | - | - |
| X1 | Recycle | 12 | 1110 | - | - | - | 3 |

TABLE C-5. SCRUBBER OPERATING CONDITIONS—SERIES P-XX—PADUCAH-SHAWNEE NO. 9 LIMESTONE

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| P1 | Statistical | 8 | 442 | 6.0 | 1:1 | 325 | 3 |
| P2 | Statistical | 8 | 422 | 6.0 | 1:2 | 325 | 3 |
| P3 | Statistical | 8 | 420 | 12.0 | 1:1 | 325 | 3 |
| P4 | Statistical | 8 | 426 | 3 | 1:2 | 325 | 3 |
| P5 | Statistical | 8 | 620 | 12.0 | 1:1 | 325 | 3 |
| P6 | Statistical | 8 | 620 | 12.0 | 1:2 | 325 | 3 |
| P7 | Statistical | 8 | 617 | 6.0 | 1:1 | 325 | 3 |
| P8 | Statistical | 8 | 615 | 6.0 | 1:2 | 325 | 3 |
| P9 | Statistical | 8 | 415 | 6.0 | 1:2 | 325 | 3 |
| P10 | Statistical | 8 | 415 | 6.0 | 1:1 | 200 | 3 |
| P11 | Statistical | 8 | 417 | 12.0 | 1:2 | 200 | 3 |
| P12 | Statistical | 8 | 417 | 12.0 | 1:1 | 200 | 3 |
| P13 | Statistical | 8 | 617 | 6.0 | 1:1 | 200 | 3 |
| P14 | Statistical | 8 | 618 | 6.0 | 1:2 | 200 | 3 |
| P15 | Statistical | 8 | 619 | 12.0 | 1:1 | 200 | 3 |
| P16 | Statistical | 8 | 619 | 12.0 | 1:2 | 200 | 3 |
| P17 | – | – | – | – V O I D | – | – | – |
| P18 | – | – | – | – V O I D | – | – | – |

TABLE C-5. (Cont.)  SCRUBBER OPERATING CONDITIONS—SERIES P-XX- —PADUCAH-SHAWNEE NO.9 LIMESTONE

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| P19 | Centerpoint | 8 | 518 | 9.0 | 1:1.5 | 325 | 3 |
| P20 | Centerpoint | 8 | 518 | 9.0 | 1:1.5 | 325 | 3 |
| P21 | Centerpoint | 8 | 517 | 9.0 | 1:1.5 | 325 | 3 |
| P22 | Centerpoint | 8 | 520 | 9.0 | 1:1.5 | 325 | 3 |
| P23 | Centerpoint | 8 | 520 | 9.0 | 1:1.5 | 200 | 3 |
| P24 | Centerpoint | 8 | 520 | 9.0 | 1:1.5 | 200 | 3 |
| P25 | Centerpoint | 8 | 520 | 9.0 | 1:1.5 | 200 | 3 |
| P26 | Centerpoint | 8 | 520 | 9.0 | 1:1.5 | 200 | 3 |
| P27 | Catalyst | 8 | 522 | 9.0 | 1:1.5 | 325 | 3 |
| P28 | Catalyst | 8 | 522 | 9.0 | 1:1.5 | 325 | 3 |
| P29 | Catalyst | 8 | 522 | 9.0 | 1:1.5 | 200 | 3 |
| P30 | Inhibitor | 8 | 517 | 9.0 | 1:1.5 | 325 | 3 |
| P31 | Inhibitor | 8 | 517 | 9.0 | 1:1.5 | 325 | 3 |
| P32 | Dry collector Bypassed | 8 | 523 | 9.0 | 1:1.5 | 325 | 3 |
| P33 | Dry Collector Bypassed | 8 | 620 | 6.0 | 1:1 | 325 | 3 |
| P34 | Dry Collector Bypassed | 8 | 619 | 12.0 | 1:1 | 325 | 3 |

TABLE C-5. (Cont.) SCRUBBER OPERATING CONDITIONS--SERIES P-XX- --PADUCAH-SHAWNEE NO.9 LIMESTONE

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| P35 | Dry Collector Bypassed | 8 | 524 | 9.0 | 1:1.5 | 325 | 1 |

TABLE C-6.  SCRUBBER OPERATING CONDITIONS--SERIES PA-XX, and PS-XX--PADUCAH-SHAWNEE,  NO. 9
ARAGONITE AND SIMULATED KEY WEST LIMESTONE

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO $\left(\dfrac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}\right)$ | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| PA1 | Statistical | 8 | 620 | 6.0 | 1:1 | 325 | 3 |
| PA2 | Statistical | 8 | 620 | 6.0 | 1:2 | 325 | 3 |
| PA3 | Statistical | 8 | 386 | 12.0 | 1:1 | 325 | 3 |
| PA4 | Statistical | 8 | 386 | 12.0 | 1:2 | 325 | 3 |
| PA5 | Dry Collector Bypassed | 8 | 520 | 9.0 | 1:1.5 | 325 | 3 |
| PA6 | Dry Collector Bypassed | 8 | 520 | 9.0 | 1:1.5 | 325 | 3 |
| PA7 | Centerpoint | 8 | 522 | 9.0 | 1:1.5 | 325 | 3 |
| PA8 | Centerpoint | 8 | 522 | 9.0 | 1:1.5 | 325 | 3 |
| PS1 | Simulated Salt Water | 8 | 525 | 9.0 | 1:1.5 | 325 | 3 |
| PS2 | Simulated Salt Water | 8 | 525 | 9.0 | 1:1.5 | 325 | 3 |
| PS3 | Simulated Salt Water | 8 | 525 | 9.0 | 1:2 | 325 | 3 |

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TABLE C-7  SCRUBBER OPERATING CONDITIONS--SERIES IPA-XX AND IP-XX--PADUCHA-SHAWNEE NO. 10

