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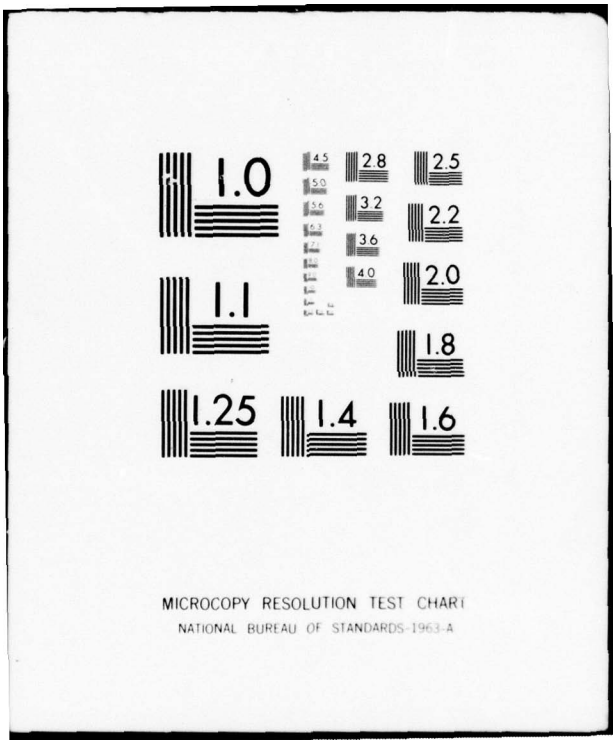
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EDGEWOOD ARSENAL CONTRACTOR REPORT

ED-CR-76078

SPECIES-DIFFERENTIATING CONTINUOUS MONITOR FOR AIRBORNE ACIDS

QUARTERLY PROGRESS REPORT
OCTOBER 1975 TO DECEMBER 1975

by

Martin S. Frant

Donald H. Beck

May 1976

ORION RESEARCH, INC.
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DEPARTMENT OF THE ARMY
Headquarters, Edgewood Arsenal
Aberdeen Proving Ground, Maryland 21010

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Wetted wall column
Ultrasonic nebulizer
Steam condensation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Further testing of a wetted wall column scrubber for preferential removal of nitric acid vapor showed a high collection efficiency for vapor and a high rejection of ammonium chloride particles. Calculations show that the wetted wall column can be designed to give a 1-2 minute response time. For sulfuric acid mist collection commercially available ultrasonic nebulizers must be modified. Work was begun on the investigation of steam condensation as a means of collecting particles.

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FOREWORD

Work was performed under Project 1T76208DO48, authorized by contract DAAA15-75-C-0199 with title the same as this report. Work was carried out from October 1975 through December of the same year.

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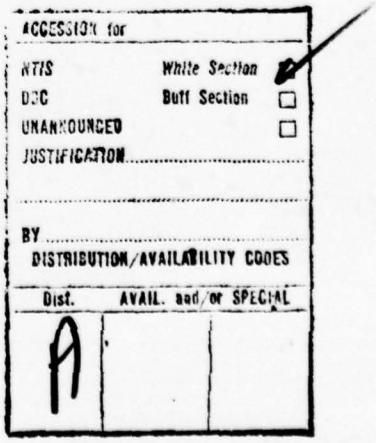

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I. BACKGROUND

The previous report gave the theoretical background for the work that has been undertaken in this project, and described in detail the proposed scrubbers for removal of nitric acid vapor and sulfuric acid mist. For the nitric acid scrubber, two proposed schemes were evaluated during the first quarter. The first of these used a wetted wall collector, with a frosted glass tube. The second approach used a "Celgard" membrane, with flow parallel to the membrane surface. Our preliminary results with the wetted wall column were particularly promising and the decision was made to go further with that approach. In the second quarter, some additional work was done on the nitric acid scrubber, but most of the efforts were on approaches for removal of the sulfuric acid mist.

II. WORK COMPLETED DURING THIS QUARTER

A. Nitric Acid Scrubber

The optimum configuration for the nitric acid scrubber, based on experiments during the previous quarter, was tested both for efficiency in removing gases (where a high collection efficiency is desired) and for efficiency in allowing particles to pass (where a low collection efficiency is needed). We found that, at a liquid flow rate of 0.6 ml (about 7 gallons/month) and air flow rate of 2 liters per minute (l/min), 96.5 to 99.7% of the gas was collected, and 99.0 to 99.4% of the particles passed through. See Table 1.

Table 1
Experimental Results on Preferred Nitric Acid Scrubber Design

(Test Performed Using Ammonia Gas & Ammonium Chloride Particles)

Air Flow Rate, (l/min)	Liquid Flow Rate, (ml/min)	Tubing Length	Substance Sought	Efficiency
2	0.6	37.5cm	Particles	1.0%
2	0.6	37.5cm	Gas	99.7%
2	0.6	50.0cm	Particles	0.6%
2	0.6	50.0cm	Gas	96.5%

Figures 1 and 2 show typical test results, in the form of calibration graphs, using an ammonia sensing electrode for the solution analysis. The vertical line indicates the electrode millivolt reading for zero ammonia present (0.1 M NaOH only). The solid curved line is the electrode response

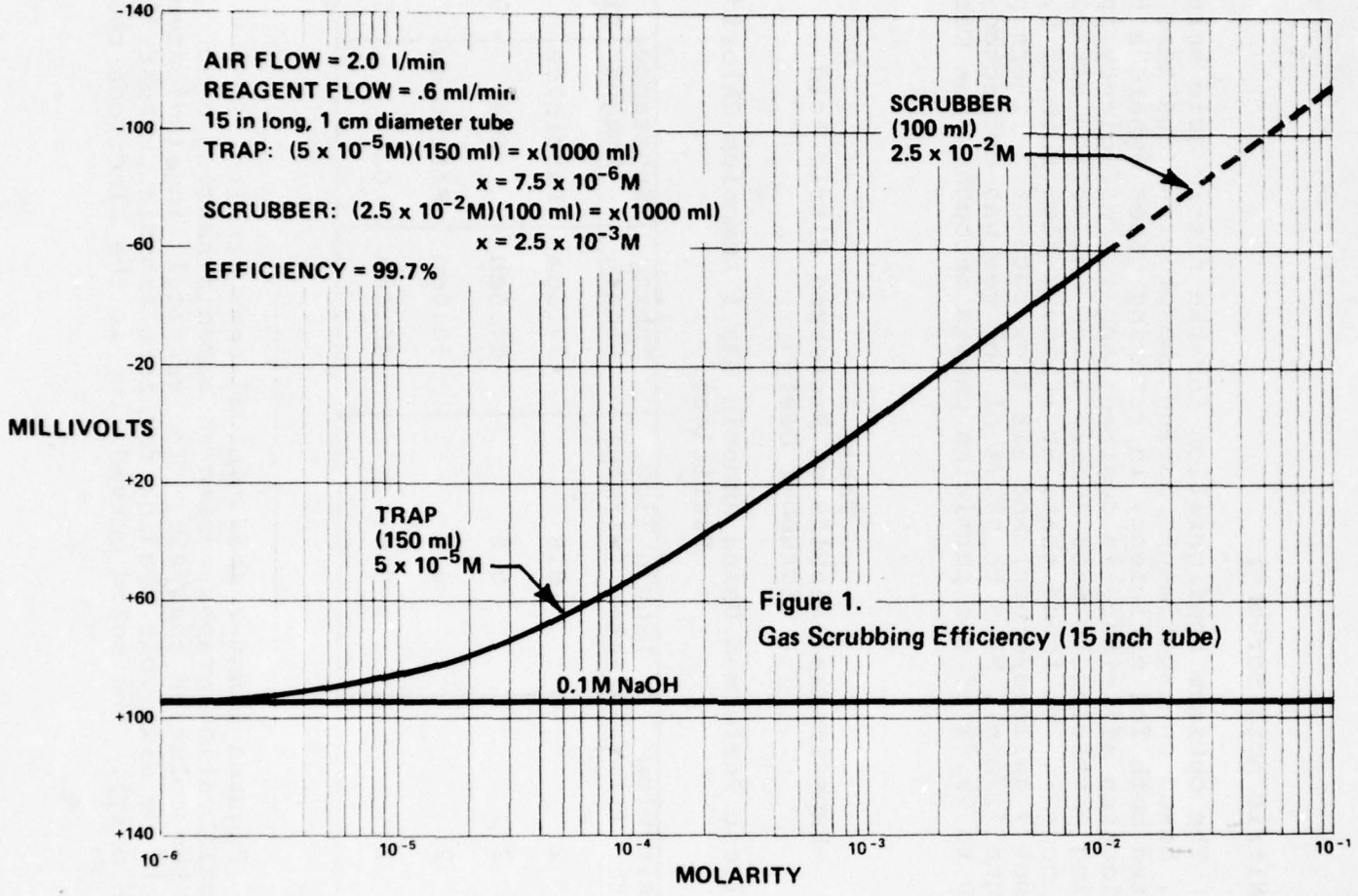

Figure 1.
Gas Scrubbing Efficiency (15 inch tube)

