

THE DESIGN OF A LIQUID JET-GAS EDUCTOR REACTOR
SPECIFICALLY FOR THE SELECTIVE SEPARATION
OF SMALL AMOUNTS OF COPPER AND ZINC
FROM STRONG NICKEL SULFATE SOLUTIONS

by

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A Thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science, Chemical and Petroleum-Refining Engineering.

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ABSTRACT

A liquid jet-gas eductor was studied specifically for the selective sulfide precipitation of small amounts of copper and zinc from strong nickel sulfate solutions. Design variables for the reactor included: nozzle diameter, jet length, mixing tube length and gas nozzle length. The study also considered the system parameters: temperature, initial pH and zinc to copper ratio of the feed solution. Complete copper precipitation and ninety percent zinc precipitation at selectivity over nickel of 5 to 7 were obtained from a fifty gram per liter nickel - one gram per liter copper and zinc solution. With continued research, the liquid jet-gas eductor can be more fully developed as a reactor.

To my parents,
Robert A. and Dorris M. Knecht

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INTRODUCTION

A major mill operation of the AMAX Port Nickel Refinery in Louisiana is the production of saleable nickel. However, following recovery and concentrating, the nickel electrolyte contains undesirable amounts of copper and zinc. The present method of removing these impurities is "H₂S scavenging" by sparging the gas into a pipeline reactor. Although working reasonably well, the method does not produce a clean product (the solid product copper to nickel ratio being approximately one to ten, 1:10) and does not remove zinc to very low levels.

An alternative to this pipeline reactor seems to be a liquid-gas eductor. Because of the large surface area created between the liquid and the gas, more intimate mixing should take place between the liquid and the gas. J. H. Witte (1) studied the mixing characteristics of a liquid-gas ejector, proposing a theory for the liquid-gas mixing mechanism as well as ejector design conditions. Based on this study, C. S. Simons (2), working for Thompson Engineering, helped develop a liquid-gas eductor for the selective removal of copper and arsenic from nickel electrolyte. The process worked extremely well, producing a clean product (the solid product copper to nickel ratio being approximately ten to one, 10:1). Further study was not made to "optimize" the eductor design.

The primary objective of this work was to study the design characteristics of a liquid jet-gas eductor for the selective removal of copper and zinc impurities from strong nickel electrolyte. The secondary objective was to study the effects of temperature, pH, and zinc to copper ratio of the feed on the proposed eductor design.

SUMMARY AND CONCLUSIONS

Three major variables resulted from the Reactor Design Study. Increasing the nozzle diameter, D_n , significantly increased the fraction of zinc precipitating. Increasing the mixing tube length, L_{mt} , improved the fraction of zinc precipitating but was detrimental to the selectivity over nickel. The gas nozzle length, L_{gn} , was detrimental to zinc precipitation when positioned very close to the jet stream.

Based on a limited amount of data, the system parameters were observed to be critical to the process. Increased temperature was detrimental to the fraction of zinc precipitated as well as the selectivity over nickel. The initial pH was important for increasing the selectivity of the zinc precipitation. The copper to zinc ratio of the feed indicated possible seeding of nickel precipitation due to increased zinc concentration of the solution. The system parameter data introduced a number of serious questions about the jet pump system that should be studied in greater detail.

The liquid jet-gas eductor is a very efficient reactor for the selective precipitation of copper and zinc from strong nickel sulfate solutions. With the following reactor design characteristics:

ratio of nozzle diameter to mixing tube diameter

D_n/D_{mt} : 0.75

ratio of mixing tube length to mixing tube diameter

L_{mt}/D_{mt} : 15

position of the gas nozzle

L_{gn} : parallel to the
reactor wall

ratio of nozzle length to mixing tube diameter

L_n/D_{mt} : 3

excess H_2S gas over required for copper-zinc precipitation

E_g : 15%

back pressure on the reactor

P_b : 10 psig

and the system parameters:

temperature : room

pH : 3.0 to 3.5

the following process results are expected for a zinc to copper ratio of one in the feed:

selectivity of copper over nickel

$S_{Cu/Ni}$: 5 to 7

selectivity of zinc over nickel

$S_{Zn/Ni}$: 4 to 6

fraction of zinc reacting

f_{Zn} : 0.8 to 0.9

fraction of hydrogen sulfide reacting

f_{H_2S} : 0.75 to 0.85

pressure drop across the reactor

ΔP : 7 to 9 psig.

RECOMMENDATIONS

Having concluded the initial study of the liquid jet-gas eductor for the selective precipitation of metal values, three specific areas of continued research are suggested: a) greater development of the reactor's potential, b) evaluation of engineering data, and c) development of pilot plant data.

Based on published technical data and experimental reactor data, a general model could be developed for the selective separation of various metal values. Published literature should be surveyed to obtain a) kinetic and rate data, b) system parameter data, and c) modelling data related to sulfide precipitation of metal values. Continued research of the major reactor variables, including additional studies for various mixing tube diameters, should be conducted to generalize the reactor design characteristics. More accurate and detailed data should be collected to determine the effects of a) temperature, b) pH, c) other metal values on specific metal precipitation (seeding), and d) high and low pressure drops across the reactor on the reactor system. The data should be evaluated to prepare a general reactor model that could be extended to include metal values with solubility constants between copper and zinc.

Based on the experimental data an engineering evaluation could be made to design the reactor specifically for

the Port Nickel flowsheet. A cost comparison could also be made between the liquid jet-gas eductor and a) H_2S scavenging in a pipeline reactor, b) conventional liquid gas mixers, and c) liquid and solid ion exchange methods.

The reactor could be scaled up to collect pilot plant data preferable at flowrates around 20 to 40 gallons per minute. Consideration should be given to scale up factors and the use of actual solution for testing the reactor. Related data such as filtering, settling, scale and ease of operation should also be evaluated.

EXPERIMENTAL EQUIPMENT AND PROCEDUREEquipment

The overall set up of the experimental equipment is shown in Figure 1. From the floor, the liquid was transferred between two 55 gallon LPN neoprene tanks by a Sundstrand Sunflo centrifugal pump, series PlBCA, capable of 6 to 8 GPM at 240 ft head.

A more detailed view of the reactor panel is shown in Figures 2 and 2b. The liquid stream flowed through 316 SS schedule 40 piping, controlled by two Whitey metering valves, series SS 75F8 L4. The rate of liquid flow was monitored on Fisher Porter extruded body rotameters, series 10 A 3500 and the pressure was observed on Duragauge pressure gauges with capacity of 0 to 60 psig. The inlet pressure gauge was eventually replaced by a Marsh Service gauge with capacity 0 to 100 psig.

The gas stream flowed through one quarter inch titanium tubing and was controlled by a Whitey metering valve, series SS 4LS4 and a Nupro metering valve, series SS 4L. The flow-rate was monitored on a Gilmont No. 3 rotameter and the pressure was observed on a Marsh Service gauge with capacity 0 to 100 psig.

A more detailed view of the liquid jet-gas eductor is shown in Figures 3 and 3b. The shell was machined from 316 SS schedule 80 piping with a Conax tube adaptor welded in place

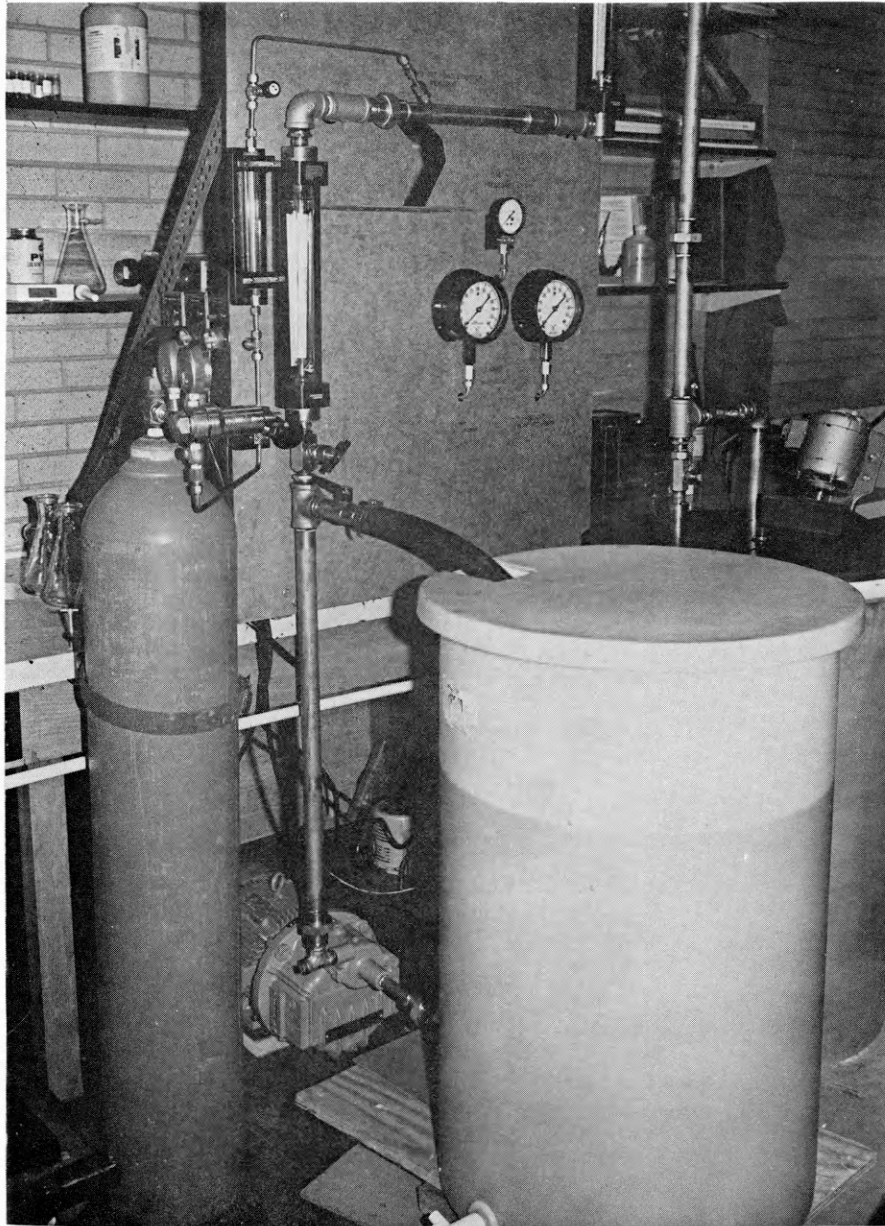


Figure 1. - - Overall view of liquid jet-gas eductor reactor process equipment.