ARAGONITE  AND LIMESTONE INJECTION

| Test Number | PURPOSE | TUBE SIZE (inches) | GAS FLOW RATE (scfm) | PRESSURE DROP (inches $H_2O$) | STOICHIOMETRIC RATIO ($\frac{\text{lb-mole reactant}}{\text{lb-mole entering } SO_2}$) | PARTICLE SIZE (mesh) | SLURRY CONCENTRATION (weight %) |
|---|---|---|---|---|---|---|---|
| IPA1 | Statistical | 8 | 615 | 6.0 | 1:1.4 | - | - |
| IPA2 | Statistical | 8 | 622 | 12.0 | 1:2 | - | - |
| IPA3 | Statistical | 8 | 419 | 6.0 | 1:2 | - | - |
| IPA4 | Statistical | 8 | 421 | 12.0 | 1:1 | - | - |
| IP1 | Centerpoint | 8 | 516 | 9.0 | 1:1.85 | - | - |
| IP2 | Centerpoint | 8 | 525 | 9.0 | 1:3.0 | - | - |
| IP3 | Centerpoint | 8 | 523 | 9.0 | 1:0.68 | - | - |
| IP4 | Centerpoint | 8 | 513 | 9.0 | 1:1.11 | - | - |
| IP5 | Centerpoint | 8 | 522 | 9.0 | 1:2.46 | - | - |
| IP6 | Centerpoint | 8 | 526 | 9.0 | 1:1.31 | - | - |
| IP7 | Centerpoint | 8 | 512 | 9.0 | 1:1.47 | - | - |
| IP8 | Centerpoint | 8 | 513 | 9.0 | 1:1.47 | - | - |
| IP9 | Special | 8 | 618 | 12.0 | 1:0.95 | - | - |
| IP10 | Special | 8 | 618 | 12.0 | 1:0.95 | - | - |
| IP11 | Special | 8 | 614 | 12.0 | 1:1.45 | - | - |
| IP12 | Special | 8 | 617 | 6.0 | 1:0.99 | - | - |
| IP13 | Special | 8 | 368 | 6.0 | 1:0.99 | - | - |

# APPENDIX D

# SUMMARY OF TEST DATA

Table D-1.   DATA CONSOLIDATION -- SERIES S-XX -- KEY WEST INITIAL SALT WATER TESTS

| Test Number | GAS HUMIDITY (lb/lb dry air) IN | GAS HUMIDITY (lb/lb dry air) OUT | DEW POINT (°F) IN | DEW POINT (°F) OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft³) | LIQUID/GAS RATIO (lb/lb) | ABSORPTION PARAMETERS Entering SO₂ Concentration (ppm) | ABSORPTION PARAMETERS Leaving SO₂ Concentration (ppm) | SO₂ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S5 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| S6 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| S7 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| S8 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| S9 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| S10 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| S11 | 0.130 | 0.072 | 138.0 | 116.0 | 107.12 | 2644.9 | 46.26 | 142.20 | 21.85 | 505 | 245 | 51.5 |
| S12 | 0.078 | 0.071 | 118.8 | 115.7 | 56.29 | 656.9 | 21.58 | 75.71 | 10.83 | 470 | 350 | 25.6 |
| S13 | 0.085 | 0.063 | 121.5 | 112.2 | 55.57 | 656.9 | 21.67 | 75.42 | 10.90 | 510 | 360 | 29.4 |
| S14 | 0.085 | 0.050 | 121.3 | 104.5 | 55.99 | 656.9 | 21.71 | 75.27 | 10.81 | 495 | 305 | 38.4 |
| S15 | 0.086 | 0.092 | 121.8 | 124.0 | 109.05 | 2644.9 | 44.56 | 147.62 | 22.33 | 520 | 320 | 38.4 |
| S16 | 0.069 | 0.084 | 115.0 | 121.0 | 110.78 | 2644.9 | 44.56 | 147.62 | 22.33 | 510 | 290 | 43.2 |
| S17 | 0.089 | 0.076 | 123.0 | 118.0 | 116.81 | 2644.9 | 46.90 | 140.27 | 20.79 | 460 | 190 | 58.7 |
| S18 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| S19 | 0.106 | 0.078 | 128.6 | 118.5 | 54.58 | 656.9 | 21.81 | 74.90 | 10.88 | 655 | 485 | 26.0 |
| S20 | 0.084 | 0.066 | 120.8 | 113 5 | 55.26 | 656.9 | 21.88 | 74.68 | 10.96 | 805 | 540 | 32.9 |
| S21 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| S22 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| S23 | 0.093 | 0.059 | 124.2 | 110.0 | 56.01 | 3764.8 | 22.88 | 340.45 | 61.50 | 672 | 375 | 44.2 |

NOTE:  Tests S1 through S4 were preliminary tests.  No calculations were performed.

Table D-1 (cont)    DATA CONSOLIDATION -- SERIES S-XX -- KEY WEST INITIAL SALT WATER TESTS

| Test Number | GAS HUMIDITY (lb/lb dry air) IN | OUT | DEW POINT (°F) IN | OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft$^3$) | (lb/lb) | ABSORPTION PARAMETERS Entering SO$_2$ Concentration (ppm) | Leaving SO$_2$ Concentration (ppm) | SO$_2$ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S24 | 0.094 | 0.078 | 124.7 | 118.5 | 55.96 | 3764.8 | 22.88 | 340.45 | 61.50 | 690 | 405 | 41.3 |
| S25 | 0.089 | 0.100 | 122.8 | 126.5 | 105.78 | 750.8 | 43.40 | 43.03 | 6.52 | 565 | 408 | 27.8 |
| S26 | 0.086 | 0.090 | 121.8 | 123.3 | 104.79 | 750.8 | 43.71 | 42.72 | 6.60 | 622 | 438 | 29.6 |
| S27 | 0.093 | 0.077 | 124.3 | 118.1 | 104.47 | 750.8 | 43.61 | 42.82 | 6.58 | 620 | 430 | 30.6 |
| S28 | 0.091 | 0.090 | 123.7 | 123.1 | 105.51 | 750.8 | 43.33 | 43.10 | 6.52 | 630 | 462 | 26.7 |
| S29 | 0.092 | 0.088 | 124.0 | 122.3 | 104.92 | 750.8 | 43.71 | 42.72 | 6.55 | 630 | 450 | 28.6 |
| S30 | 0.088 | 0.079 | 122.5 | 119.2 | 104.76 | 750.8 | 42.95 | 39.29 | 6.59 | 625 | 445 | 28.8 |
| S31 | 0.086 | 0.087 | 121.8 | 122.0 | 105.79 | 2883.8 | 42.65 | 167.33 | 25.10 | 518 | 325 | 37.3 |
| S32 | 0.092 | 0.077 | 124.0 | 118.0 | 106.26 | 2883.8 | 43.12 | 166.34 | 24.85 | 505 | 290 | 42.6 |
| S33 | 0.078 | 0.068 | 118.7 | 114.0 | 106.14 | 2883.8 | 42.87 | 167.33 | 25.20 | 500 | 260 | 48.0 |
| S34 | 0.074 | 0.046 | 117.0 | 102.0 | 58.07 | 3131.2 | 22.07 | 352.88 | 50.20 | 482 | 225 | 53.4 |
| S35 | 0.085 | 0.060 | 121.4 | 110.5 | 55.07 | 2883.8 | 21.88 | 327.84 | 48.26 | 465 | 270 | 41.9 |
| S36 | 0.085 | 0.068 | 121.3 | 114.0 | 55.07 | 2883.8 | 21.94 | 326.89 | 48.26 | 510 | 254 | 50.2 |
| S37 | 0.085 | 0.087 | 121.3 | 122.0 | 106.45 | 2644.9 | 43.18 | 152.33 | 22.90 | 465 | 257 | 44.7 |
| S38 | 0.089 | 0.083 | 122.8 | 120.5 | 103.80 | 802.0 | 43.29 | 46.08 | 7.09 | 450 | 322 | 28.5 |
| S39 | 0.081 | 0.069 | 119.8 | 114.8 | 55.84 | 3131.2 | 21.75 | 358.05 | 51.87 | 443 | 236 | 46.7 |
| S40 | 0.086 | 0.061 | 121.7 | 110.7 | 55.45 | 3131.2 | 21.77 | 357.70 | 52.00 | 445 | 242 | 45.6 |
| S41 | 0.082 | 0.045 | 120.1 | 101.9 | 55.58 | 3131.2 | 21.79 | 357.35 | 52.07 | 465 | 210 | 54.8 |
| S42 | 0.085 | 0.076 | 121.5 | 117.8 | 55.35 | 3131.2 | 21.71 | 358.75 | 52.13 | 480 | 242 | 49.6 |
| S43 | 0.084 | 0.055 | 121.0 | 107.7 | 55.26 | 802.0 | 21.84 | 91.35 | 13.39 | 410 | 220 | 46.3 |