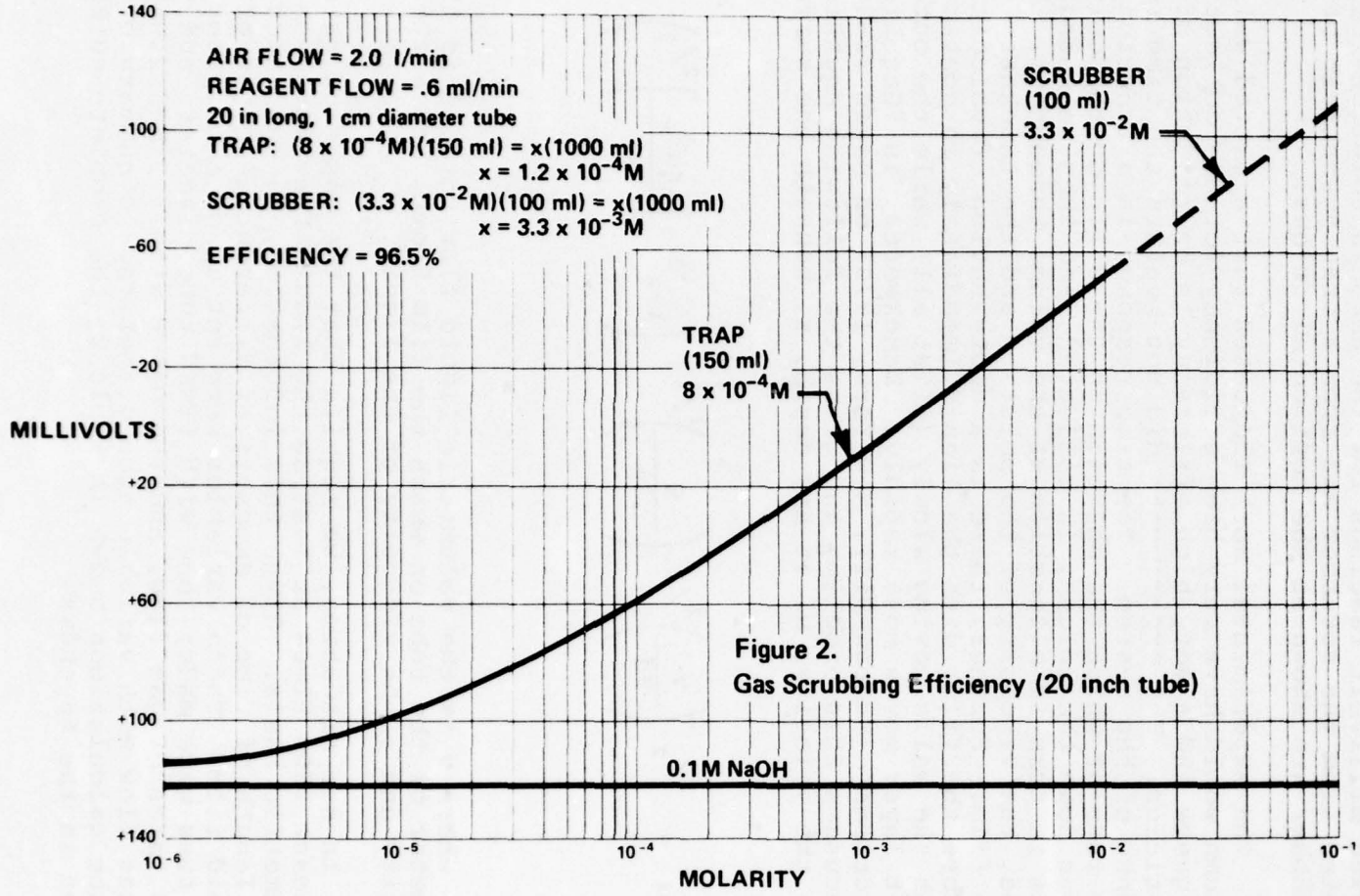

Figure 2.
Gas Scrubbing Efficiency (20 inch tube)

to ammonia solutions in the 0.1 M NaOH background. The observed millivolt readings for the ammonia solutions collected from the scrubber and from a trap downstream of the scrubber are shown at the horizontal arrows.

The experimental work indicated that a wetted wall column would have very high efficiency for the collection of gases and a very high efficiency in be rejection of particles. The experiments did not measure the time response of the system. The time response is a function of the rate at which the solution on the walls of the column moves down the column, is collected, and then is measured. This in turn is a function of the volume throughput, the area, the viscosity of the solution and the thickness of the film. Further, there is a distribution of velocities across the film, with the liquid immediately in contact with the walls moving slowly (if at all) while the outer most layer moves most rapidly. Danckwerts, in "Gas-Liquid Reactions" (McGraw-Hill, New York, 1970) on pages 73-80 discusses this problem, and gives the following equation for the velocity, u, at any depth, x, beneath the surface:

$$u = {}^{3}/_{2} \left(\frac{v}{\pi d}\right)^{2/3} \left(\frac{g}{3\mu}\right)^{1/3} \left(1-x^{2} \left[\frac{\pi g d \rho}{3\mu v}\right]^{2/3}\right)$$

Where v is the volumetric liquid flow rate, d is the diameter of the tube on which the film flows, and ρ the density and μ the viscosity of the liquid.

In our situation, we require that the gas flow rate be at least 2500 times as fast as the liquid flow rate, on a volumetric basis. Given this information, we can calculate the length of time of exposure of different segments of the liquid film. These variables were set up on a computer, and two runs were made: one with fixed tube diameters and variable rates of gas flow, and the other with a fixed 2.0 l/min. of gas flow with variable tube diameters. A summary of part of the calculations shown in Table 2; the complete output is given in the Appendix.

Table 2

Calculated 50% Response Times for the Wetted-Wall Nitric Acid Scrubber

Column Diam. (cm.)	Gas Flow Rate (l/min)	Height of Column (cm)	Liquid Flow Rate (ml/min)	50% Response Time (sec)
Part 1:				
0.5	0.5	16.7	0.2	28
0.5	1.0	33.3	0.4	35
0.5	4.0	133.3	1.6	56
0.5	7.0	233.3	2.8	68
0.5	10.0	333.3	4.0	76
1.0	0.5	333.3	4.0	45
1.0	1.0	333.3	4.0	56
1.0	4.0	333.3	4.0	89
1.0	7.0	333.3	4.0	107
1.0	10.0	333.3	4.0	121
2.0	10.0	333.3	4.0	71
2.0	10.0	333.3	4.0	89
2.0	10.0	333.3	4.0	141
2.0	10.0	333.3	4.0	170
2.0	10.0	333.3	4.0	192
Part 2:				
0.5	0.5	16.7	0.2	28
1.0	0.5	16.7	0.2	45
2.0	0.5	16.7	0.2	71
3.0	0.5	16.7	0.2	93
4.0	0.5	16.7	0.2	112
5.0	0.5	16.7	0.2	130

As can be seen, the results indicate that 50% response times in 1 to 2 minutes are quite feasible.

B. Sulfuric Acid Scrubber:

After the nitric acid vapor has been removed from the sample, the sulfuric acid which remains must be measured. Sulfuric acid exists in the form of mist, or fine liquid droplets, suspended in the cleaned sample stream. In order

to determine the concentration of this mist, it must either be absorbed into a liquid and pumped to a pH electrode, or it can be impinged directly on the face of an electrode placed in the gas stream. This latter technique will only work if there is sufficient liquid on the face of the electrode to provide a conducting path between the sensing element and the reference electrode. If sufficient additional liquid can be added to the system as a reagent mist, this approach should work. Since it should give a much faster response time, we concentrated initially on the impingement approach. The work divided itself into two phases - first, generating a suitable regent mist and second, determining if the combined mists would impinge on an electrode surface.

B.1. Nebulizers:

We have looked at several commercially available ultrasonic nebulizers for creating the mist for the H_2SO_4 scrubber. The advantages of using ultrasonics for mist creation is that we can generate an aerosol without also injecting additional air into the sample stream. This is important because we are working at low sulfuric acid levels and any air injected into the sample will dilute it further.

We borrowed a DeVilbiss Model 35B Ultrasonic Nebulizer for a two-week trial. This unit was designed to humidify air for medical inhalation devices. A schematic representation of the unit is shown in Figure 3. A fine mist is created in a chamber and an air stream is used to carry the mist to the point where it is to be used. In principle, the air stream could be the sample stream. The intermediate chamber is used to trap larger droplets that are created with the mist, and allow just the smallest mist particles to be carried away.

A quick experiment (see Figure 4) showed that with some development it would be possible to use a unit similar to this. A water column, contained in a brass tube with a flexible membrane at each end, was used to transmit the ultrasonic energy to what was in effect a remote transducer. The end of this column could be placed in the sample and generate the mist where it is needed (see Figure 5). The length of the column was varied and a maximum length of approximately 6 inches still worked.