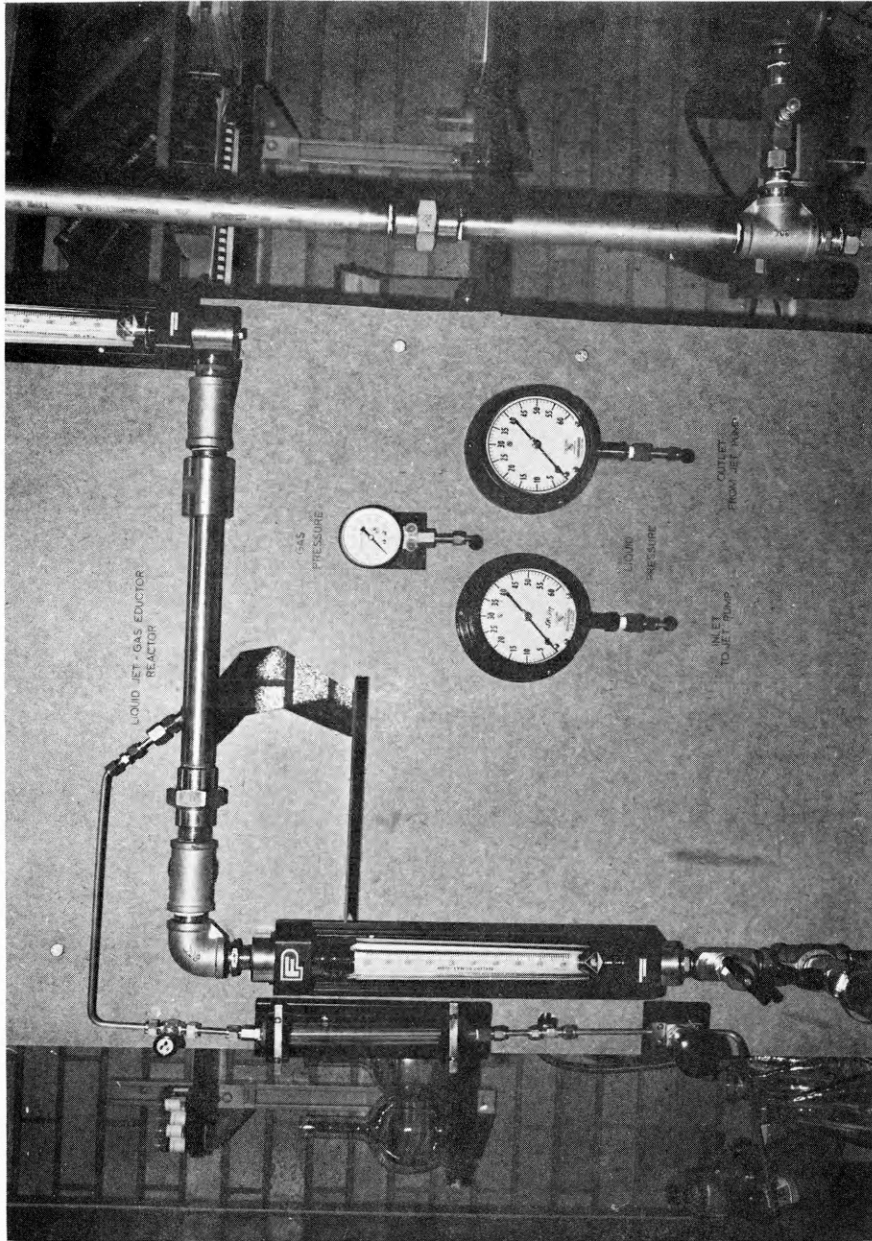


Figure 2. - - Reactor panel for the liquid jet-gas eductor reactor process.

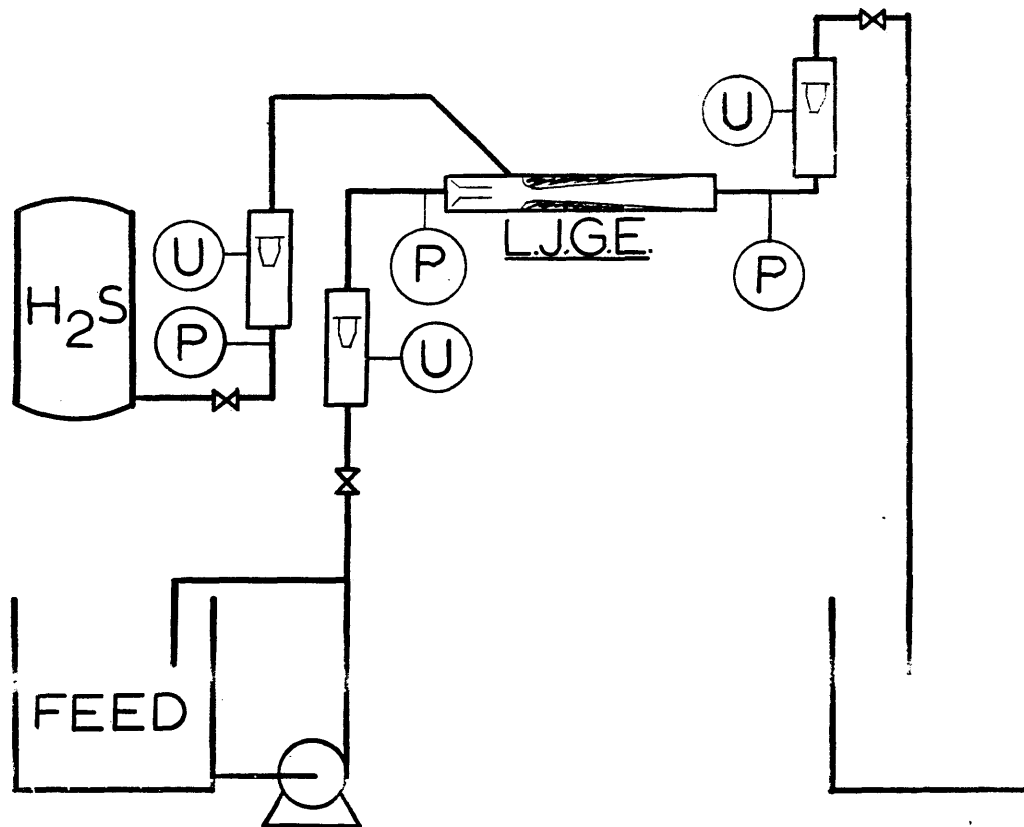


Figure 2b: Schematic drawing of Liquid Jet Gas Eductor Reactor Process.