Table D-2. DATA CONSOLIDATION -- SERIES C-XX -- KEY WEST CORAL

| Test Number | GAS HUMIDITY (lb/lb dry air) IN | GAS HUMIDITY OUT | DEW POINT (°F) IN | DEW POINT OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft³) | LIQUID/GAS RATIO (lb/lb) | ABSORPTION PARAMETERS Entering SO₂ Concentration (ppm) | Leaving SO₂ Concentration (ppm) | SO₂ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| C2 | 0.076 | 0.073 | 117.9 | 116.5 | 54.87 | 704.4 | 21.75 | 80.00 | 11.71 | 438 | 97 | 77.9 |
| C3 | 0.087 | 0.083 | 122.0 | 120.5 | 55.18 | 704.4 | 21.81 | 79.77 | 11.74 | 465 | 100 | 78.5 |
| C4 | 0.029 | 0.094 | 122.7 | 124.6 | 104.47 | 807.5 | 43.29 | 46.08 | 7.14 | 454 | 173 | 61.9 |
| C5 | 0.087 | 0.097 | 122.3 | 125.5 | 104.69 | 807.5 | 43.39 | 45.97 | 7.15 | 436 | 174 | 60.1 |
| C6 | 0.089 | 0.103 | 122.6 | 127.8 | 104.40 | 2439.6 | 43.39 | 138.88 | 21.66 | 492 | 154 | 68.7 |
| C7 | 0.091 | 0.103 | 123.5 | 128.0 | 104.31 | 2439.6 | 43.93 | 137.20 | 21.44 | 436 | 128 | 70.7 |
| C8 | 0.094 | 0.091 | 124.8 | 123.6 | 54.75 | 704.4 | 22.05 | 78.92 | 11.80 | 415 | 147 | 64.6 |
| C9 | 0.085 | 0.077 | 121.2 | 118.0 | 54.93 | 704.4 | 21.84 | 79.69 | 11.74 | 414 | 75 | 81.9 |
| C10 | 0.087 | 0.093 | 122.2 | 124.4 | 104.82 | 807.5 | 43.18 | 46.19 | 7.10 | 415 | 180 | 56.6 |
| C11 | – | – | – | – | – | V O I D | – | – | – | – | – | – |
| C12 | 0.095 | 0.103 | 124.9 | 127.8 | 95.99 | 2903.5 | 46.26 | 155.05 | 27.52 | 695 | 240 | 65.5 |
| C13 | 0.089 | 0.077 | 123.0 | 118.2 | 51.03 | 2663.0 | 23.58 | 279.03 | 47.97 | 690 | 67.5 | 90.2 |
| C14 | 0.094 | 0.103 | 124.5 | 127.8 | 103.46 | 2983.4 | 44.14 | 162.50 | 7.08 | 960 | 240 | 75.0 |
| C15 | 0.079 | 0.093 | 119.0 | 124.2 | 55.02 | 723.6 | 22.11 | 78.69 | 12.19 | 960 | 155 | 83.8 |
| C16 | 0.092 | 0.106 | 124.0 | 128.8 | 102.57 | 829.4 | 42.44 | 47.00 | 7.42 | 980 | 410 | 58.2 |
| C17 | 0.091 | 0.097 | 123.5 | 125.6 | 54.39 | 2982.4 | 21.35 | 335.98 | 50.17 | 980 | 191 | 80.5 |
| C18 | 0.075 | 0.068 | 117.5 | 114.1 | 107.30 | 807.5 | 41.97 | 47.52 | 7.00 | 920 | 298 | 67.6 |
| C19 | 0.078 | 0.072 | 118.7 | 116.0 | 104.29 | 2903.5 | 40.95 | 175.13 | 25.83 | 715 | 80 | 88.8 |

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Table D-2 (cont).  DATA CONSOLIDATION -- SERIES C-XX -- KEY WEST CORAL