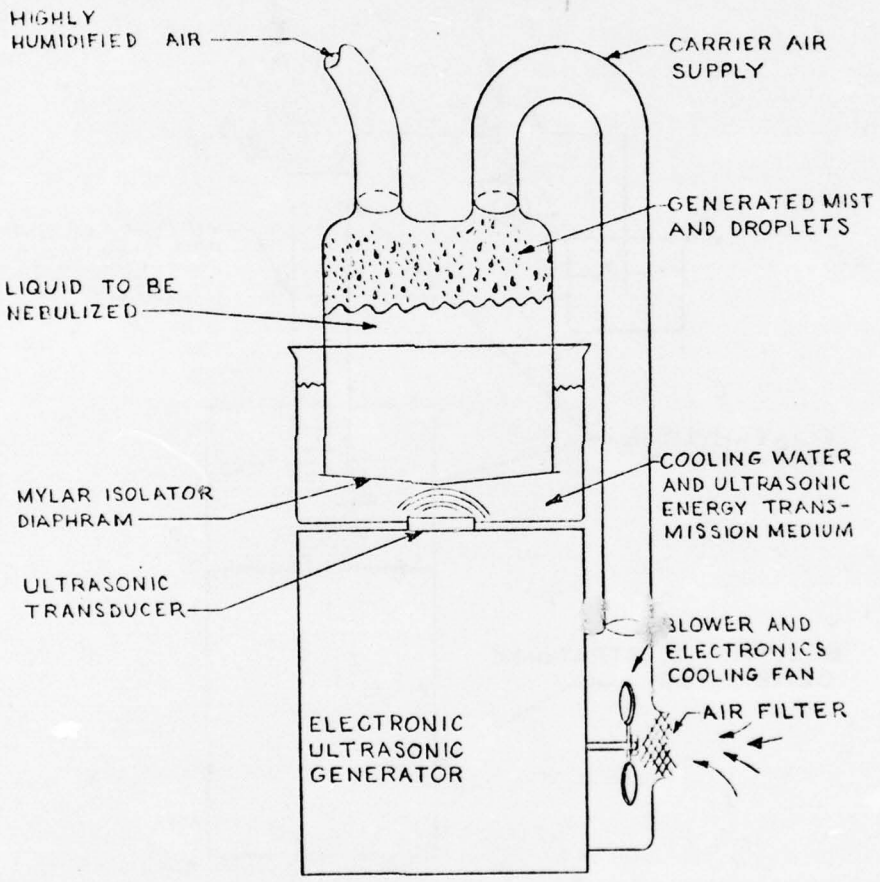

Figure 3. DeVilbiss Ultrasonic Nebulizer

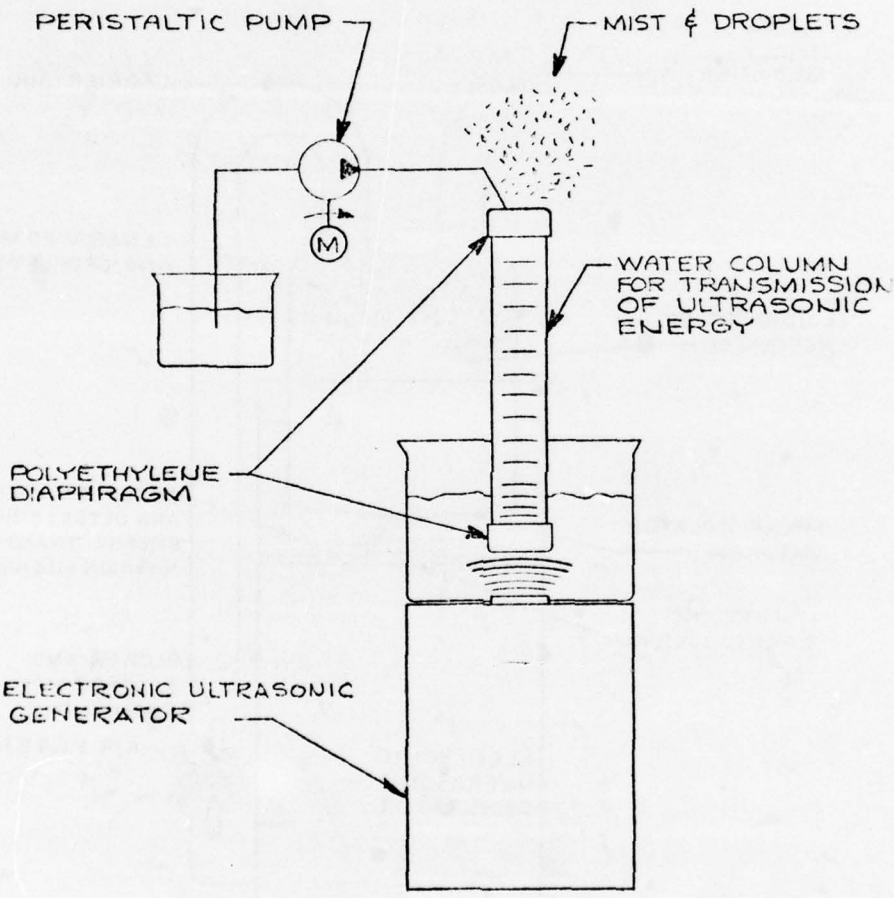

Figure 4. Ultrasonic Energy Transmission Column

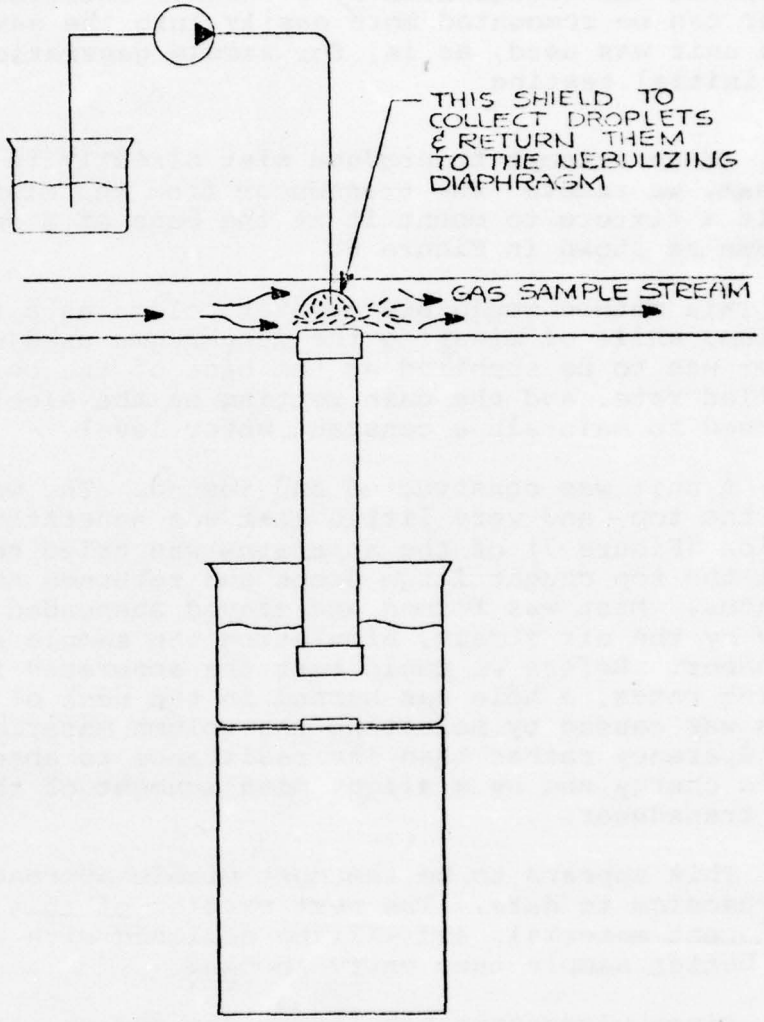

Figure 5. Mist Introduction Scheme

Another medical unit, a MistOGen Model UN14's was also obtained on trial and later purchased. The main advantage of this unit is that the transducer and the coolant water chamber are contained in a detachable unit which is connected to the electronics by a cable. Therefore the transducer can be remounted more easily into the sample stream. This unit was used, as is, for sample generation in some of the initial testing.

In an attempt to produce mist directly in the sample stream, we removed the transducer from the MistOGen cup and built a fixture to mount it at the base of a small water column as shown in Figure 6.

This method would use a water column as a transmission medium, while eliminating the diaphragms used previously. Water was to be supplied at the base of the column at a controlled rate, and the gain setting on the electronics would be used to maintain a constant water level.

A unit was constructed and tested. The water splashed out the top, and very little mist was generated. A modification (Figure 7) of the apparatus was tried next. The cap over the top caught large drops and returned them to the apparatus. Mist was formed and stayed suspended until carried away by the air stream, simulating the sample stream in the scrubber. Before we could test the apparatus for mist atomizing rates, a hole was burned in the neck of the column. This was caused by selecting the column material for its transparancy rather than its resistance to absorbing ultrasonic energy and by a slight misalignment of the column with the transducer.

This appears to be the most viable approach to using ultrasonics to date. The next version of this will use a different material, and will be designed with a lower volume and better sample tube entry in mind.

Since ultrasonic nebulizers for medical use are not directly applicable to our case, we looked at other fields where ultrasonics were used in ways which may be more directly applicalbe to our requirements.