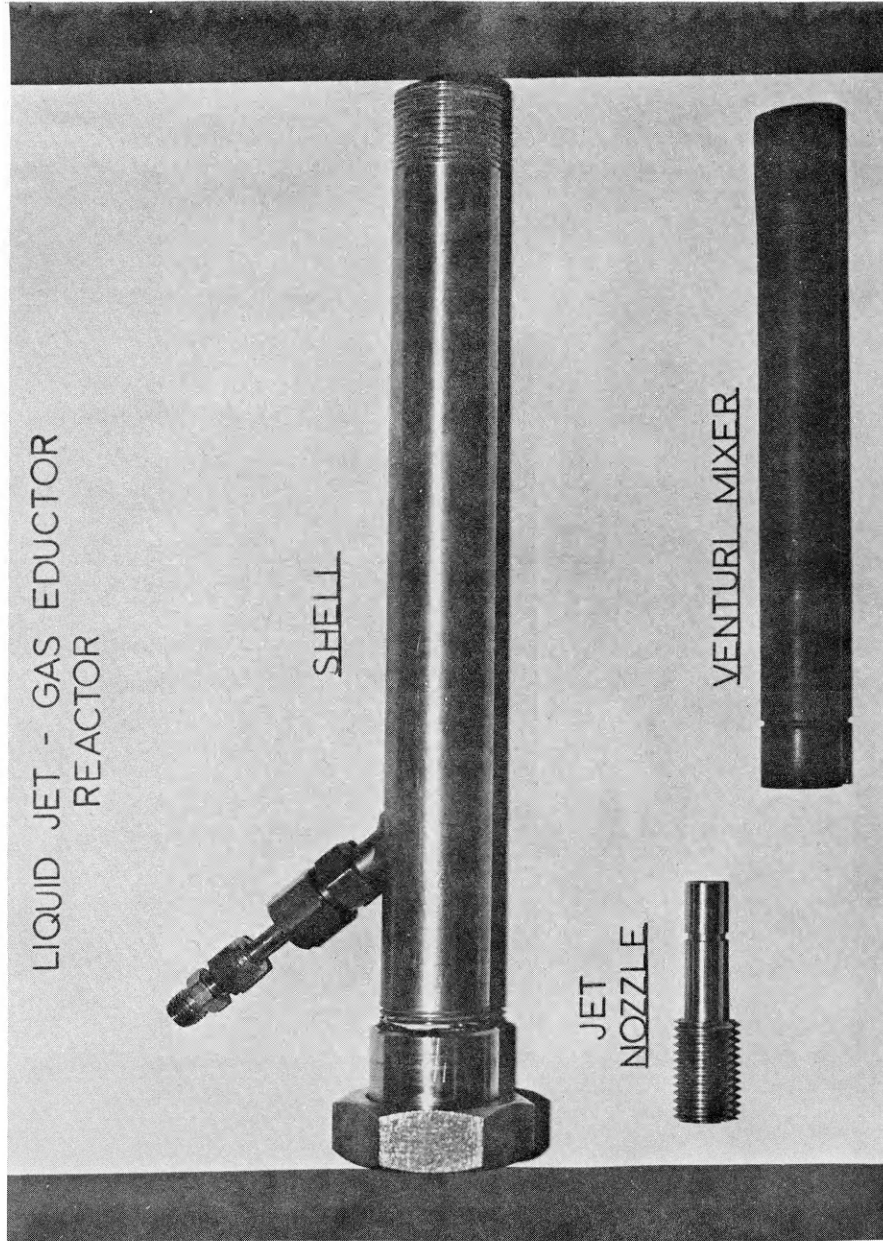
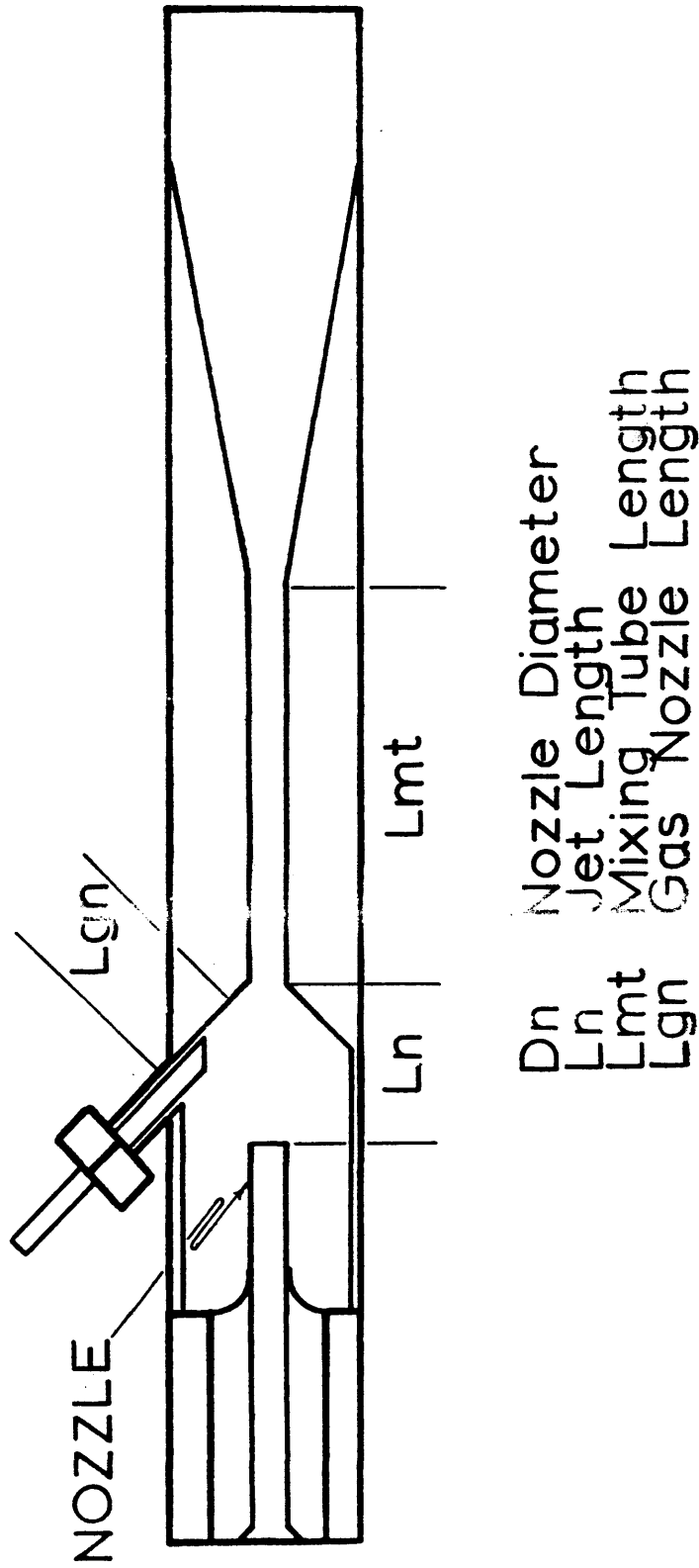


Figure 3. - - Nozzle and mixer components for the liquid jet-gas eductor reactor.



APPENDIX 3: Schematic drawing of the Liquid Jet Gas Eductor Reactor

for the gas entrance. This provided the capacity of adjusting the position of the gas nozzle, L_{gn} , from the IN position (in contact with the liquid jet) to the OUT position (parallel to the reactor wall). The shell was threaded on one end to accept any of a series of three nozzles, machined from 3/4 inch 316 SS barstock. The threaded nozzle provided a range of nozzle lengths, L_n , from 0.25 to 1.25 inch. The nozzle diameter, D_n , ranged from 0.125 inch to 0.250 inch. A series of three venturi mixers were machined from one inch carbon filled teflon barstock. The venturi diffuser had a total angle of 12° . The length of the mixing tube, L_{mt} , ranged from 2.5 inches to 5.0 inches.

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Procedure

The feed solution was adjusted to fifty gram per liter nickel, one gram per liter copper and zinc, except for the test series studying the effects of zinc-copper ratio of the feed. The liquid jet-gas eductor was assembled according to the test conditions and inserted into the process stream.

The gas flowrate was adjusted to the desired conditions prior to adjusting the liquid flowrate. The liquid outlet valve was closed until the desired backpressure was set. The system was observed for a few minutes to assure operational consistency. One minute prior to sampling the physical system data was recorded (Data Sheet, Appendix I). A seven second sample was drawn and the system was shut down.

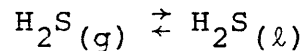
The sample was filtered and the solids were washed twice with deionized water. The liquid volume and density were recorded. Following drying, the solid sample was weighed. Both liquid and solid samples were submitted to the AMAX Metallurgical Laboratory for Analytical Analysis.

The system material balances and process evaluation calculations were computerized (Appendix 2) for rapid data analysis.

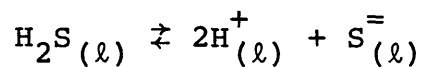
DISCUSSION

1. Literature Survey

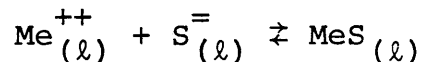
Sulfide precipitation of metal values from sulfate solutions is the conclusion of a series of chemical mechanisms: a) the mass transfer of hydrogen sulfide gas from the gas phase to the liquid phase,



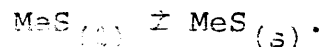
b) the dissolution of the hydrogen sulfide gas in the liquid phase,



c) the chemical reaction of metal ions with sulfur ions and



d) the precipitation of metal sulfides



C. S. Simons (3) reported the solubility products,

$$K_{\text{SP}} = [\text{Me}^{++}] [\text{S}^{=}]$$

as a function of temperature indicating the chemical reaction favored the precipitation of $\text{Cu} \gg \text{Zn} > \text{Ni}$ ($\approx 10^{-36} \gg \approx 10^{-25} > \approx 10^{-21}$).

Bird, Stewart and Lightfoot (5) related the mass transfer of a gas, absorbed into a liquid, to the diffusivity and the system geometry. Brimacombe (6), in a study of submerged gas jets, theorized that chemical reactants cannot coexist at the interface if the reaction rate was very rapid but that

the mass transfer was either gas or liquid phase controlled. Aris (4), in a theoretical discussion of chemical reactors, stated that the rate of chemical reactions was a function of the metal ion concentration.

The present method of copper and zinc removal is hydrogen sulfide sparging into a pipeline reactor. The method removes all the copper from the solution, but not the zinc. The solid product produced is contaminated with large amounts of coprecipitated nickel (approximately ten units of nickel for every unit of copper). Therefore the present procedure appears to be mass transfer limited.

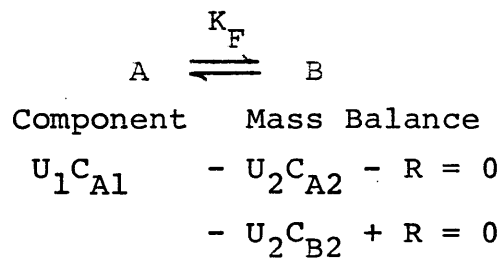
An alternative reactor, based primarily on the data presented by Witte (1), was suggested as a more intimate gas-liquid mixer. The purpose of the intimate mixing was to expose the copper and zinc to the hydrogen sulfide gas resulting in greater selectivity for copper and zinc as favored by the solubility products. Interest existed also in observing the effects of the alternative reactor on the mechanism of sulfide precipitation.

This program was designed to study the effects of the reactor and process design of a liquid jet gas eductor reactor on sulfide precipitation of copper and zinc from nickel sulfate solutions. An ejector, as studied by Witte, is a general term for all types of jet pumps which discharge at a pressure intermediate to motive and suction pressures. More specifically an eductor, as studied in this report, is a jet

pump which uses a liquid as the motive fluid.

The major design characteristics (Figure 3b) of interest were a) the nozzle diameter, D_n , b) the nozzle length, L_n , and c) the length of the mixing tube. D. F. Bagster (8), discussing a gas ejector as a refrigeration unit, commented on the importance of the restriction allowing the gas to mix with the liquid (specifically the effects of annular area and choking) to mass transfer. Therefore the position of the gas nozzle, L_{gn} , was included as a design characteristic.

Assuming ideal mixing Franks developed chemical reactor models as follows:



where $R = K_F \cdot V \cdot C_{A2}$

K_F = reaction coefficient.

For the specific project a set of equations (Appendix 4) was developed based on Frank's modelling procedure. The rate of reaction expression or more specifically the equilibrium extent of reaction expression, R , was dependent on the eductor geometry and the system parameters.

$R = f$ (eductor geometry, system parameters).

Data was recorded for the flowrates and components of each stream, the eductor geometry and system parameters. The system constraints or objectives (selectivities and fraction

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reacting) were calculated. The selectivity was the ratio of mass precipitation of two metal sulfide. The fraction of hydrogen sulfide gas reacting was calculated based on the difference of gas into the system and the required sulfur for the metal sulfides out of the system. The extent of the reaction was observed with respect to changes of eductor geometry and the system parameters.

2. Process Feasibility and Reproducibility

The primary objectives of the initial study were to evaluate the feasibility of the reaction process and to establish the reproducibility of the experimental data. The secondary objectives were to define a set of starting conditions and to prepare a set of operating procedures.

The copper and zinc selectivities for the initial test series are recorded in Table 1. The copper was completely precipitated from the nickel solution, whereas only three percent of the zinc was precipitated. The solid product was a fairly clean product with high copper selectivity but poor zinc selectivity.