| Test Number | GAS HUMIDITY (lb/lb dry air) IN | OUT | DEW POINT (°F) IN | OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft³) | (lb/lb) | ABSORPTION PARAMETERS Entering SO₂ Concentration (ppm) | Leaving SO₂ Concentration (ppm) | SO₂ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C20 | 0.074 | 0.061 | 117.0 | 110.6 | 56.92 | 704.4 | 21.50 | 80.95 | 11.52 | 735 | 108 | 85.3 |
| C21 | 0.075 | 0.069 | 117.5 | 114.8 | 56.87 | 2903.5 | 21.43 | 334.65 | 47.49 | 735 | 198 | 73.1 |
| C22 | 0.081 | 0.084 | 119.6 | 121.0 | 103.78 | 807.5 | 41.59 | 47.96 | 7.20 | 815 | 355 | 56.4 |
| C23 | 0.081 | 0.088 | 119.6 | 122.4 | 104.95 | 829.4 | 42.55 | 46.88 | 7.26 | 800 | 202 | 74.7 |
| C24 | 0.081 | 0.089 | 119.6 | 122.9 | 56.13 | 2735.4 | 22.28 | 295.24 | 45.08 | 750 | 48 | 93.6 |
| C25 | 0.082 | 0.103 | 120.2 | 128.0 | 105.47 | 2982.4 | 42.29 | 169.59 | 26.14 | 750 | 128 | 82.9 |
| C26 | 0.088 | 0.101 | 122.4 | 126.9 | 81.10 | 1689.2 | 32.25 | 127.63 | 19.14 | 780 | 225 | 71.2 |
| C27 | 0.084 | 0.101 | 121.0 | 127.0 | 81.83 | 1689.2 | 32.47 | 126.80 | 19.04 | 825 | 243 | 70.5 |
| C28 | 0.081 | 0.088 | 119.6 | 122.4 | 56.13 | 723.6 | 21.75 | 80.00 | 11.92 | 770 | 166 | 78.4 |
| C29 | - | - | - | - | - | V O I D | - | - | - | - | - | - |
| C30 | 0.083 | 0.095 | 120.5 | 124.8 | 55.60 | 2982.4 | 21.75 | 329.76 | 49.53 | 810 | 45 | 94.4 |
| C31 | 0.083 | 0.094 | 120.5 | 124.5 | 79.63 | 1436.7 | 32.36 | 108.20 | 16.66 | 1000 | 262 | 73.8 |
| C32 | 0.083 | 0.094 | 120.5 | 124.5 | 79.63 | 1436.7 | 32.36 | 108.20 | 16.66 | 1000 | 230 | 77.0 |
| C33A | 0.085 | 0.101 | 121.3 | 126.9 | 79.48 | 1436.7 | 32.57 | 107.49 | 16.66 | 1000 | 312 | 68.8 |
| C33B | 0.085 | 0.101 | 121.3 | 126.9 | 79.48 | 1436.7 | 32.57 | 107.49 | 16.66 | 1000 | 265 | 73.5 |
| C34A | 0.085 | 0.101 | 121.3 | 126.9 | 79.48 | 1436.7 | 32.57 | 107.49 | 16.66 | 1000 | 265 | 73.5 |
| C34B | 0.085 | 0.101 | 121.3 | 126.9 | 79.48 | 1436.7 | 32.57 | 107.49 | 16.66 | 1000 | 255 | 74.5 |

Table D-3.  DATA CONSOLIDATION -- SERIES F-XX -- KEY WEST FREDONIA VALLEY LIMESTONE

| Test Number | GAS HUMIDITY (lb/lb dry air) IN | OUT | DEW POINT (°F) IN | OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft$^3$) | (lb/lb) | ABSORPTION PARAMETERS Entering $SO_2$ Concentration (ppm) | Leaving $SO_2$ Concentration (ppm) | $SO_2$ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F1 | - | - | - | - | - | V O I D | - | - | - | - | - | - |
| F2 | - | - | - | - | - | V O I D | - | - | - | - | - | - |
| F3 | 0.092 | 0.099 | 123.9 | 126.3 | 54.72 | 704.4 | 22.49 | 77.36 | 11.79 | 491 | 142 | 71.1 |
| F4 | 0.077 | 0.088 | 118.2 | 122.5 | 54.77 | 704.4 | 22.22 | 78.32 | 11.94 | 494 | 83 | 83.2 |
| F5 | 0.091 | 0.094 | 123.5 | 124.6 | 103.18 | 704.4 | 43.46 | 40.04 | 6.26 | 465 | 210 | 54.8 |
| F6 | 0.090 | 0.093 | 123.2 | 124.2 | 104.27 | 807.5 | 43.08 | 46.31 | 7.10 | 415 | 172 | 58.6 |
| F7 | 0.085 | 0.098 | 121.4 | 126.0 | 104.68 | 2903.5 | 43.25 | 165.85 | 25.56 | 415 | 97.5 | 76.5 |
| F8 | 0.079 | 0.083 | 119.0 | 120.6 | 55.45 | 704.4 | 21.94 | 79.30 | 11.77 | 413 | 111 | 73.1 |
| F9 | 0.092 | 0.103 | 123.9 | 127.5 | 103.51 | 2982.4 | 43.12 | 166.30 | 26.38 | 414 | 52 | 87.4 |
| F10 | 0.087 | 0.093 | 122.1 | 124.2 | 54.22 | 723.6 | 22.07 | 78.85 | 12.22 | 414 | 48 | 88.4 |
| F11 | 0.093 | 0.110 | 124.3 | 130.0 | 105.46 | 829.4 | 45.16 | 44.17 | 7.20 | 414 | 207 | 50.0 |
| F12 | 0.094 | 0.099 | 124.7 | 126.3 | 103.39 | 807.5 | 44.77 | 44.55 | 7.14 | 414 | 116 | 71.9 |
| F13 | 0.092 | 0.082 | 124.0 | 120.5 | 48.94 | 2903.5 | 20.39 | 351.72 | 54.33 | 510 | 49 | 90.4 |
| F14 | 0.079 | 0.075 | 119.0 | 117.5 | 55.79 | 2735.4 | 20.99 | 313.45 | 45.49 | 920 | 460 | 50.0 |
| F15 | 0.080 | 0.072 | 119.5 | 116.0 | 105.52 | 2903.5 | 41.06 | 174.68 | 25.48 | 775 | 135 | 82.6 |
| F16 | 0.075 | 0.061 | 117.5 | 111.0 | 57.16 | 704.4 | 21.43 | 81.19 | 11.46 | 780 | 165 | 78.8 |
| F17 | 0.075 | 0.070 | 117.5 | 115.5 | 57.02 | 2903.5 | 21.43 | 334.70 | 47.37 | 780 | 183 | 76.5 |
| F18 | 0.082 | 0.091 | 120.5 | 123.5 | 104.47 | 807.5 | 43.08 | 46.31 | 7.14 | 840 | 435 | 48.2 |
| F19 | 0.077 | 0.088 | 118.2 | 122.7 | 57.20 | 723.6 | 22.13 | 78.62 | 11.75 | 775 | 143 | 81.5 |