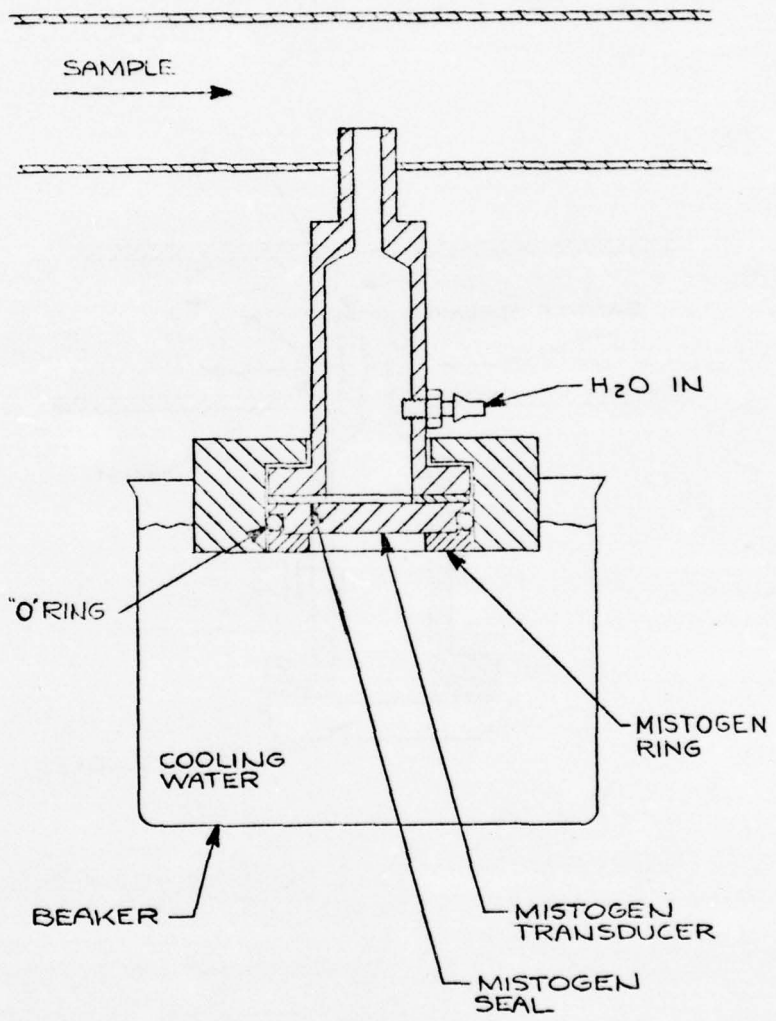

Figure 6. Modified Transducer Housing

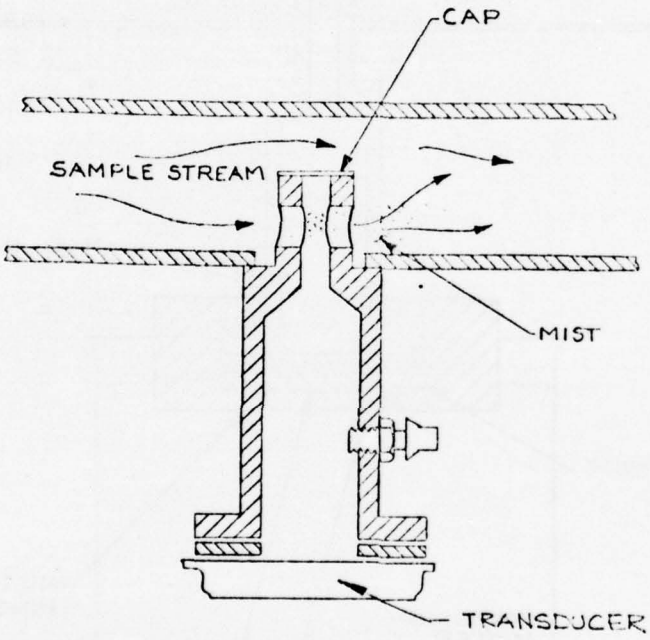

Figure 7. Capped Column

Ultrasonic equipment on the market is dedicated to a variety of jobs. The principle differences are in the amount of power, the frequency, and the horn, nozzle, or transducer configuration. Medical units are relatively low power and high frequency (1 to 3 MHz). Ultrasonic welding equipment is high power with frequencies around 20 KHz. Ultrasonic disrupter probes for cell destruction, homogenizing, soldering, cleaning, etc., are medium power and operate at 50 to 70 KHz.

Two vendors of ultrasonic welders volunteered to try some experiments for us with horns for their equipment. They are checking the feasibility of atomizing water with a configuration similar to that shown in Figure 8.

We borrowed a Dentsply/Cavitron Model 1010 ultrasonic tooth cleaning probe for two weeks from a local dentist. (See Figure 9.) It has a pick which vibrates and a water stream which is atomized as it passes through the vibrating base of the pick and then sprays onto the pick. The water is used to cool the transducer and then to flush the teeth. The fact that a mist could be produced from a small probe which could easily be inserted into a sample stream was encouraging. Due to the low operating frequency of the device however, the droplets were too course, and their settling rate too fast for use in a scrubber.

B.2. Steam Condensation:

In attempting to correct extremely fine mist particles, the major problem is increasing their size. See Table 3. In the nebulizer approach, it was hoped that mist particles would increase in size by collision with particles of the reagent mist. An alternative approach would be to run the mist stream through an area where active condensation of steam is taking place. It is wellknown that such condensation occurs preferentially on dust and other particles which act as condensation nuclei.

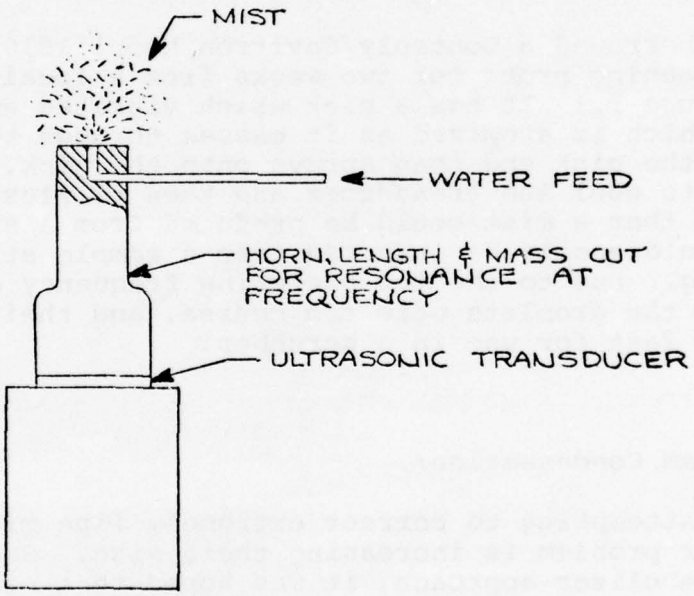

Figure 8. Mist Generating Horn

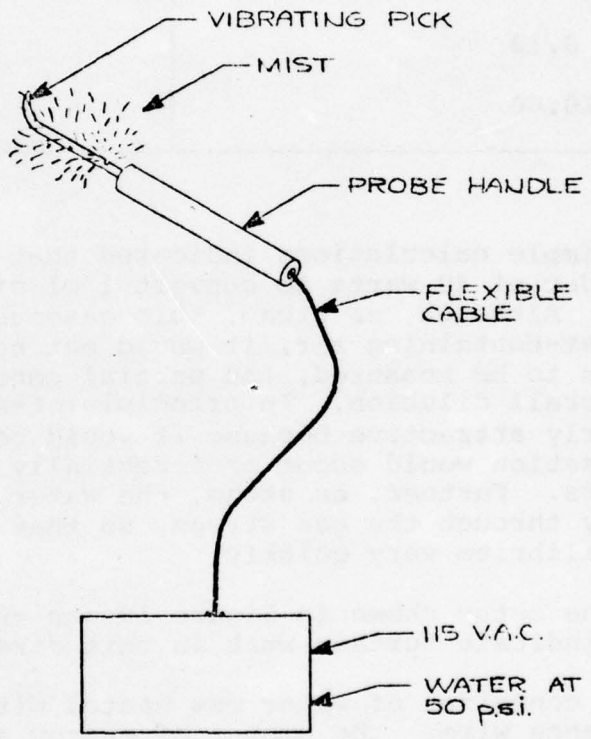

Figure 9. Dental Pick

Table 3

Effect of Particle Size on Settling Rate in Air[1]
(Spheres, specific gravity = 2.0, in air at 25°C)

Diameter, micrometers	Settling Velocity, cm/sec
0.01	1.5×10^{-5}
0.10	1.8×10^{-4}
10.00	0.5

Simple calculations indicated that it would require on the order of 40 watts to convert 1 ml of water per minute to steam. Although, as steam, this gaseous stream would dilute the mist-containing air, it would not contain any of the materials to be measured, and partial condensation would minimize the overall dilution. In principle, the approach looked particularly attractive because it would be highly efficient - condensation would occur preferentially on the hydroscopic mist droplets. Further, as steam, the water vapor would diffuse rapidly through the gas stream, so that the system would come to equilibrium very quickly.

The setup shown in Figure 10 was run and the initial results indicate further work in this direction is warranted.

A container of water was heated with an immersed coil of resistance wire. The amount of energy added to the water can be closely regulated by controlling the voltage and the current to the heater. If the container is well insulated so that there is no heat loss, all the energy is used to convert water

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[1]Data from Perry and Chilton, Chemical Engineers' Handbook, McGraw-Hill, 5th ed., 1973, p. 20-79.