Evaluating the overall test series, a good indication of data reproducibility was determined. Because copper precipitation was complete, the spread of copper selectivity values were dependent on the relatively small amount of nickel reported in the solids. Consequently the copper selectivity mean value varied by approximately $\pm 25\%$. Because of the operating conditions, only a small amount of zinc precipitated, varying by $\pm 100\%$. Therefore at condi-

TABLE 1
Copper and Zinc Selectivity and Fraction of Zinc and
Hydrogen Sulfide Reacting for the Initial Process
Feasibility Study.

		⁶⁵ Cu/Ni	⁶⁵ Zn/Ni	Zn	H ₂ S
2 min. sample					
1	(3)	4.33	0.10		0.889
2	(4)	5.73	0.13	0.023	0.750
3	(5)	6.23	0.06	0.012	0.862
4	(6)	4.62	0.03	0.007	0.908
5	(7)	6.63	0.03	0.008	0.615
AVERAGE		5.51	0.08	0.016	0.807
Std. Dev.		±1.00	±0.04	±0.010	±0.121
3 min. sample					
1	(3)	4.67	0.12	0.027	0.772
2	(4)	5.06	0.35	0.073	0.822
3	(5)	4.76	0.15	0.043	
4	(6)	8.53	0.02	0.003	0.743
5	(7)	6.11	0.20	0.027	0.686
AVERAGE		5.83	0.17	0.035	0.757
Std. Dev.		±1.62	±0.12	±0.026	±0.057
6 min. sample					
1	(3)	6.83	0.50	0.080	0.791
2	(4)	3.92	0.30	0.083	0.916
3	(5)	7.89	0.02	0.003	0.766
4	(6)	3.90	0.02	0.007	0.917
5	(7)	5.03	0.20	0.034	0.772
AVERAGE		5.51	0.23	0.041	0.807
Std. Dev.		±1.70	±0.21	±0.039	±0.149
OVERALL					
AVERAGE		5.62	0.16	0.031	0.790
STD. DEV.		±1.40	±0.10	±0.022	±0.110

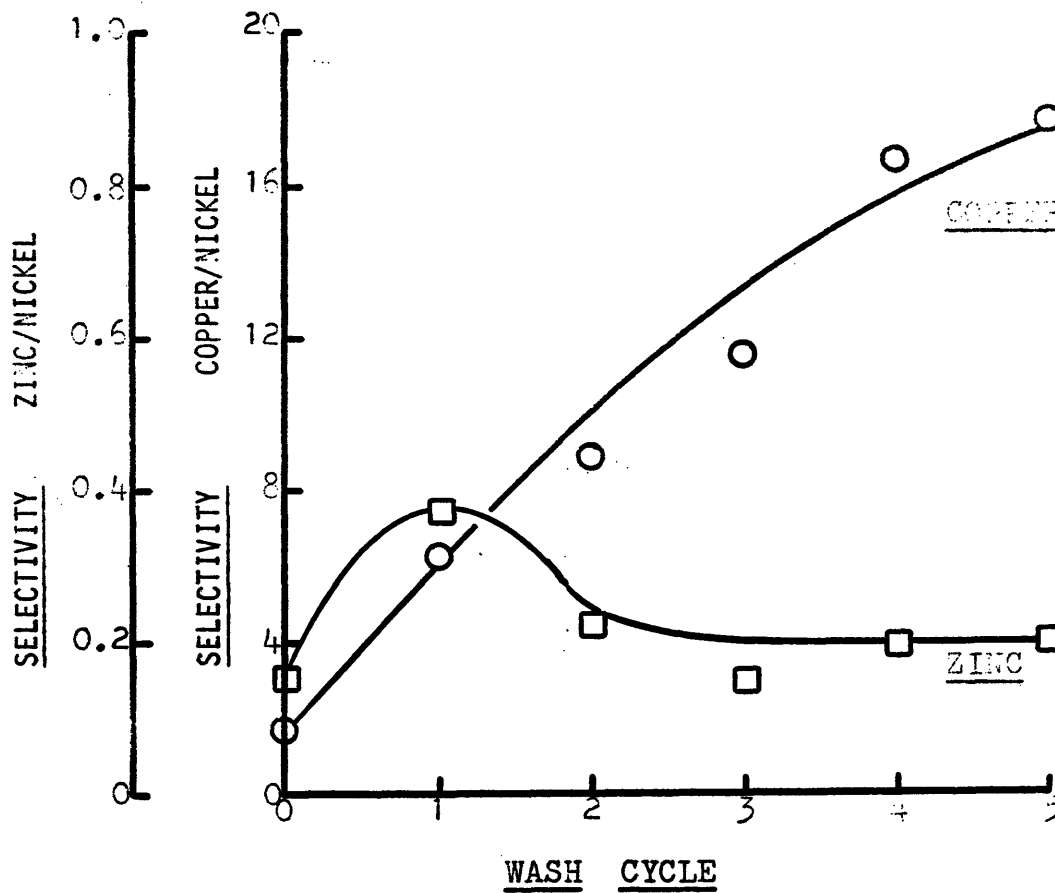


TABLE 2
Mass Concentration (Nickel, Copper, Zinc) and Copper and Zinc Selectivity for Sulfide Solids after a Series of One Hour Wash Cycles with Deionized Water.

WASH CYCLE	MASS CONCENTRATION			SELECTIVITY	
	NICKEL	COPPER	ZINC	Cu/Ni	Zn/Ni
HEAD	24.56	41.20	3.76	1.68	0.153
1	6.75	42.16	2.53	6.25	0.375
2	4.67	41.37	1.05	8.86	0.225
3	3.37	39.09	0.51	11.60	0.151
4	2.19	36.64	0.44	16.73	0.201
5	1.92	34.03	0.40	17.75	0.151

tions of very small amounts of precipitation the selectivity was also expected to vary by an equal amount.

Because sulfide solids have a tendency to be coated with the original solution, a composite solid sample from the initial test series was washed several times. The solids were stirred for one hour with fresh deionized water after which they were filtered and allowed to dry. The results of each wash series is recorded in Table 2.

The copper selectivity significantly improved as the nickel sulfate was washed from the solids. The zinc selectivity remained essentially constant indicating the presence of zinc sulfate in the solids. It would be reasonable to assume that the reproducibility of copper and zinc selectivity would improve by more thorough washing of the solid products. Although the operating procedure included two wash cycles of the solid product, increased selectivity may be realized beyond the scope of this work.

One of the initial tests was run using a higher gas flowrate. The results of this test are recorded in Table 3. The zinc precipitation increased (3% to 84%) and the selectivity approached the values of copper selectivity. The reproducibility of this test agreed with the expected value ($\pm 25\%$) discussed earlier in the section.

Based on these initial tests, it was concluded that the complete precipitation of copper was possible and that the selectivity for copper was dependent on the amount of

TABLE 3

Copper and Zinc Selectivity and Fraction of Zinc
and Hydrogen Sulfide Reacting for the Initial
Test at a High Gas Flowrate

Time	$S_{Cu/Ni}$	$S_{Zn/Ni}$	f_{Zn}	f_{H_2S}
7	2.81	2.04	0.787	0.473
10	3.74	2.80	0.831	0.492
14	2.54	2.26	0.894	0.477
Average	3.6	2.37	0.838	0.481
Std. Dev.	± 0.9	± 0.39	± 0.054	± 0.010

nickel in the solids. Because the precipitation of zinc was more difficult, the fraction of zinc reacting and the selectivity for zinc were chosen as the major reactor evaluation variables. The reproducibility was reasonably acceptable at high values of selectivity but varied by as much as $\pm 100\%$ at low values. The reproducibility can be improved by a more thorough washing of the solid product.

3. Process Mixing Characteristics

The objectives of this series of tests were to define the major variables improving the reactor efficiency and to orient the direction of studies for future work.

The reactor variables (Figure 3b) were studied using the Box-Wilson method (9), a program based on statistical factorial experimentation design. The benefit of this method was the ability to scan a large number of variables and to distinguish the important few for more detailed testing. The method also has the potential to establish the variable direction (increasing or decreasing) required to obtain more desirable operating regions. The analytical analysis for the

technique was self contained (Appendix 4 and 5) requiring very little background knowledge of actual statistical analysis.

The results of the mixing characteristics study were divided into two parts: a) the reactor design evaluation, and b) the process design evaluation. The reactor design evaluation considered the effects of design variables on the response variables associated with the design of the reactor: the selectivity of copper and zinc and the fraction of zinc reacting (precipitating). The process design evaluation considered the effects of design variables on the response variables associated with the process system: the pressure drop across the reactor and the fraction of H_2S reacting. The operating conditions, specifying the response variables and values of the independent variable are recorded in Table 4. The ordering of the independent variables in decreasing order of significance for each response variable is recorded in Table 5.

3.1 Reactor Design Evaluation

Because of the relatively insignificant effect of the back pressure and the percent excess gas, these variables were not considered during later evaluation. Since the nozzle length assumed a decreasing direction for all the response variables, its value was set at 0.75 inches for all future work.

The selectivity for copper was improved by decreasing the independent variables, even below the low level conditions of the test series. Since copper precipitation was complete and copper selectivity was dependent on nickel precipitation,

TABLE 4

Values of the Independent Variables and the Response Variables for the Box Wilson Factorial Design Test Program

Independent Variables		Values	
		High	Low
Dn	Nozzle Diameter	0.1875 in.	0.125 in.
Ln	Jet Length	1.25 in.	0.75 in.
Lmt	Mixing Tube Length	3.75 in.	2.50 in.
Lgn	Gas Nozzle Length	Out	In
Ul	Liquid Flowrate	2.5 GPM	2.0 GPM
Eg	Excess H ₂ S	25%	15%
Pb	Back Pressure	15 psig	10 psig
<u>Response Variables</u>			
	S _{Cu/Ni}	Selectivity for Copper	
	S _{Zn/Ni}	Selectivity for Zinc	
	f _{Zn}	Fraction Zn Reacting	
	f _{H₂S}	Fraction H ₂ S Reacting	
	ΔP	Pressure Drop Across Reactor	

TABLE 5

Ordering of Independent Variables According to Their Significance with Respect to the Response Variable

ORDER	RESPONSE VARIABLE				
	S _{Cu/Ni}	S _{Zn/Ni}	f _{Zn}	f _{H₂S}	ΔP
1	Lmt -	Lmt -	Lgn +	Lmt +	Dn -
2	Ul -	Lgn +	Ln -	Ln -	Ul +
3	Dn -	Dn +	Dn +	Dn +	Lgn +
4	Lgn -	Pb +	Eg +	Lgn +	Pb -
5	Eg -	Eg +	Ul +	Pb +	Lmt +
6	Ln -	Ln -	Lmt +	Eg +	Ln -
7	Pb -	Ul -	Pb +	Ul +	Eg +

the direction of low level operating conditions was unfavorable to nickel precipitation. The three major variables improving copper selectivity were the mixing tube length, the nozzle diameter and the liquid flowrate.