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## Table D-3 (cont). DATA CONSOLIDATION — SERIES F-XX — KEY WEST FREDONIA VALLEY LIMESTONE

| Test Number | GAS HUMIDITY (lb/lb dry air) IN | OUT | DEW POINT (°F) IN | OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft³) | (lb/lb) | ABSORPTION PARAMETERS Entering SO₂ Concentration (ppm) | Leaving SO₂ Concentration (ppm) | SO₂ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F20 | 0.086 | 0.110 | 121.6 | 130.0 | 103.02 | 2982.4 | 42.06 | 170.53 | 26.66 | 830 | 420 | 49.4 |
| F21 | 0.088 | 0.10 | 122.5 | 126.5 | 103.33 | 829.4 | 42.76 | 46.65 | 7.38 | 830 | 260 | 68.7 |
| F22 | 0.078 | 0.073 | 118.7 | 116.5 | 54.64 | 2735.6 | 21.16 | 310.93 | 46.44 | 720 | 30 | 95.8 |
| F23 | 0.085 | 0.088 | 121.5 | 122.5 | 78.56 | 1689.2 | 31.41 | 131.08 | 19.82 | 780 | 120 | 84.6 |
| F24 | 0.085 | 0.088 | 121.3 | 122.5 | 80.90 | 1689.2 | 32.04 | 128.48 | 19.24 | 780 | 110 | 85.9 |
| F25 | 0.084 | 0.088 | 121.0 | 122.6 | 81.83 | 1689.2 | 32.57 | 126.38 | 19.04 | 820 | 122 | 85.1 |
| F26 | 0.083 | 0.089 | 120.5 | 122.8 | 56.17 | 2982.4 | 21.60 | 332.02 | 49.03 | 780 | 195 | 75.0 |
| F27 | 0.088 | 0.095 | 122.5 | 125.0 | 101.91 | 2903.5 | 42.23 | 169.85 | 26.19 | 810 | 185 | 77.2 |
| F28 | 0.081 | 0.103 | 120.0 | 127.7 | 102.93 | 2982.4 | 42.23 | 169.85 | 26.80 | 800 | 112 | 86.0 |
| F29 | 0.090 | 0.094 | 123.4 | 124.6 | 54.96 | 2982.4 | 21.96 | 326.57 | 49.78 | 855 | 82.5 | 90.4 |
| F30 | 0.089 | 0.103 | 123.0 | 127.6 | 55.01 | 723.6 | 22.17 | 78.47 | 12.08 | 855 | 225 | 73.7 |
| F31 | 0.077 | 0.080 | 118.5 | 119.5 | 94.16 | 2663.0 | 38.51 | 170.80 | 26.26 | 922 | 204 | 79.4 |
| F32 | 0.086 | 0.070 | 121.5 | 115.5 | 78.77 | 2783.2 | 31.62 | 217.45 | 32.56 | 965 | 155 | 83.9 |
| F33 | 0.092 | 0.069 | 123.8 | 115.0 | 47.81 | 2439.6 | 18.67 | 322.73 | 46.73 | 1015 | 57 | 94.4 |
| F34 | 0.092 | 0.069 | 123.8 | 115.0 | 55.28 | 3152.6 | 21.75 | 358.05 | 52.22 | 1015 | 70 | 93.1 |
| F35 | 0.089 | 0.069 | 123.0 | 114.7 | 32.17 | 1846.9 | 12.43 | 366.89 | 52.72 | 1015 | 38 | 96.3 |
| F35A | 0.089 | 0.069 | 123.0 | 114.7 | 102.66 | 2293.6 | 42.95 | 131.92 | 20.51 | 1015 | 180 | 82.3 |
| F36 | 0.082 | 0.076 | 120.0 | 118.0 | 77.78 | 2663.0 | 31.83 | 206.67 | 31.64 | 1000 | 144 | 85.6 |
| F37 | 0.088 | 0.062 | 122.5 | 111.5 | 74.45 | 755.9 | 68.05 | 61.75 | 9.33 | 965 | 286 | 70.4 |

Table D-3 (cont). DATA CONSOLIDATION -- SERIES F-XX -- KEY WEST FREDONIA VALLEY LIMESTONE

| Test Number | GAS HUMIDITY (lb/lb dry air) IN | GAS HUMIDITY (lb/lb dry air) OUT | DEW POINT (°F) IN | DEW POINT (°F) OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft³) | LIQUID/GAS RATIO (lb/lb) | ABSORPTION PARAMETERS Entering SO$_2$ Concentration (ppm) | Leaving SO$_2$ Concentration (ppm) | SO$_2$ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F38 | 0.088 | 0.058 | 122.3 | 109.0 | 53.43 | 953.5 | 47.56 | 111.45 | 16.40 | 965 | 183 | 81.0 |
| F39 | 0.086 | 0.054 | 121.7 | 107.0 | 39.49 | 919.2 | 34.34 | 149.23 | 21.43 | 975 | 116 | 88.1 |
| F40 | - | - | - | - | - | 859.0 | 30.66 | 155.76 | 22.95 | 975 | 94.5 | 90.3 |
| F41 | 0.086 | 0.070 | 121.8 | 115.3 | 93.33 | 438.1 | 85.96 | 28.33 | 4.34 | 965 | 415 | 57.0 |
| F42 | 0.086 | 0.101 | 121.5 | 126.8 | 80.05 | 1436.7 | 33.74 | 103.77 | 16.53 | 970 | 285 | 70.6 |

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Table D-4. DATA CONSOLIDATION -- SERIES HL-XX, D-XX, PC-XX, AND X-XX -- KEY WEST LIME, DOLOMITE, PRECIPITATED CaCO$_3$, AND RECYCLED LIMESTONE

| Test Number | GAS HUMIDITY (lb/lb dry air) IN | OUT | DEW POINT (°F) IN | OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft³) | (lb/lb) | ABSORPTION PARAMETERS Entering SO$_2$ Concentration (ppm) | Leaving SO$_2$ Concentration (ppm) | SO$_2$ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HL1 | 0.080 | 0.096 | 119.5 | 125.5 | 103.02 | 807.5 | 41.59 | 47.96 | 7.26 | 750 | 102 | 86.4 |
| HL2 | 0.088 | 0.077 | 122.5 | 118.1 | 55.91 | 2903.5 | 21.81 | 328.79 | 47.73 | 216 | 40 | 94.9 |
| HL3 | 0.085 | 0.077 | 121.6 | 118.1 | 55.50 | 704.4 | 21.75 | 80.00 | 11.70 | 775 | 51 | 93.4 |
| HL4 | 0.087 | 0.089 | 122.1 | 123.0 | 102.36 | 2903.5 | 41.91 | 171.14 | 25.92 | 815 | 20 | 97.5 |
| D1 | 0.089 | 0.094 | 123.0 | 124.5 | 101.11 | 807.5 | 42.44 | 47.00 | 7.33 | 860 | 580 | 32.6 |
| D2 | 0.089 | 0.086 | 122.7 | 121.7 | 101.11 | 2903.5 | 42.44 | 169.00 | 26.37 | 860 | 420 | 51.2 |
| D3 | 0.085 | 0.081 | 121.2 | 120.0 | 54.79 | 704.4 | 22.03 | 79.00 | 11.85 | 880 | 425 | 51.7 |
| D4 | 0.085 | 0.094 | 121.2 | 124.6 | 54.79 | 2903.5 | 22.03 | 325.63 | 48.84 | 830 | 400 | 51.8 |
| PC1 | 0.085 | 0.094 | 121.5 | 124.5 | 101.55 | 807.48 | 42.44 | 47.00 | 7.33 | 860 | 280 | 67.4 |
| PC2 | 0.100 | 0.092 | 126.5 | 124.0 | 55.42 | 2903.5 | 21.90 | 327.52 | 48.47 | 825 | 120 | 85.5 |
| PC3 | 0.083 | 0.087 | 120.4 | 122.3 | 54.96 | 704.4 | 21.92 | 79.38 | 11.83 | 830 | 150 | 81.9 |
| PC4 | – | – | – | – | – | VOID | – | – | – | – | – | – |
| X1 | 0.088 | 0.097 | 122.5 | 125.5 | 78.56 | 1689.2 | 31.62 | 130.20 | 19.76 | 860 | 258 | 70.0 |