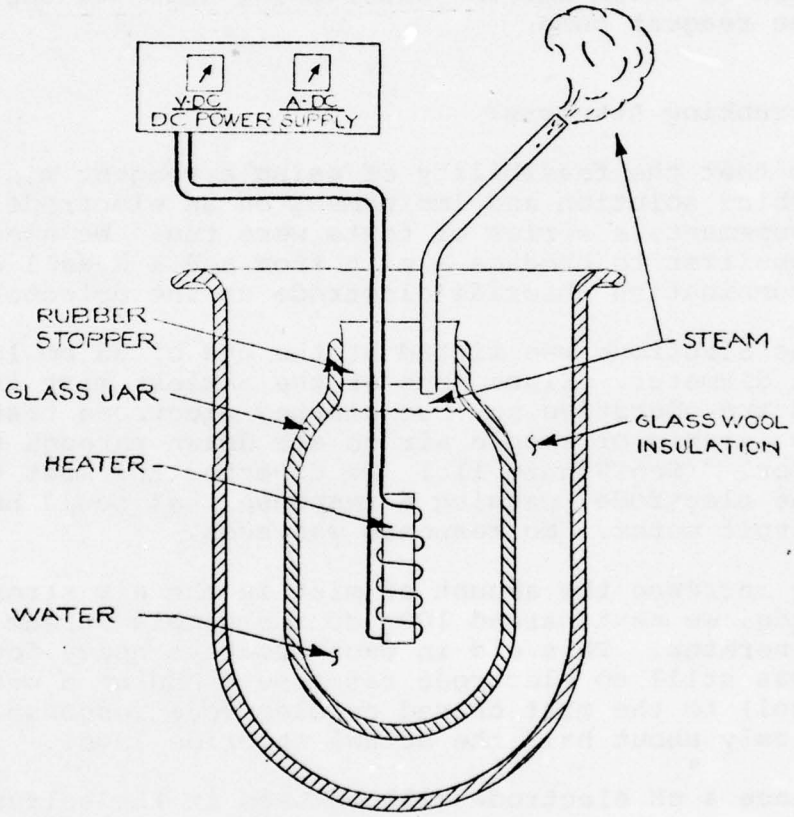

Figure 10. Steam Generator

to steam, and a close control of the water quantity being converted to steam is maintained. Since our first pass was not well-insulated, we did not get 100% conversion, but we were getting close to theoretical, about one ml of water per minute with about 40 watts to the heater. Once equilibrium was reached, the quantity of steam, by visual inspection, could be very closely controlled by adjusting the voltage control, and there was instantaneous response. A final system easily could have a close balance between the water being converted to steam and the water being added to the chamber with the reagent pump.

B.3. Scrubbing Attempts:

To test the feasibility of using a reagent mist as a scrubbing solution and impingment on an electrode as a means of measurement, a series of tests were run. We used the Mist-OGen nebulizer to produce a mist from a 0.1 M NaCl solution and a combination chloride electrode as the detector.

The electrode was fitted at the end of 33 cm long tube, 2 cm in diameter. Since none of the airless mist injection schemes are operative yet, we started electrode testing with a 10 to 1 ratio of sample air to air drawn through the mist generator. (See Figure 11.) We expected the mist to impinge upon the electrode, causing a response that could be read on a millivolt meter. No response was seen.

To increase the amount of mist in the air stream past the electrode, we next passed 100% of the sample stream through the mist generator. This did in fact create a heavy fog in the tube. There was still no electrode response. Adding a wetting agent (Tergitol) to the mist caused an electrode response, but it showed only about half the actual chloride level.

Since a pH electrode will be used in the sulfuric acid scrubbing, and it is more sensitive than the chloride electrode, we decided to repeat our experiments with a combination pH electrode.

We interchanged two buffer solutions, pH 4.00 and 6.86, in the nebulizer to test the time response of the apparatus. Experiments were run with all the sample stream coming from the mist generator.

In the first trial, the electrode showed 99% of the correct reading in about nine minutes after the mist has been changed from one buffer to the other. The change was geo-

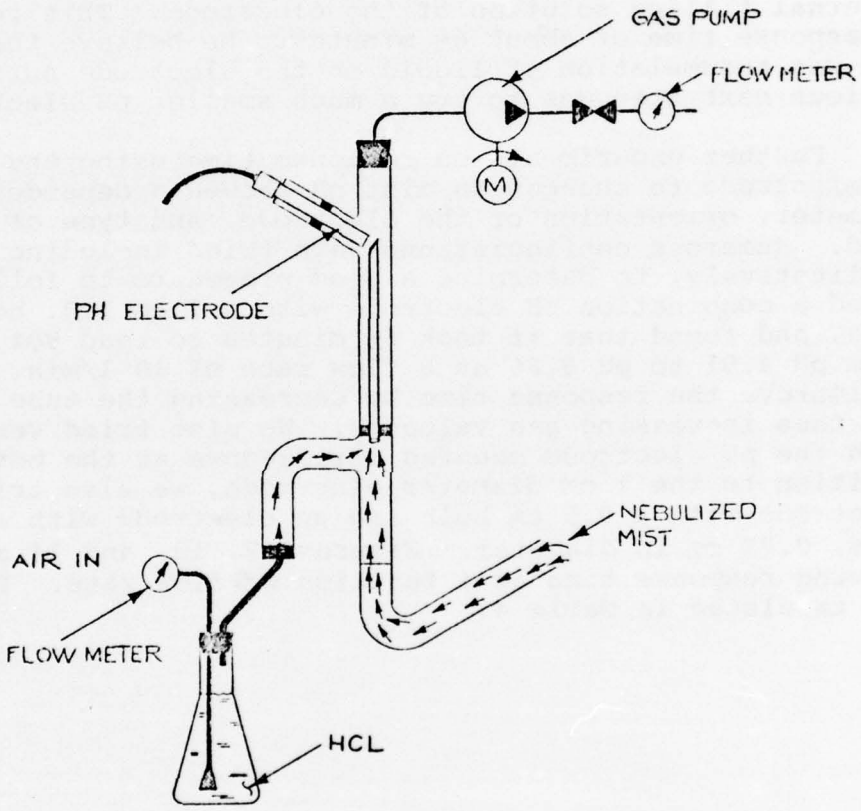

Figure 11. Impinying Test for Mixture of HCl Gas and H_2O Mist

metric: quite rapid at first, then gradually approaching the true reading.

We suspected that the slow response time was due to the time required to wet the large surface of the electrode. We tried to reduce the effective area to be wetted by placing a strip of filter paper between the sensing element and reference element of the electrode. The strip was soaked in the internal filling solution of the electrode. This resulted in a response time of about 6½ minutes. We believe that the problem was accumulation of liquid on the electrode surface. The obvious next step was to try a much smaller pH electrode.

Further experiments on response time using the smaller pH electrode to changes in mist pH showed a dependence on tube diameter, orientation of the electrode, and type of electrode used. Numerous configurations were tried including some only qualitatively, to determine a good procedure to follow. We tried a combination pH electrode with a 1 cm I.D. horizontal tube, and found that it took 6½ minutes to read 90% of a change from pH 4.01 to pH 6.86 at a flow rate of 10 l/min. We tried to improve the response time by decreasing the tube diameter and thus increasing gas velocity. We also tried vertical tubes with the pH electrode mounted upside-down at the bottom. In addition to the 1 cm diameter electrode, we also tried a pH electrode with a 0.5 cm bulb and an electrode with a flat surface, 0.75 cm in diameter. Figures 12, 13, and 14 are graphs showing response time as a function of flow rate. Results are tabulated in Table 4.