The selectivity of zinc was more critically controlled by the independent variables but was similar to the copper selectivity. Decreasing the length of the mixing tube was the major variable improving zinc selectivity; by reducing the nickel precipitation. The nozzle diameter and the gas nozzle length were also important variables but required increasing values to improve zinc selectivity.

Since the selectivity was the ratio of precipitation of two metals, additional observations were made about the system. As has been concluded from the improved selectivity, nickel precipitation decreased with decreasing mixing tube length. Increasing the nozzle diameter and gas nozzle length increased the nickel precipitation as indicated by the alternating significance of these variables for increased copper and zinc selectivity. Increasing the liquid flowrate increased copper selectivity indicating a possible relationship between the flowrate and the kinetics of reactions.

Some of these conclusions concurred with the results for the fraction of zinc reacting. The amount of zinc precipitated increased as the major variables, gas nozzle length and nozzle diameter, increased. Although relatively insignificant increasing the liquid flowrate and the length

of the mixing tube improved the amount of zinc precipitating.

3.2 Process Design Evaluation

Since it was desirable to minimize the pressure drop across the reactor, the direction of the reported values, Table 5, should be reversed. By increasing the nozzle diameter the pressure drop was reduced. Consistent with conclusions from the reactor design evaluation, reducing the liquid flowrate was significant for reducing the pressure drop across the reactor. Using these two variables the pressure drop was also related to the Reynolds number through the nozzle and is included (Appendix 6).

The results for the fraction of H_2S reacting were similar to the results for the fraction of zinc reacting. Increasing the nozzle diameter and the gas nozzle length increased the amount of reaction. Increased H_2S reaction was most significantly related to the increased length of the mixing tube.

4. Process Design Characteristics

The objective of this test series was to study in more detail the major variables resulting from the mixing characteristics study.

The variables; mixing tube length, nozzle diameter and gas nozzle length; were studied individually holding all other variables constant. The operating values for U_1 , L_n , E_g and P_b were set at the low level values of the preceding

tests. Because of limitations of equipment, only three point curves were generated to evaluate these variables. The test conditions are defined in Table 6.

TABLE 6
Major Variables, Operating Values and
Dimensionless Quantities for the
Process Design Characteristics Test Program

Variable	Value	Dimensionless Quantity	Value
Lmt	2.5 in.	Lmt/Dmt	10
	3.75 in.		15
	5.0 in.		20
Dn	0.125 in.	Dn/Dmt	0.5
	0.1875 in.		0.75
	0.250 in.		1.0
Lgn	Out Mid - .25 In	--	

4.1 Reactor Design Evaluation

The effects of the mixing tube length on the selectivity for copper and zinc and on the fraction of zinc reacting are plotted in Figure 4 (Table 8A, Appendix 8). The selectivity of zinc was relatively unaffected by Lmt, indicating the precipitation of nickel was similar to the precipitation of zinc. Observing f_{Zn} , the precipitation dropped very rapidly for values of Lmt/Dmt below 15. Therefore the selectivity of copper should be significantly increased as the Lmt decreases, as was observed.

The effects of the nozzle diameter on the selectivity for copper and zinc and on the fraction of zinc reacting are

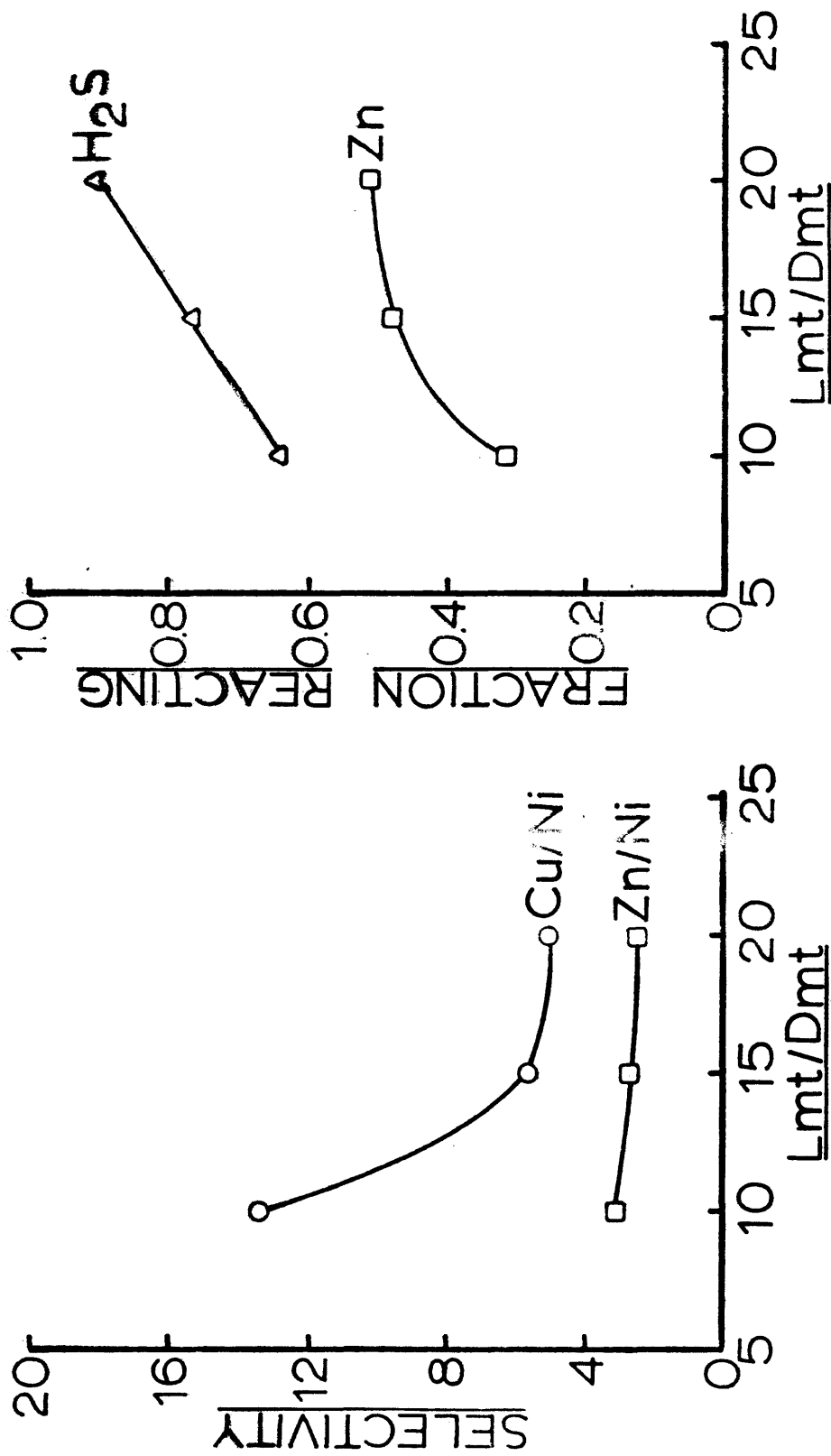


Figure 4 : Copper and Zinc selectivity and fraction of Zn and H₂S reacting as a function of the ratio of mixing tube length to mixing tube diameter. The mixing tube diameter was held constant at 0.25 inch.