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Table D-5.  DATA CONSOLIDATION — SERIES P-XX — PADUCAH-SHAWNEE NO. 9 LIMESTONE

| Test Number | GAS HUMIDITY (1b/1b dry air) IN | OUT | DEW POINT (°F) IN | OUT | DRY GAS FLOW RATE (1b/min) | LIQUID FLOW RATE (1b/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft$^3$) | (1b/1b) | ABSORPTION PARAMETERS Entering SO$_2$ Concentration (ppm) | Leaving SO$_2$ Concentration (ppm) | SO$_2$ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P1 | 0.071 | 0.054 | 115.9 | 107.0 | 31.78 | 281.0 | 26.02 | 60.55 | 8.26 | 2450 | 1175 | 52.0 |
| P2 | 0.074 | 0.049 | 117.0 | 104.5 | 30.256 | 281.0 | 24.83 | 63.46 | 8.65 | 2350 | 1080 | 54.0 |
| P3 | 0.072 | 0.051 | 116.0 | 105.0 | 30.17 | 800.4 | 24.59 | 182.52 | 24.75 | 2350 | 700 | 70.2 |
| P4 | 0.048 | 0.040 | 103.0 | 97.5 | 31.30 | 698.2 | 24.11 | 162.38 | 21.29 | 1900 | 310 | 83.7 |
| P5 | 0.059 | 0.065 | 110.0 | 113.0 | 45.08 | 698.2 | 36.76 | 106.49 | 14.63 | 1995 | 765 | 61.7 |
| P6 | 0.051 | 0.063 | 105.1 | 112.0 | 45.42 | 698.2 | 37.62 | 104.06 | 14.63 | 1500 | 490 | 67.3 |
| P7 | 0.061 | 0.060 | 111.0 | 110.5 | 44.78 | 289.5 | 37.25 | 43.59 | 6.09 | 1500 | 980 | 34.7 |
| P8 | 0.077 | 0.066 | 118.3 | 113.1 | 43.97 | 289.5 | 37.58 | 43.20 | 6.11 | 1750 | 1090 | 37.7 |
| P9 | 0.059 | 0.033 | 110.0 | 92.0 | 30.17 | 289.5 | 24.64 | 65.89 | 9.06 | 940 | 440 | 53.2 |
| P10 | 0.061 | 0.053 | 110.8 | 106.3 | 30.12 | 289.5 | 24.64 | 65.89 | 9.06 | 940 | 505 | 46.3 |
| P11 | 0.054 | 0.059 | 107.0 | 110.0 | 30.46 | 698.2 | 24.02 | 163.02 | 21.75 | 2200 | 575 | 73.9 |
| P12 | 0.054 | 0.059 | 107.0 | 110.0 | 30.46 | 698.2 | 24.02 | 163.02 | 21.75 | 2200 | 660 | 70.0 |
| P13 | 0.060 | 0.066 | 110.5 | 113.5 | 44.82 | 289.5 | 37.58 | 43.20 | 6.09 | 2230 | 1420 | 36.3 |
| P14 | 0.051 | 0.058 | 105.5 | 109.5 | 45.15 | 289.5 | 37.24 | 43.59 | 6.08 | 1450 | 840 | 42.1 |
| P15 | 0.051 | 0.068 | 105.5 | 114.0 | 45.22 | 698.2 | 37.24 | 105.13 | 14.65 | 1470 | 550 | 62.6 |
| P16 | 0.051 | 0.068 | 105.5 | 114.0 | 45.22 | 698.2 | 37.24 | 105.13 | 14.65 | 1470 | 475 | 67.7 |
| P17 | − | − | − | − | − | V O I D | − | − | − | − | − | − |
| P18 | − | − | − | − | − | V O I D | − | − | − | − | − | − |
| P19 | 0.059 | 0.068 | 110.0 | 114.0 | 37.66 | 604.6 | 31.13 | 108.90 | 15.16 | 1900 | 730 | 61.6 |

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Table D-5 (cont).  DATA CONSOLIDATION -- SERIES P-XX -- PADUCAH-SHAWNEE NO. 9 LIMESTONE