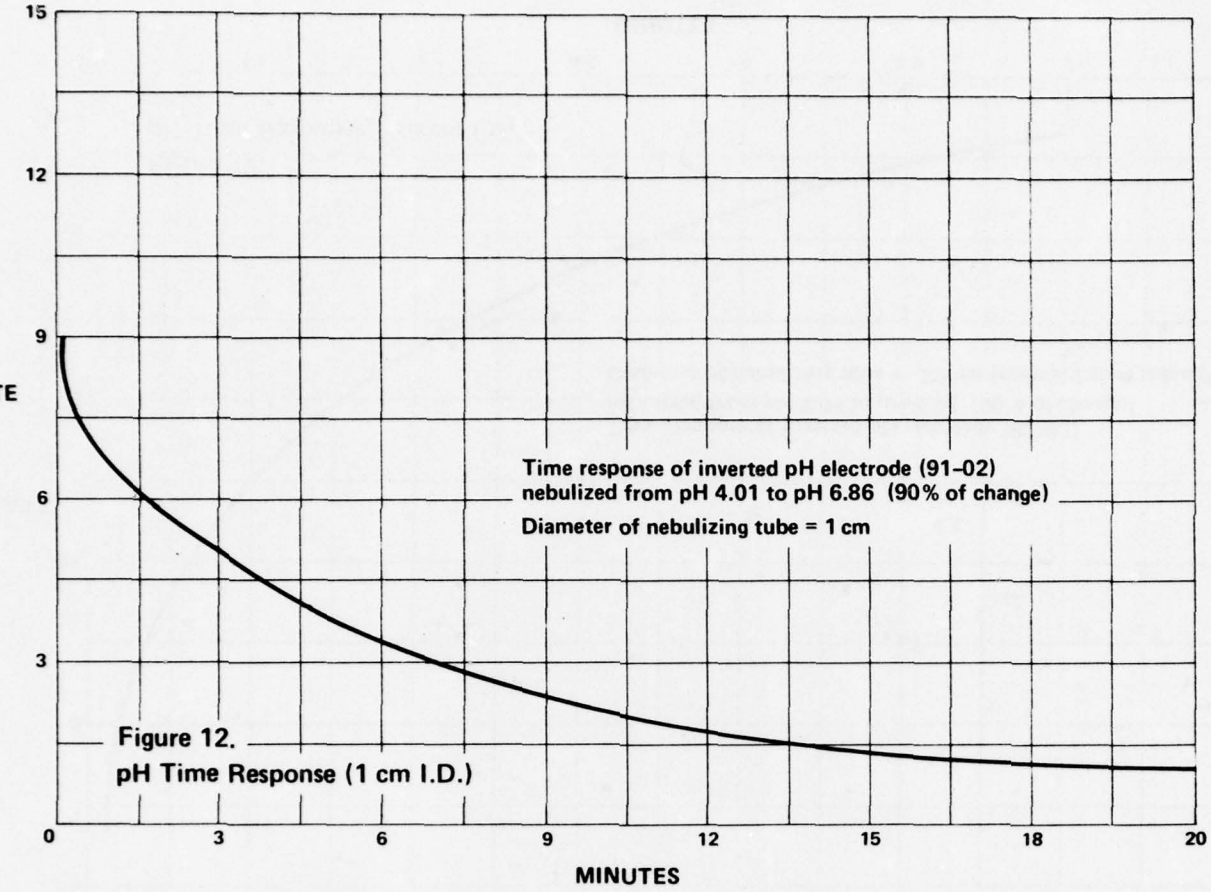

Figure 12.
pH Time Response (1 cm I.D.)

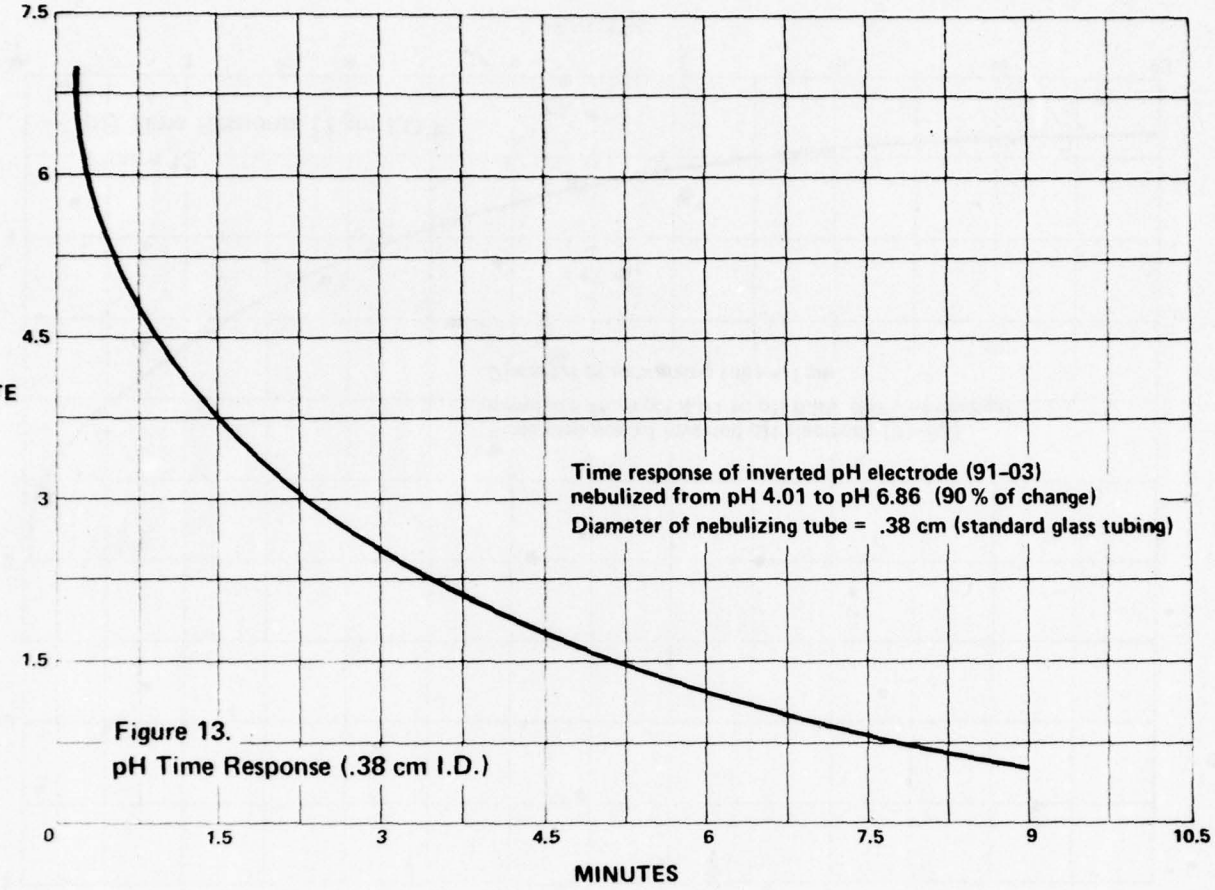

Figure 13.
pH Time Response (.38 cm I.D.)

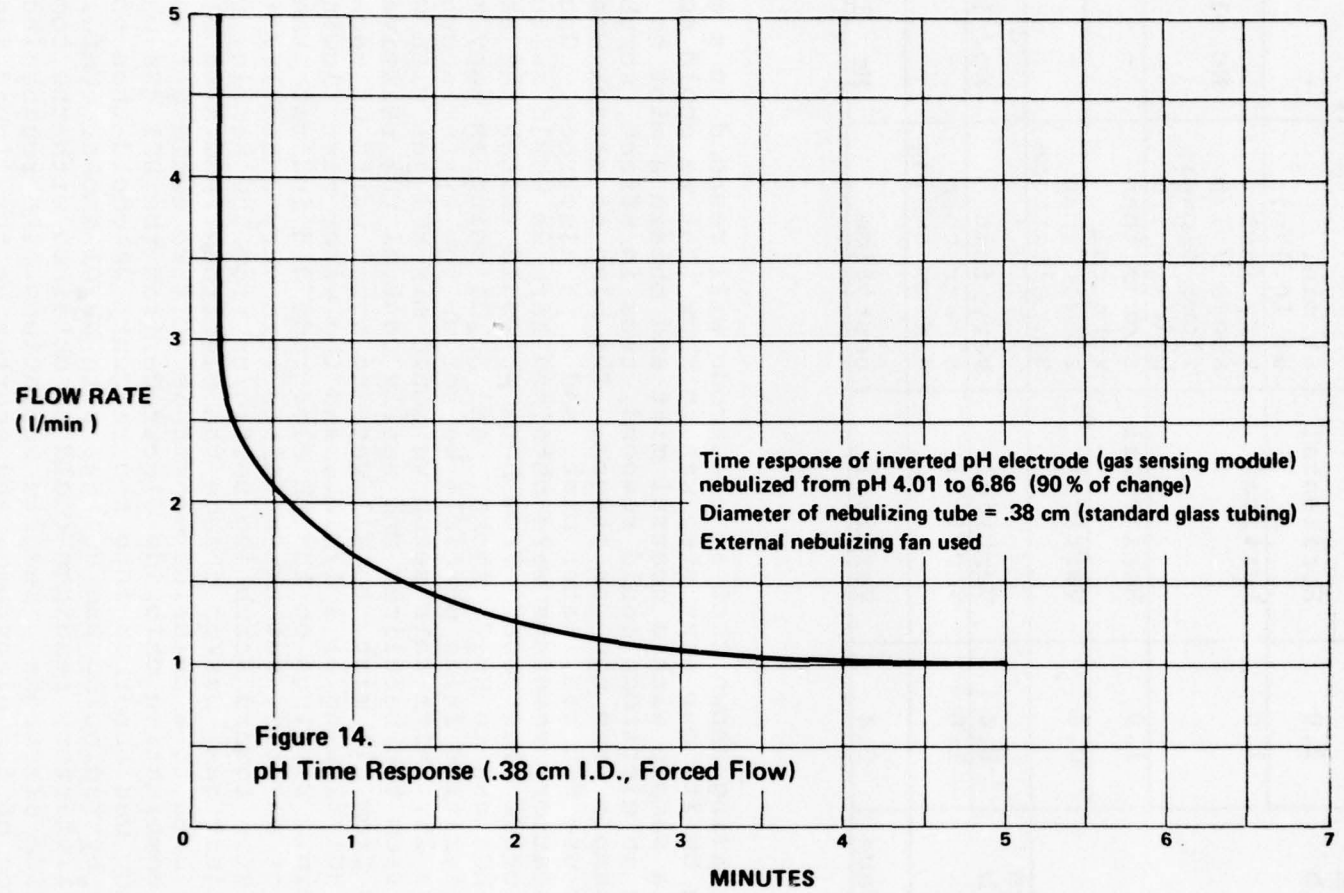

Figure 14.
pH Time Response (.38 cm I.D., Forced Flow)

Table 4
Results of Nebulizer Collecting Experiments

Electrode	Tubing Diameter (cm)	Electrode Position	Response Time	Figure No. of Data
1.0 cm bulb	2.0	Horizontal	6½ min. at 10 l/min	-
	1.0	Vertical	very fast above 7 l/m flow; slower below 7 l/m	No. 12
	1.0	Horizontal	slower than vertical	-
	0.4	Vertical	slower than sm. electrode	-
0.5 cm bulb	0.4	Vertical	very fast	No. 13
	1.0	Vertical	slower than 0.4 cm tubing	-
Flat surface	0.4	Vertical	best time	No. 14

Having shown that an electrode will respond to a mist going by it, our next step was to show that we could combine a sample with a neutral mist and obtain a mist to which an electrode could respond, thus in effect, scrubbing the sample from the gas stream. The plan of attack was to first use HCL gas, water mist, and a pH electrode. Once satisfactory readings were obtained here we would switch to a chloride electrode. From here we would switch the sample from HCl gas to NH_4Cl smoke. And NH_4Cl being an easy means of generating frine particle we set up the system shown in Figure 15. With this setup we could mix HCl gas with water mist from the nebulizer and easily control the relative flow rates from all mist, to all gas, to equal parts of each. With HCl flowing at 1 l/min., and the water mist flowing at 1 l/min., readings on the pH electrode did indicate the presence of an acid, but the readings were very unstable. The next step toward scrubbing particles from the sample, rather than just gas, was to change the electrode from a pH electrode back to a chloride electrode. If we could get readings on a combination chloride electrode from the HCl gas which we know was absorbed into the reagent, we could then continue by replacing the HCl gas with NH_4Cl smoke. Unfortunately no satisfactory readings could be obtained with the combination chloride electrode. Despite variations like roughening the surface of the electrode, and shortening the liquid junction path, no stable or reproducible readings were obtained.