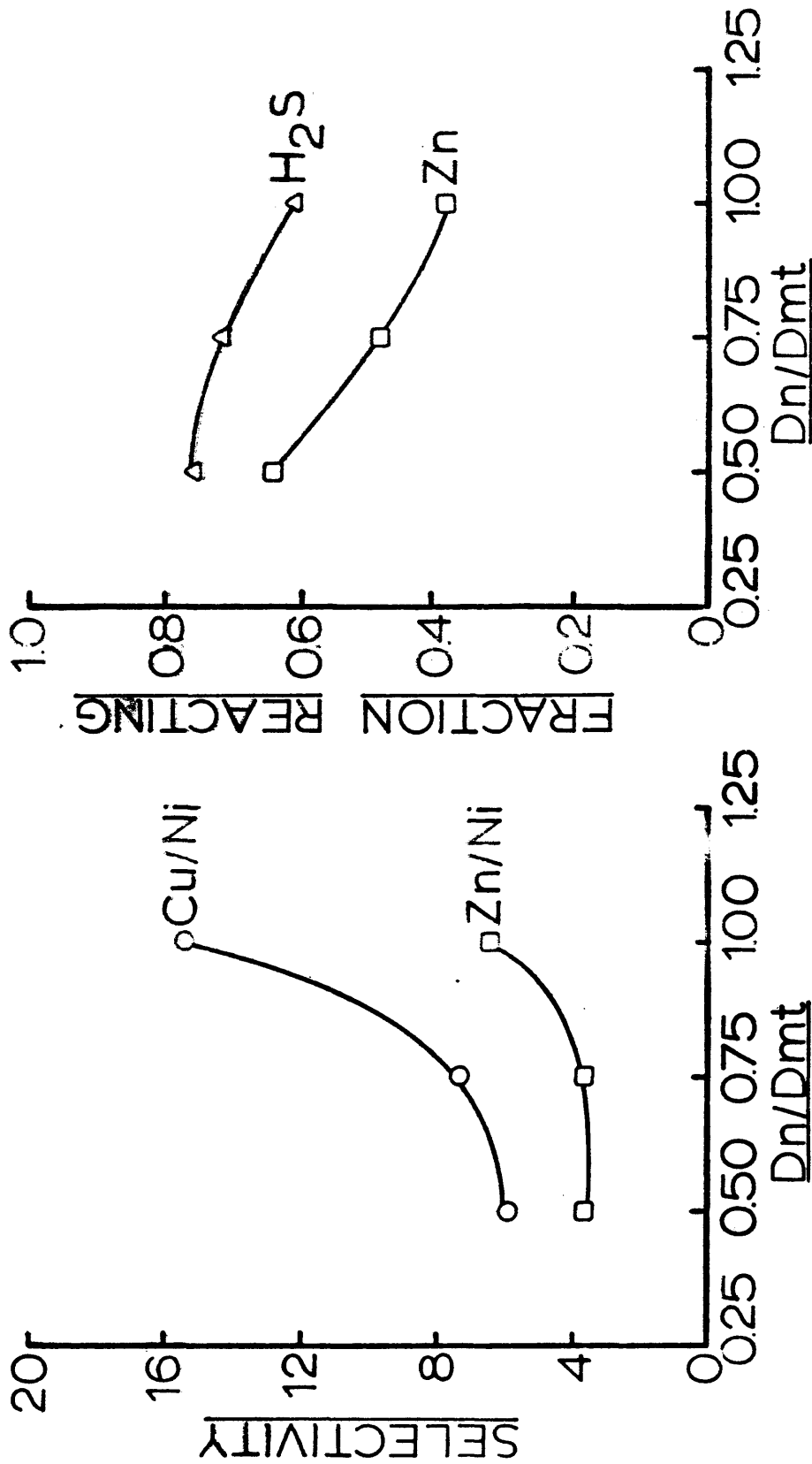


Figure 5 : Copper and Zinc selectivity and fraction of Zn and H₂S reacting as a function of the ratio of nozzle diameter to mixing tube diameter. The mixing tube diameter was held constant at 0.25 inch.

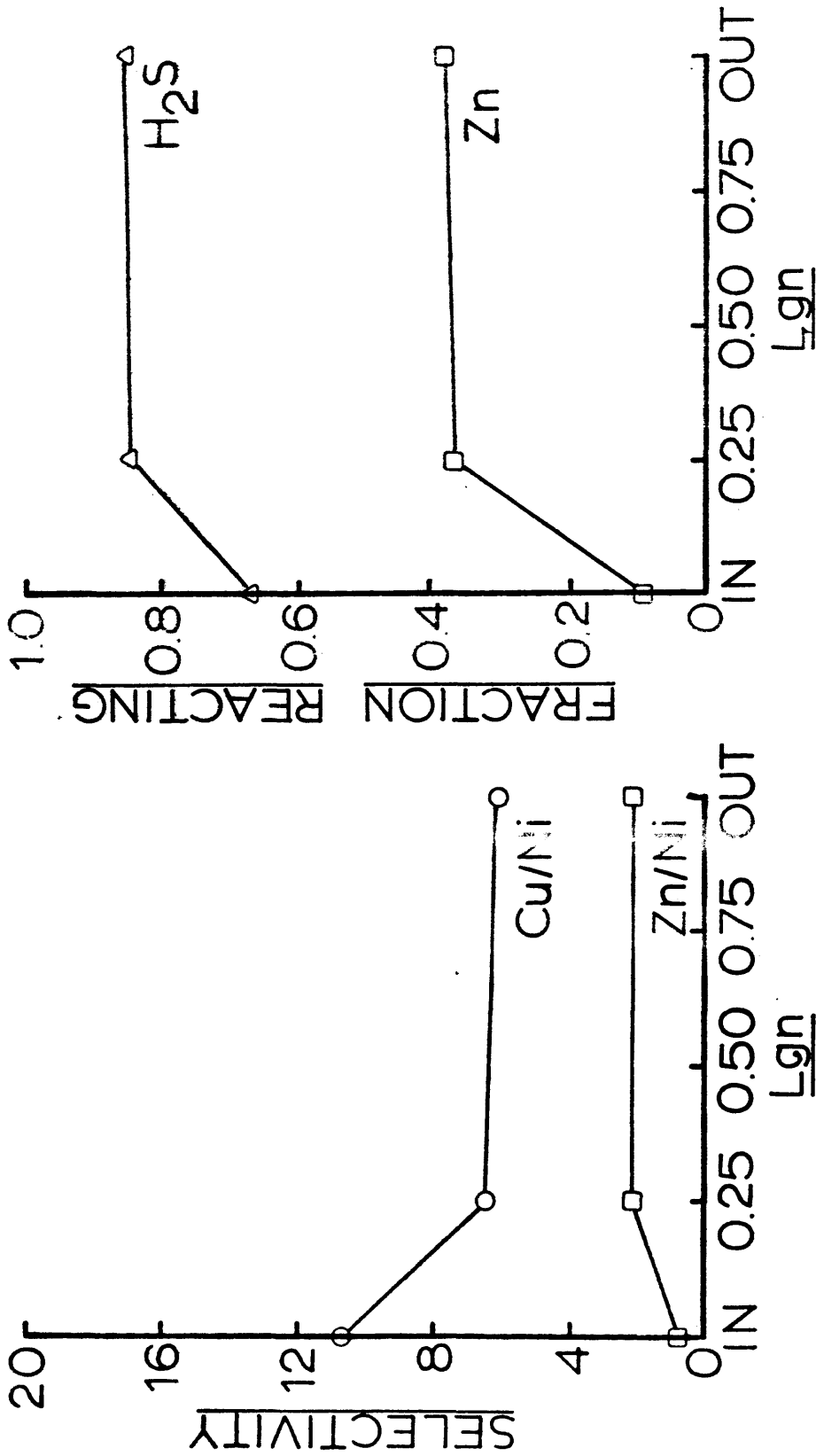


Figure 6 : Copper and Zinc selectivity and fraction of Zn and H₂S reacting as a function of the gas nozzle length.

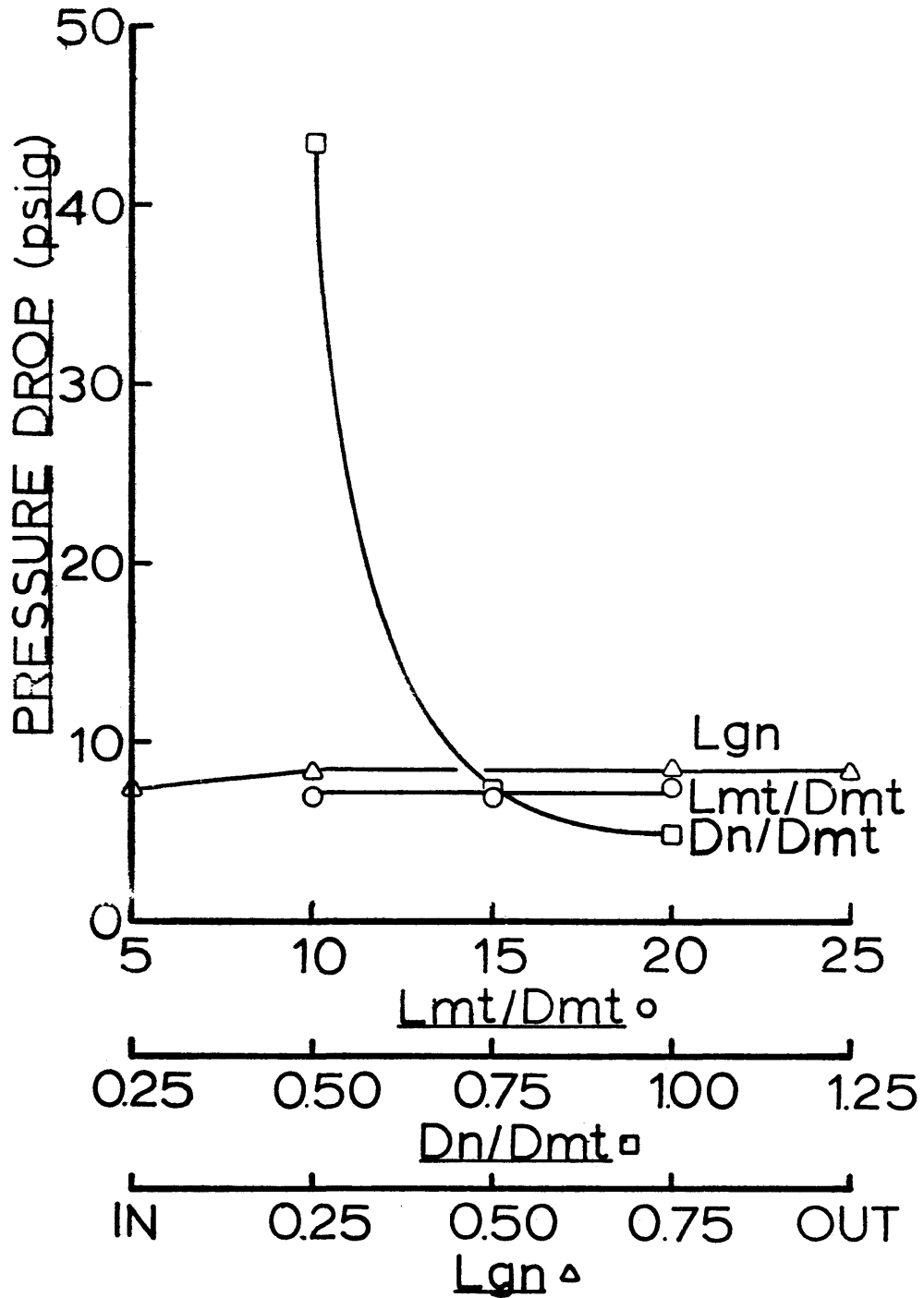


Figure 7 : Pressure drop across the reactor as a function of mixing tube length, nozzle diameter, and gas nozzle length. The mixing tube diameter was held constant at 0.25 inches.

plotted in Figure 5 (Table 8B, Appendix 8). As the nozzle diameter decreased the selectivity for both copper and zinc decreased eventually leveling off. Based on the increase of zinc precipitation with decreasing nozzle diameter, the selectivity should level off with increasing precipitation of other metal values in relation to the favoritism of the chemistry, $\text{Cu} \gg \text{Zn} > \text{Ni}$.