| Test Number | GAS HUMIDITY (lb/lb dry air) IN | OUT | DEW POINT (°F) IN | OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft³) | (lb/lb) | ABSORPTION PARAMETERS Entering SO₂ Concentration (ppm) | Leaving SO₂ Concentration (ppm) | SO₂ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P20 | 0.061 | 0.068 | 111.0 | 114.0 | 37.59 | 604.6 | 31.27 | 108.40 | 15.16 | 2050 | 800 | 61.0 |
| P21 | 0.060 | 0.068 | 110.5 | 114.0 | 37.56 | 604.6 | 31.42 | 107.90 | 15.19 | 2000 | 750 | 62.5 |
| P22 | 0.053 | 0.058 | 106.6 | 109.3 | 38.02 | 604.6 | 30.94 | 109.57 | 15.10 | 2025 | 700 | 65.4 |
| P23 | 0.056 | 0.056 | 108.1 | 107.9 | 37.92 | 604.6 | 31.42 | 107.90 | 15.10 | 1875 | 700 | 62.7 |
| P24 | 0.060 | 0.056 | 108.0 | 107.9 | 37.77 | 604.6 | 31.61 | 107.25 | 15.10 | 2025 | 775 | 64.2 |
| P25 | 0.055 | 0.061 | 107.0 | 110.7 | 37.84 | 604.6 | 31.61 | 107.25 | 15.10 | 1650 | 525 | 63.2 |
| P26 | 0.054 | 0.061 | 107.0 | 110.7 | 37.99 | 604.6 | 31.61 | 107.25 | 15.10 | 1850 | 715 | 61.4 |
| P27 | 0.059 | 0.065 | 109.7 | 113.0 | 37.95 | 604.6 | 31.27 | 108.40 | 15.04 | 1650 | 500 | 69.7 |
| P28 | 0.059 | 0.065 | 109.7 | 113.0 | 37.95 | 604.6 | 31.27 | 108.40 | 15.04 | 1700 | 550 | 67.6 |
| P29 | 0.054 | 0.063 | 107.0 | 111.7 | 37.66 | 604.6 | 30.84 | 109.91 | 15.04 | 1850 | 775 | 58.1 |
| P30 | 0.059 | 0.068 | 110.0 | 114.4 | 37.59 | 604.6 | 30.80 | 110.08 | 15.19 | 1730 | 560 | 67.6 |
| P31 | 0.062 | 0.065 | 111.5 | 113.0 | 37.48 | 604.6 | 30.80 | 110.08 | 15.19 | 1700 | 590 | 65.3 |
| P32 | 0.069 | 0.072 | 114.5 | 116.0 | 37.60 | 604.6 | 31.23 | 108.56 | 15.01 | 2100 | 760 | 63.8 |
| P33 | 0.077 | 0.074 | 118.1 | 117.0 | 44.33 | 289.5 | 37.91 | 42.82 | 6.06 | 2300 | 1125 | 51.1 |
| P34 | 0.076 | 0.072 | 117.7 | 116.0 | 43.30 | 698.2 | 38.10 | 102.76 | 14.65 | 2420 | 975 | 59.7 |
| P35 | 0.069 | 0.072 | 114.6 | 116.3 | 37.74 | 596.3 | 31.27 | 108.40 | 14.78 | 2620 | 1040 | 60.3 |

Table D-6.  DATA CONSOLIDATION -- SERIES PA-XX, AND PS-XX -- PADUCAH-SHAWNEE

NO. 9 ARAGONITE AND SIMULATED KEY WEST LIMESTONE

| Test Number | GAS HUMIDITY (lb/lb dry air) | | DEW POINT (°F) | | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO | | ABSORPTION PARAMETERS | | |
| | | | | | | | | | | Entering $SO_2$ Concentration (ppm) | Leaving $SO_2$ Concentration (ppm) | $SO_2$ Removal Efficiency (%) |
| | IN | OUT | IN | OUT | | | | (gal/1000ft$^3$) | (lb/lb) | | | |
| PA1 | 0.060 | 0.081 | 110.5 | 120.0 | 45.04 | 289.5 | 37.05 | 43.81 | 6.06 | 2050 | 780 | 62.0 |
| PA2 | 0.060 | 0.078 | 110.5 | 118.7 | 45.04 | 289.5 | 37.05 | 43.81 | 6.06 | 2050 | 700 | 65.9 |
| PA3 | 0.056 | 0.051 | 108.0 | 105.0 | 28.15 | 698.2 | 21.25 | 184.27 | 23.49 | 1600 | 160 | 90.0 |
| PA4 | 0.056 | 0.049 | 108.0 | 103.7 | 28.15 | 698.2 | 21.25 | 184.27 | 23.49 | 1200 | 84 | 93.0 |
| PA5 | 0.087 | 0.064 | 122.2 | 112.5 | 36.84 | 698.2 | 31.75 | 123.31 | 17.44 | 2500 | 820 | 67.2 |
| PA6 | 0.086 | 0.069 | 122.0 | 115.0 | 36.87 | 698.2 | 31.89 | 122.75 | 17.44 | 2700 | 860 | 68.1 |
| PA7 | 0.088 | 0.064 | 122.3 | 112.0 | 36.94 | 698.2 | 30.56 | 128.13 | 17.37 | 2350 | 600 | 74.5 |
| PA8 | 0.086 | 0.064 | 121.7 | 112.3 | 37.01 | 698.2 | 30.84 | 126.93 | 17.37 | 2100 | 590 | 71.9 |
| | | | | | | | | | | | | |
| PS1 | 0.058 | 0.063 | 109.0 | 112.0 | 38.21 | 604.6 | 30.37 | 111.64 | 14.96 | 2000 | 450 | 77.5 |
| PS2 | 0.058 | 0.068 | 109.0 | 114.2 | 38.21 | 604.6 | 30.37 | 111.64 | 14.96 | 2020 | 525 | 74.0 |
| PS3 | 0.059 | 0.057 | 110.0 | 108.3 | 38.17 | 604.6 | 30.37 | 111.64 | 14.96 | 2020 | 525 | 74.0 |

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| Test Number | GAS HUMIDITY (lb/lb dry air) IN | OUT | DEW POINT (°F) IN | OUT | DRY GAS FLOW RATE (lb/min) | LIQUID FLOW RATE (lb/min) | GAS VELOCITY (ft/sec) | LIQUID/GAS RATIO (gal/1000ft³) | (lb/lb) | ABSORPTION PARAMETERS Entering SO₂ Concentration (ppm) | Leaving SO₂ Concentration (ppm) | SO₂ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IPA1 | 0.052 | 0.061 | 106.0 | 111.0 | 45.01 | 289.5 | 39.25 | 41.36 | 6.11 | 750 | 180 | 76.0 |
| IPA2 | 0.055 | 0.067 | 108.0 | 113.8 | 45.40 | 698.2 | 37.62 | 104.06 | 14.58 | 415 | 31.5 | 92.4 |
| IPA3 | 0.053 | 0.064 | 106.5 | 112.3 | 30.64 | 698.2 | 25.73 | 152.13 | 21.64 | 415 | 78 | 81.2 |
| IPA4 | 0.049 | 0.052 | 104.0 | 105.5 | 30.90 | 698.2 | 24.92 | 157.09 | 21.54 | 510 | 30 | 94.1 |
| IP1 | 0.051 | 0.054 | 105.0 | 106.8 | 37.80 | 698.2 | 31.18 | 125.57 | 17.57 | 420 | 37.5 | 91.1 |
| IP2 | 0.063 | 0.051 | 111.7 | 105.3 | 38.03 | 698.2 | 30.37 | 128.93 | 17.27 | 700 | 46.5 | 93.4 |
| IP3 | 0.061 | 0.51 | 111.0 | 105.0 | 37.96 | 698.2 | 30.56 | 128.13 | 17.34 | 975 | 262 | 73.1 |
| IP4 | 0.051 | 0.059 | 105.3 | 109.5 | 37.58 | 698.2 | 31.42 | 124.62 | 17.68 | 1080 | 285 | 73.6 |
| IP5 | 0.053 | 0.057 | 106.2 | 108.7 | 38.10 | 698.2 | 31.18 | 125.57 | 17.37 | 420 | 40 | 90.5 |
| IP6 | 0.052 | 0.055 | 106.0 | 107.8 | 38.50 | 698.2 | 30.51 | 128.33 | 17.24 | 495 | 75 | 84.8 |
| IP7 | 0.052 | 0.051 | 105.7 | 105.5 | 37.48 | 698.2 | 31.23 | 125.38 | 17.71 | 250 | 30 | 88.0 |
| IP8 | 0.075 | 0.089 | 117.5 | 122.7 | 36.75 | 698.2 | 33.42 | 117.14 | 17.68 | 2000 | 600 | 70.0 |
| IP9 | 0.063 | 0.068 | 111.9 | 114.3 | 44.77 | 800.4 | 38.05 | 117.94 | 16.82 | 2625 | 1050 | 60.0 |
| IP10 | 0.063 | 0.068 | 111.9 | 114.3 | 44.77 | 800.4 | 38.05 | 117.94 | 16.82 | 2625 | 1050 | 60.0 |
| IP11 | 0.085 | 0.070 | 121.3 | 115.4 | 43.57 | 800.4 | 38.58 | 116.34 | 16.93 | 2450 | 460 | 81.2 |
| IP12 | 0.087 | 0.071 | 122.2 | 115.5 | 43.71 | 289.5 | 38.48 | 42.18 | 6.09 | 1520 | 540 | 64.5 |
| IP13 | 0.085 | 0.071 | 121.3 | 115.5 | 26.12 | 272.5 | 22.30 | 68.52 | 9.62 | 1250 | 350 | 72.0 |