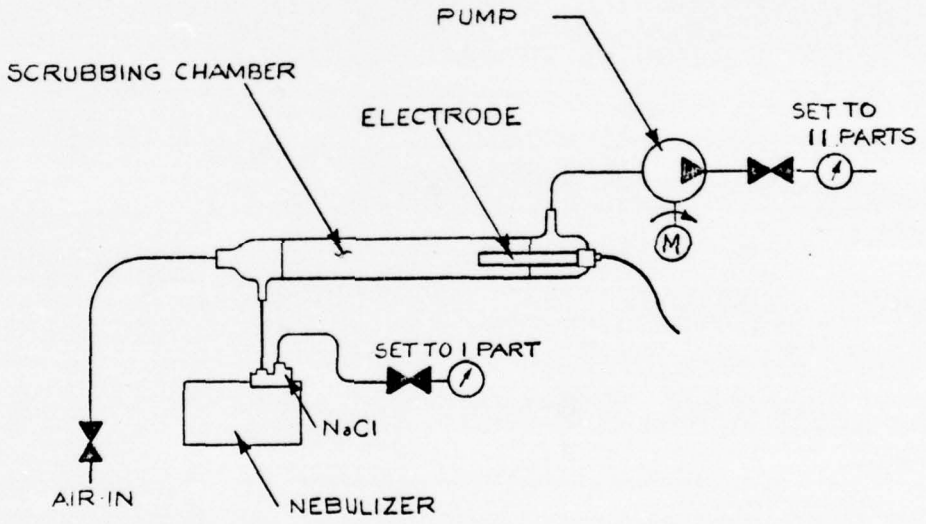

Figure 15. Test for Electrode Operation in Mist

III. Conclusions

The additional tests on the nitric acid scrubber continued to show a high collection efficiency for gas and a high rejection rate for particulates. Calculations show that the part of the response time of the nitric acid scrubber system required for the reagent to fall down the walls of the scrubber and exit to the electrode can feasibly be held down to one or two minutes. Evaluation of commercially available ultrasonic nebulizers has shown that there is none currently on the market which is directly applicable or adaptable to our application in the sulfuric acid scrubber section of the monitor. Work began on the first alternative method to mist generation by building a controlled rate steam generator. Concurrently work was being done to evaluate the feasibility of getting electrode readings by having a mist stream impinge on the electrode surface. We found that exposure of a smaller surface area on an electrode gave the best time response.

IV. Future Work

The next steps on the nitric acid scrubber will be to generate some gases of known concentrations and to check response of the system while changing from one gas to another. On the sulfuric acid scrubber, the feasibility of a steam scrubber system will be further investigated.