The effects of the gas nozzle length on the selectivity for copper and zinc and on the fraction of zinc reacting are plotted in Figure 6 (Table 8C, Appendix 8). The data indicated the Lgn affected the response variables only in the out position or only in the in position (very close to the liquid jet). The values of Lgn between these positions responded similarly to the out position. The rapid drop in zinc precipitation when Lgn was very close to the liquid jet may indicate a choking effect on the gas-liquid mixing.

4.2 Process Design Evaluation

The effects of Lmt, Dn and Lgn on the pressure drop across the reactor are plotted in Figure 7 (Appendix 8). The pressure drop varied significantly only with respect to the nozzle diameter, increasing rapidly as the diameter decreased. Based on this observation and the results of the reactor design evaluation, the liquid jet-gas eductor reactor could be studied from two approaches: (a) the low pressure drop system, and (b) the high pressure drop system.

The effects of Lmt, Dn and Lgn on the fraction of H_2S reacting were similar to the results for the fraction of

zinc reacting. The amount of H_2S reacting very seldom exceeds 0.9, averaging approximately 0.8. From Figure 5 the H_2S reacting began to level off at 0.80 but from Figure 4 the H_2S reacting would level off at 0.90. Therefore control of the H_2S reacting was most significantly related to the length of the mixing tube.

The process evaluation was self directed toward a low pressure drop across the reactor (7 to 10 psig). At this condition the D_n/D_{mt} should be maintained at approximately 0.75; therefore maintaining reasonable zinc precipitation at constant selectivity. The mixing tube length, critical to the fraction of zinc precipitating, should be maintained at a ratio with the mixing tube diameter, L_{mt}/D_{mt} , of approximately 15. The gas nozzle length, detrimentally significant to the system when very close to the liquid jet, should be maintained in the out position. The expected range of response variables for these conditions were:

$S_{Cu/Ni}$	→ 5 to 7
$S_{Zn/Ni}$	→ 3 to 4
f_{Zn}	→ 0.50 to 0.60
f_{H_2S}	→ 0.75 to 0.85
ΔP	→ 7 to 9 psig.

5. System Parameter Characteristics

The objective of this study was to determine the effects of temperature, initial pH and the copper to zinc ratio of the feed solution on the efficiency of the reactor.

The system parameters were studied individually over the following ranges:

Temperature: 25°C to 65°C
pH : 2 to 5
Cu:Zn : 1:60 to 1:1

The reactor variables were set, based on the mixing characteristics study (Box Wilson):

Dn = 0.1875 in. Ul = 2.0 GPM
Lmt = 2.5 in. Ln = 0.75 in. Eg = 15%
Lgn = Out Pb = 10 psig

The effects of temperature on the selectivity of copper and zinc and on the fraction of zinc and H₂S reacting are plotted in Figure 8 (Table 9A, Appendix 9). Increasing temperature was extremely detrimental to copper and zinc selectivity over nickel as well as the fraction of zinc reacting. This effect indicated an increasing nickel precipitation with increasing temperature. From the solubility data reported by C. S. Simons (3), the selectivity of zinc over nickel was expected to decrease with increasing temperature.

The increasing nickel precipitation was not consistent with the solubility data, indicating a possible rate controlled mechanism. Because copper precipitation was complete and preferential to nickel, even in the presence of high nickel concentrations, the system was most likely not mass transfer limited. The increasing fraction of nickel

precipitating with increasing temperature indicated the system was not solubility limited. However, chemical reaction rate changes with increasing temperature would cause an observed change of one metal value relative to a second metal value, such as the increasing nickel precipitation and decreasing zinc precipitation.

A more in-depth study of the technical literature as well as more accurate experimental data, specifically to study the effects of temperature should be continued to verify the controlling mechanism for this system.

The effect of pH on the selectivity of copper and zinc and on the fraction of zinc and H_2S reacting are plotted in Figure 9 (Table 9B, Appendix 9). The selectivity of zinc reached a maximum around pH 3.2. The increasing selectivity indicated a preferential range of operation for zinc precipitation (pH values greater than 3.2) whereas the decreasing selectivity indicated the limiting range of operation due to increased nickel precipitation. Because of the significance of pH for the selective precipitation of zinc, a more detailed and accurate test program should be run.

The effects of the zinc to copper ratio of the feed on the selectivity of copper and zinc and on the fraction of zinc and H_2S reacting are plotted in Figure 10 (Table 9C, Appendix 9). The copper selectivity decreased as the zinc to copper ratio approached one. Since the copper selectivity

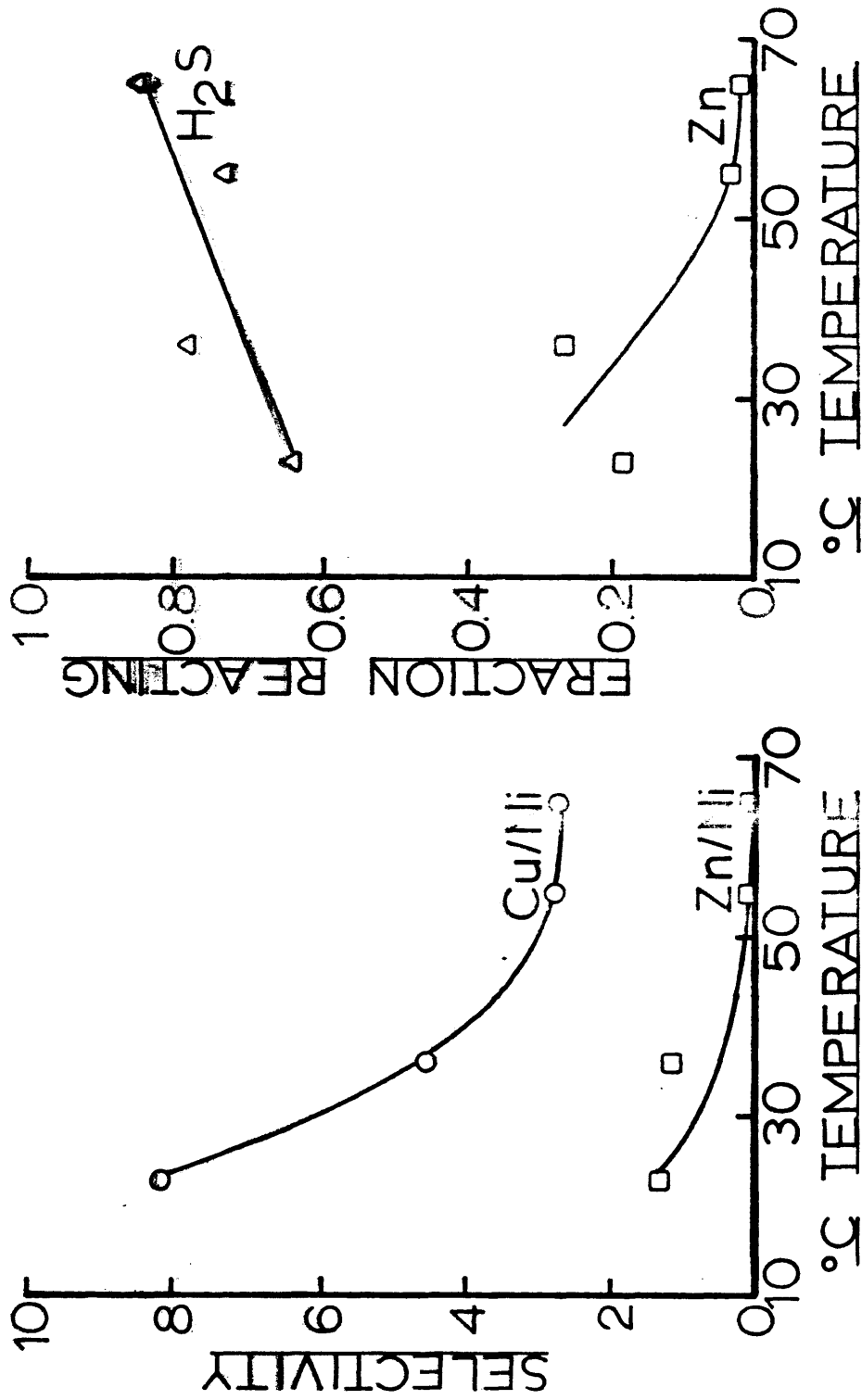


Figure 8: Copper and Zinc selectivity and fraction of Zn and H₂S reacting as a function of temperature