# APPENDIX E

## UNITS OF MEASURE

It is EPA policy to express all measurements in metric units. If undue costs or difficulty in clarity result from implementing this practice, British units may be employed and a conversion table provided. Such is the case with this document, the first draft of which was submitted before promulgation of the EPA policy.

|  | British | Metric |
|---|---|---|
| Length | 1 inch (in.) | 2.54 centimeters |
|  | 1 foot (ft) | 0.3048 meters |
| Power | 1 horsepower (HP) | 746 watts |
| Volume | 1 cubic foot (cf)(ft$^3$) | 28.3161 liters |
|  | 1 gallon (gal) | 3.7853 liters |
| Pressure | 1 inch of water (in.H$_2$O) | 2419 dynes per square centimeter |
|  | 1 inch of mercury (in.Hg) | 338639 " " |
|  | 1 pound per square inch (psi) | 689476 " " |
| Density | 1 pound per cubic foot (lb ft$^{-3}$) | 0.0160 grams per cubic centimeter |
| Mass | 1 ounce (oz) | 28.3495 grams |
|  | 1 pound (lb) | 453.5923 grams |
|  | 1 ton (T) | 907.1846 kilograms |
|  | 1 grain (gr) | 0.0648 grams |
| Temperature | 1$^\circ$ Fahrenheit ($^\circ$F) | (5/9)($^\circ$F-32) $^\circ$Centigrade |
|  | 1$^\circ$ Rankine ($^\circ$R) | (5/9)($^\circ$R) $^\circ$Kelvin |

| ORT NO.<br>>A-650/2-74-077 | 2. | | 3. RECIPIENT'S ACCESSION NO. |
|---|---|---|---|
| **LE AND SUBTITLE**<br>ne/Limestone Scrubbing in a Pilot Dustraxtor--<br>Key West | | | **5. REPORT DATE**<br>September 1974 |
| | | | **6. PERFORMING ORGANIZATION CODE** |
| **THOR(S)** Burke A. Bell; Terrence A. LiPuma;<br>J. M. Craig, Ph.D.; and J. K. Allison | | | **8. PERFORMING ORGANIZATION REPORT NO.** |
| **!FORMING ORGANIZATION NAME AND ADDRESS**<br>gineering Science, Inc.<br>)3 Westpark Drive<br>Lean, Virginia 22101 | | | **10. PROGRAM ELEMENT NO.**<br>1AB013; ROAP 21AQO-001 |
| | | | **11. CONTRACT/GRANT NO.**<br>CPA 70-61 |
| **ONSORING AGENCY NAME AND ADDRESS**<br>A, Office of Research and Development<br>RC-RTP, Control Systems Laboratory<br>search Triangle Park, NC 27711 | | | **13. TYPE OF REPORT AND PERIOD COVERED**<br>Final; January-July 1971 |
| | | | **14. SPONSORING AGENCY CODE** |

**!PPLEMENTARY NOTES**

**!STRACT** The report gives results of a 7-month series of nearly 200 tests of the Dust-
tor limestone wet scrubbing system in 1971, both in Key West, Florida, and at
A's Shawnee Plant in Kentucky. At Key West, No. 6 fuel oil containing 1-2.2% sulfur
burned; at Shawnee, 2-4% sulfur pulverized coal was burned. The tests included
tematic variation of stoichiometry, reactant particle size, slurry concentration,
ssure drop, and gas flow rate. Reactants tested included coral marl, Fredonia
ley limestone, dolomite, lime, aragonite, and precipitated calcium carbonate.
ts also included evaluation of spent reactant material, boiler injection of dry arag-
e, addition of an inhibitor and catalyst, and effects on particulate and NOx removal.
r installing an annular fresh water spray ring to reduce scale formation, the
traxtor worked satisfactorily. SO2 removal efficiencies varied up to 90-plus %,
ending on the reactant used. Absorption efficiency increased significantly with
reased pressure drop, decreased gas flow rate, increased stoichiometric ratio,
increased liquid-to-gas ratio. Other variables and an inhibitor and catalyst had no
nificant effect. NOx removal in the scrubber was negligible. Particulate removal
he total pilot plant system was excellent.

**KEY WORDS AND DOCUMENT ANALYSIS**

| DESCRIPTORS | | | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|---|---|
| Pollution | Limestone | Desulfurization | Air Pollution Control | 13B, 07D |
| ubbers | Marls | Nitrogen | Stationary Sources | 07A |
| shing | Dolomite | Oxides | Dustraxtor | 13H |
| l Oil | Aragonite | | Particulates | 21D, 11H |
| l | Calcium | | | |
| cium Oxides | Carbonates | | | 07B |

| STRIBUTION STATEMENT<br>imited | **19. SECURITY CLASS** *(This Report)*<br>Unclassified | **21. NO. OF PAGES**<br>157 |
|---|---|---|
| | **20. SECURITY CLASS** *(This page)*<br>Unclassified | **22. PRICE** |

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