APPENDIX

```
NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  0.5      GAS FLOW RATE,L/MIN:  0.5
HT. OF COLUMN=   16.7
LIQUID FLOW RATE,ML/MIN=     0.2
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00402
HOLDUP VOL.,ML=    0.105240
LIQUID VELOCITY, CM/SEC: AT SURFACE=    0.791845
50% DOWN=    0.593883     90%=    0.150450    98%=    0.031356
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:  31.57
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    21.05    MIDPOINT=    26.06
90% DOWN=   110.78    98% DOWN=   531.54


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  0.5      GAS FLOW RATE,L/MIN:  1.0
HT. OF COLUMN=   33.3
LIQUID FLOW RATE,ML/MIN=     0.4
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00507
HOLDUP VOL.,ML=    0.265187
LIQUID VELOCITY, CM/SEC: AT SURFACE=    1.256980
50% DOWN=    0.942732     90%=    0.238825    98%=    0.049776
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:  39.78
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    26.52    MIDPOINT=    35.36
90% DOWN=   139.57    98% DOWN=   669.66


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  0.5      GAS FLOW RATE,L/MIN:  4.0
HT. OF COLUMN=  133.3
LIQUID FLOW RATE,ML/MIN=     1.6
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00804
HOLDUP VOL.,ML=    1.683830
LIQUID VELOCITY, CM/SEC: AT SURFACE=    3.167380
50% DOWN=    2.375540     90%=    0.601801    98%=    0.125428
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:  63.14
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    42.10    MIDPOINT=    56.13
90% DOWN=   221.56    98% DOWN=  1063.0
```

```
NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  0.5      GAS FLOW RATE,L/MIN:  7.0
HT. OF COLUMN=  233.3
LIQUID FLOW RATE,ML/MIN=     2.8
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00969
HOLDUP VOL.,ML=    3.550990
LIQUID VELOCITY, CM/SEC: AT SURFACE=    4.599660
50% DOWN=    3.449750     90%=    0.873939    98%=    0.182146
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:  76.09
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    50.73    MIDPOINT=    67.64
90% DOWN=  266.99    98% DOWN=  1281.0


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  0.5      GAS FLOW RATE,L/MIN: 10.0
HT. OF COLUMN=  333.3
LIQUID FLOW RATE,ML/MIN=     4.0
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.01091
HOLDUP VOL.,ML=    5.713280
LIQUID VELOCITY, CM/SEC: AT SURFACE=    5.834370
50% DOWN=    4.375770     90%=    1.108540    98%=    0.231050
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:  85.70
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    57.13    MIDPOINT=    76.18
90% DOWN=  300.70    98% DOWN=  1442.7


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NITRIC ACID COLUMN
==================

?28.73 @ 02.05
*W 2.05
02.05 S LS=GM*1000/60*R: S LM=60*LS
*G
RATIO OF GAS/LIQ: 2500
DIAM OF TUBE,CM:1.0
```

```
NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  1.0      GAS FLOW RATE,L/MIN:  1.0
HT. OF COLUMN=   33.3
LIQUID FLOW RATE,ML/MIN=     0.4
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00402
HOLDUP VOL.,ML=   0.420959
LIQUID VELOCITY, CM/SEC: AT SURFACE=   0.791845
50% DOWN=   0.593883     90%=   0.150450    98%=   0.031356
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:  63.14
TIME OF LIQ EXPOSURE,SEC:
SURFACE=   42.10    MIDPOINT=   56.13
90% DOWN=  221.56    98% DOWN=  1063.1


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  1.0      GAS FLOW RATE,L/MIN:  4.0
HT. OF COLUMN=  133.3
LIQUID FLOW RATE,ML/MIN=     1.6
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00638
HOLDUP VOL.,ML=   2.672920
LIQUID VELOCITY, CM/SEC: AT SURFACE=   1.995330
50% DOWN=   1.496490     90%=   0.379111    98%=   0.079015
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 100.24
TIME OF LIQ EXPOSURE,SEC:
SURFACE=   66.82    MIDPOINT=   89.10
90% DOWN=  351.70    98% DOWN=  1687.5


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  1.0      GAS FLOW RATE,L/MIN:  7.0
HT. OF COLUMN=  233.3
LIQUID FLOW RATE,ML/MIN=     2.8
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00769
HOLDUP VOL.,ML=   5.636850
LIQUID VELOCITY, CM/SEC: AT SURFACE=   2.897610
50% DOWN=   2.173200     90%=   0.550544    98%=   0.114740
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 120.79
TIME OF LIQ EXPOSURE,SEC:
SURFACE=   80.53    MIDPOINT=  107.37
90% DOWN=  423.82    98% DOWN=  2033.6
```

```
NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  1.0      GAS FLOW RATE,L/MIN: 10.0
HT. OF COLUMN=  333.3
LIQUID FLOW RATE,ML/MIN=     4.0
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00866
HOLDUP VOL.,ML=    9.069260
LIQUID VELOCITY, CM/SEC: AT SURFACE=    3.675420
50% DOWN=    2.756570     90%=    0.698328    98%=    0.145546
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 136.04
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    90.69    MIDPOINT=  120.92
90% DOWN=  477.33    98% DOWN=  2290.2


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NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  2.0      GAS FLOW RATE,L/MIN:  0.5
HT. OF COLUMN=   16.7
LIQUID FLOW RATE,ML/MIN=     0.2
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00253
HOLDUP VOL.,ML=    0.265187
LIQUID VELOCITY, CM/SEC: AT SURFACE=    0.314244
50% DOWN=    0.235683     90%=    0.059706    98%=    0.012444
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:  79.56
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    53.04    MIDPOINT=   70.72
90% DOWN=  279.15    98% DOWN=  1339.4


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  2.0      GAS FLOW RATE,L/MIN:  1.0
HT. OF COLUMN=   33.3
LIQUID FLOW RATE,ML/MIN=     0.4
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00319
HOLDUP VOL.,ML=    0.668230
LIQUID VELOCITY, CM/SEC: AT SURFACE=    0.498831
50% DOWN=    0.374123     90%=    0.094778    98%=    0.019754
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 100.24
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    66.82    MIDPOINT=   89.10
90% DOWN=  351.70    98% DOWN=  1687.5
```

```
NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  2.0      GAS FLOW RATE,L/MIN:  4.0
HT. OF COLUMN=  133.3
LIQUID FLOW RATE,ML/MIN=     1.6
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00507
HOLDUP VOL.,ML=    4.242990
LIQUID VELOCITY, CM/SEC: AT SURFACE=    1.256980
50% DOWN=    0.942732     90%=    0.238825    98%=    0.049776
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 159.11
TIME OF LIQ EXPOSURE,SEC:
SURFACE=  106.08    MIDPOINT=  141.43
90% DOWN=  558.29    98% DOWN=  2678.7


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  2.0      GAS FLOW RATE,L/MIN:  7.0
HT. OF COLUMN=  233.3
LIQUID FLOW RATE,ML/MIN=     2.8
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00610
HOLDUP VOL.,ML=    8.947930
LIQUID VELOCITY, CM/SEC: AT SURFACE=    1.825380
50% DOWN=    1.369030     90%=    0.346821    98%=    0.072285
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 191.74
TIME OF LIQ EXPOSURE,SEC:
SURFACE=  127.83    MIDPOINT=  170.44
90% DOWN=  672.78    98% DOWN=  3228.0


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  2.0      GAS FLOW RATE,L/MIN: 10.0
HT. OF COLUMN=  333.3
LIQUID FLOW RATE,ML/MIN=     4.0
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00688
HOLDUP VOL.,ML=   14.396600
LIQUID VELOCITY, CM/SEC: AT SURFACE=    2.315370
50% DOWN=    1.736530     90%=    0.439916    98%=    0.091685
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 215.95
TIME OF LIQ EXPOSURE,SEC:
SURFACE=  143.97    MIDPOINT=  191.95
90% DOWN=  757.72    98% DOWN=  3635.7


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```
NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  5.0      GAS FLOW RATE,L/MIN:  0.5
HT. OF COLUMN=   16.7
LIQUID FLOW RATE,ML/MIN=     0.2
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00187
HOLDUP VOL.,ML=   0.488480
LIQUID VELOCITY, CM/SEC: AT SURFACE=   0.170598
50% DOWN=   0.127948    90%=   0.032413   98%=   0.006755
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 146.54
TIME OF LIQ EXPOSURE,SEC:
SURFACE=   97.70   MIDPOINT=  130.26
90% DOWN=  514.20   98% DOWN=  2467.3


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  5.0      GAS FLOW RATE,L/MIN:  1.0
HT. OF COLUMN=   33.3
LIQUID FLOW RATE,ML/MIN=     0.4
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00235
HOLDUP VOL.,ML=   1.230890
LIQUID VELOCITY, CM/SEC: AT SURFACE=   0.270807
50% DOWN=   0.203106    90%=   0.051454   98%=   0.010724
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 184.63
TIME OF LIQ EXPOSURE,SEC:
SURFACE=  123.09   MIDPOINT=  164.12
90% DOWN=  647.83   98% DOWN=  3108.2


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  5.0      GAS FLOW RATE,L/MIN:  4.0
HT. OF COLUMN=  133.3
LIQUID FLOW RATE,ML/MIN=     1.6
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00373
HOLDUP VOL.,ML=   7.815650
LIQUID VELOCITY, CM/SEC: AT SURFACE=   0.682392
50% DOWN=   0.511794    90%=   0.129655   98%=   0.027024
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 293.09
TIME OF LIQ EXPOSURE,SEC:
SURFACE=  195.39   MIDPOINT=  260.52
90% DOWN=  1028.4   98% DOWN=  4933.9
```

```
NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:   5.0      GAS FLOW RATE,L/MIN:   7.0
HT. OF COLUMN=   233.3
LIQUID FLOW RATE,ML/MIN=     2.8
CONCN RATIO=   2500
LIQUID FILM THICKNSS=   0.00450
HOLDUP VOL.,ML=   16.482300
LIQUID VELOCITY, CM/SEC: AT SURFACE=    0.990967
50% DOWN=    0.743225     90%=    0.188283    98%=    0.039242
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 353.19
TIME OF LIQ EXPOSURE,SEC:
SURFACE=   235.46    MIDPOINT=   313.95
90% DOWN=   1239.3    98% DOWN=   5946.0


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:   5.0      GAS FLOW RATE,L/MIN:  10.0
HT. OF COLUMN=   333.3
LIQUID FLOW RATE,ML/MIN=     4.0
CONCN RATIO=   2500
LIQUID FILM THICKNSS=   0.00507
HOLDUP VOL.,ML=   26.518700
LIQUID VELOCITY, CM/SEC: AT SURFACE=    1.256980
50% DOWN=    0.942732     90%=    0.238825    98%=    0.049776
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 397.78
TIME OF LIQ EXPOSURE,SEC:
SURFACE=   265.19    MIDPOINT=   353.58
90% DOWN=   1395.7    98% DOWN=   6696.6


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NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:   0.5      GAS FLOW RATE,L/MIN:   0.5
HT. OF COLUMN=    16.7
LIQUID FLOW RATE,ML/MIN=     0.2
CONCN RATIO=   2500
LIQUID FILM THICKNSS=   0.00402
HOLDUP VOL.,ML=    0.105240
LIQUID VELOCITY, CM/SEC: AT SURFACE=    0.791845
50% DOWN=    0.593683     90%=    0.150450    98%=    0.031356
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:   31.57
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    21.05    MIDPOINT=    28.06
90% DOWN=   110.78    98% DOWN=   531.54
```

```
NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  1.0      GAS FLOW RATE,L/MIN:  0.5
HT. OF COLUMN=   16.7
LIQUID FLOW RATE,ML/MIN=     0.2
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00319
HOLDUP VOL.,ML=   0.167057
LIQUID VELOCITY, CM/SEC: AT SURFACE=   0.498831
50% DOWN=   0.374123     90%=   0.094778    98%=   0.019754
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:  50.12
TIME OF LIQ EXPOSURE,SEC:
SURFACE=   33.41    MIDPOINT=   44.55
90% DOWN=  175.85    98% DOWN=  843.73


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  2.0      GAS FLOW RATE,L/MIN:  0.5
HT. OF COLUMN=   16.7
LIQUID FLOW RATE,ML/MIN=     0.2
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00253
HOLDUP VOL.,ML=   0.265187
LIQUID VELOCITY, CM/SEC: AT SURFACE=   0.314244
50% DOWN=   0.235683     90%=   0.059706    98%=   0.012444
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT:  79.56
TIME OF LIQ EXPOSURE,SEC:
SURFACE=   53.04    MIDPOINT=   70.72
90% DOWN=  279.15    98% DOWN=  1339.4


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:  3.0      GAS FLOW RATE,L/MIN:  0.5
HT. OF COLUMN=   16.7
LIQUID FLOW RATE,ML/MIN=     0.2
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00221
HOLDUP VOL.,ML=   0.347493
LIQUID VELOCITY, CM/SEC: AT SURFACE=   0.239813
50% DOWN=   0.179860     90%=   0.045565    98%=   0.009497
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 104.25
TIME OF LIQ EXPOSURE,SEC:
SURFACE=   69.50    MIDPOINT=   92.67
90% DOWN=  365.78    98% DOWN=  1755.0
```

```
NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:   4.0      GAS FLOW RATE,L/MIN:   0.5
HT. OF COLUMN=    16.7
LIQUID FLOW RATE,ML/MIN=     0.2
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00201
HOLDUP VOL.,ML=    0.420958
LIQUID VELOCITY, CM/SEC: AT SURFACE=    0.197962
50% DOWN=    0.148471     90%=    0.037613    98%=    0.007839
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 126.29
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    84.19    MIDPOINT=  112.26
90% DOWN=   443.11    98% DOWN=  2126.1


NITRIC ACID COLUMN
==================

TUBE DIAM.,CM:   5.0      GAS FLOW RATE,L/MIN:   0.5
HT. OF COLUMN=    16.7
LIQUID FLOW RATE,ML/MIN=     0.2
CONCN RATIO=  2500
LIQUID FILM THICKNSS=  0.00187
HOLDUP VOL.,ML=    0.488480
LIQUID VELOCITY, CM/SEC: AT SURFACE=    0.170598
50% DOWN=    0.127948     90%=    0.032413    98%=    0.006755
TIME FOR 1 VOL CHANGE,SEC,BASED ON INPUT: 146.54
TIME OF LIQ EXPOSURE,SEC:
SURFACE=    97.70    MIDPOINT=  130.26
90% DOWN=   514.20    98% DOWN=  2467.3


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