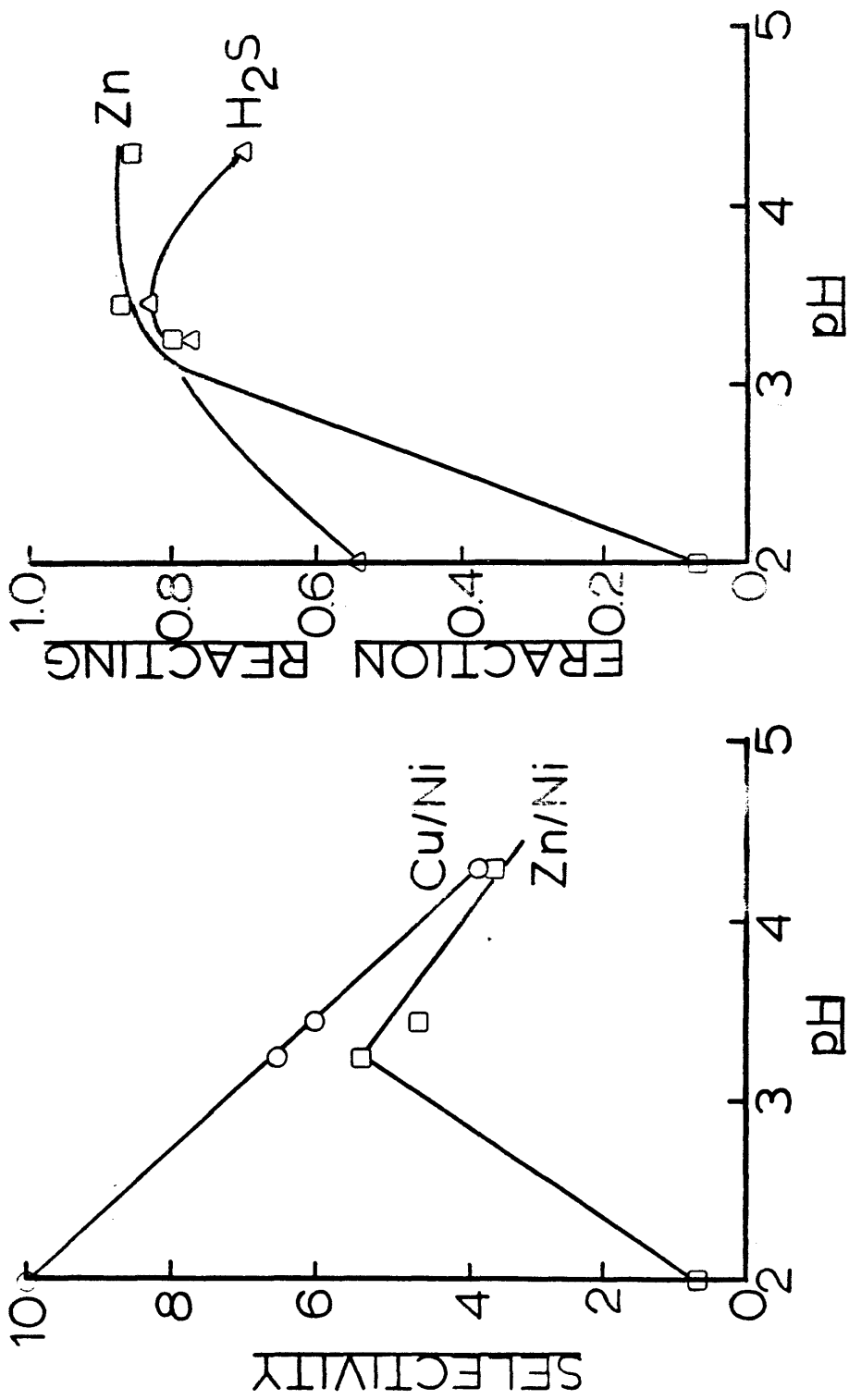


Figure 9: Copper and Zinc selectivity and fraction of Zn and H₂S reacting as a function of pH.

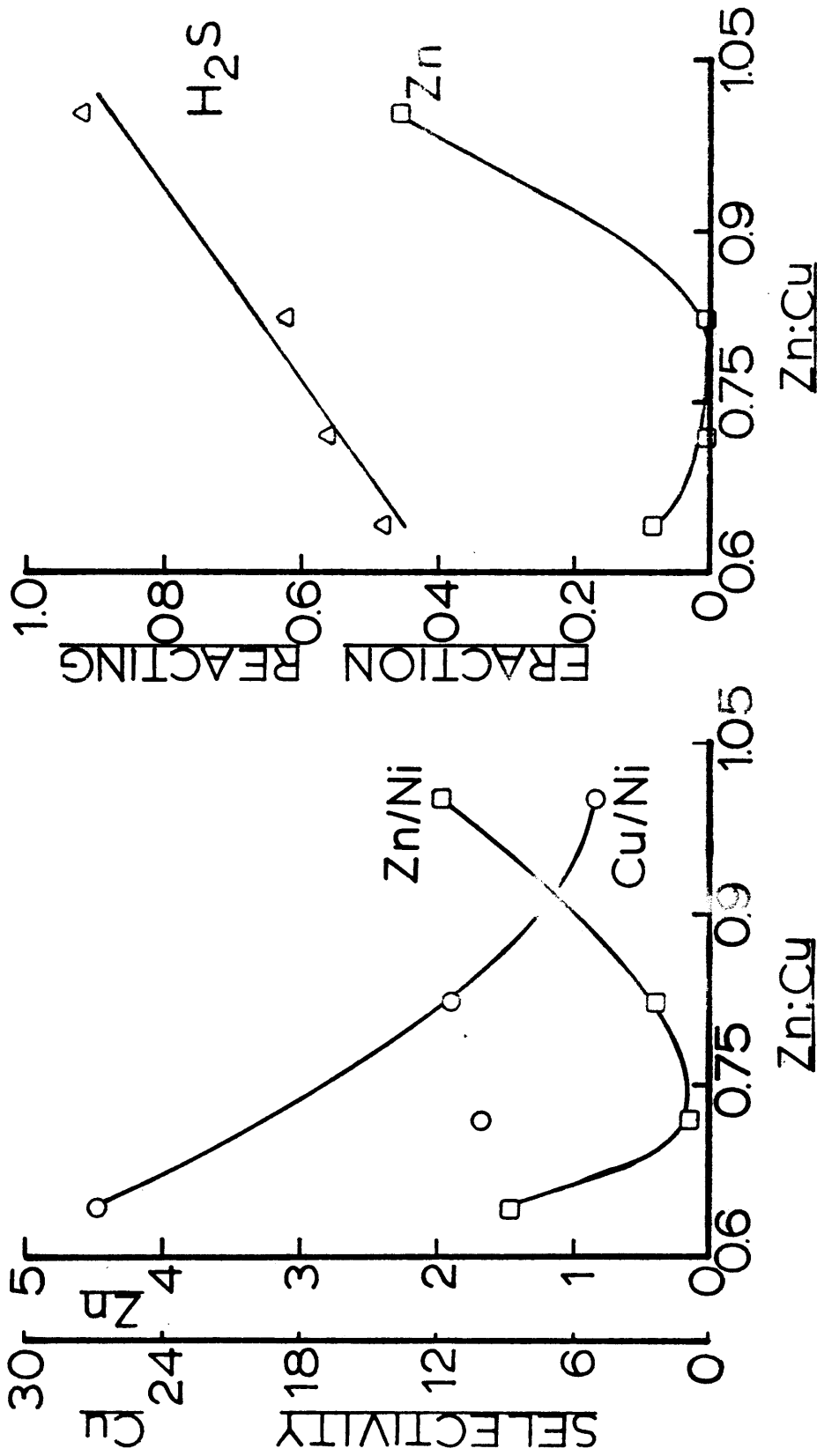


Figure 10: Copper and Zinc selectivity and fraction of Zn and H₂S reacting as a function of ratio of the feed solution

was not expected to change substantially, zinc was assumed to seed the precipitation of nickel. The zinc precipitation and selectivity were essentially zero until the zinc to copper ratio exceeded 0.82. They increased rapidly as the ratio approached one. Also the hydrogen sulfide reacting decreased as the ratio decreased. Based on the solubility data of C. S. Simons (3) the hydrogen sulfide was expected to react completely in all tests. At the present these observations are not completely understood. Research should be continued in this area since fluctuations in the zinc to copper ratio of a plant feed stream could result in dramatic changes in the amount of zinc precipitating.

6. Proposed Process Characteristics

The liquid jet gas eductor reactor was more effective for the sulfide precipitation of copper and zinc from nickel sulfate solution than the present method of hydrogen sulfide sparging into a pipeline reactor. The jet pump reactor eliminated the mass transfer control of the pipeline reactor by selectively precipitating the lesser concentrated copper and zinc ions over the more highly concentrated nickel ions. However, the data indicated the jet pump reactor has some degree of chemical reaction rate control. This was observed from the increased precipitation of nickel relative to the decreased precipitation of zinc with increased temperatures and the increased precipitation of metal sulfides with increased length of the mixing tube. The relatively incom-

plete reaction of the hydrogen sulfide gas also implied a limiting reaction mechanism due to the diffusion of hydrogen sulfide into the liquid phase.

These conclusions were very general, based on a limited amount of data. The system parameters appeared to be critical to the process mechanism and should be studied in greater detail in order to define the exact controlling mechanism of sulfide precipitation and to model the liquid jet gas eductor. Research is required to determine: a) the exact controlling reaction mechanism with greater emphasis on reaction rates and gas diffusion, b) the effects of additional reactor design specifically mixing tube diameters, and c) the effects of system parameters particularly with respect to the reaction mechanism.

Based on this limited data, a suggested set of operating parameters is:

Temperature : Room

pH : 3.0 to 3.5

and set of design characteristics is:

Ratio of nozzle diameter to mixing tube diameter

D_n/D_{mt} : 0.75

Ratio of mixing tube length to mixing tube diameter

L_{mt}/D_{mt} : 15.0

Position of the gas nozzle

L_{gn} : parallel to the reactor wall

Ratio of nozzle length to mixing tube diameter

L_n/D_{mt} : 3.0

Excess H_2S gas over required for copper and zinc precipitation

Eg : 15%

Back pressure on the reactor

Pb : 10 psig

An estimated set of values based on these conditions for a one to one zinc to copper ratio in the feed is

Selectivity of copper over nickel

$S_{Cu/Ni}$: 5 to 7

Selectivity of zinc over nickel

$S_{Zn/Ni}$: 4 to 6

Fraction of zinc reacting

f_{Zn} : 0.7 to 0.9

Fraction of hydrogen sulfide reacting

f_{H_2S} : 0.75 to 0.85

Pressure drop across the reactor

ΔP : 7 to 9 psig.

NOMENCLATURE

Dn	Nozzle Diameter
Ln	Nozzle Length
Lmt	Mixing Tube Length
Lgn	Gas Nozzle Length or Position
U _l	Volumetric Liquid Flowrate
P _b	Back Pressure to Reactor
E _g	Excess Hydrogen Sulfide Gas
Re	Reynolds Number
M	Mass Flowrate
P	Pressure
S	Selectivity: mass 1/mass 2
f	Fraction Reacting
R	Extent of Reaction
C	Concentration
K	Coefficient Constant
V	Volume
T	Temperature
ρ	Density
μ	Viscosity

Subscripts:

A	Component A
B	Component B
SP	Solubility Product
F	Reaction

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APPENDIX 1: Data Sheet for the Liquid Jet-Gas Eductor Reactor Experimental Program.

Run
Date
Test

Design Condition

Nozzle

Ln

Mixing Tube

Lgn

Ul

Eg

Pb

Physical System

LI Temp

Den

pH

GI Flow 1

LI 2

GI Pres 1

LI 2

LO 3

Flow 3

Temp

pH

Solid Data

Sam + Tare

Tare

Sam

Paper

Solids

Liquid Data

Volume

Density

APPENDIX 2

**Computer Program, Input Data and
Output Print Out for the Liquid Jet Gas
Eductor Reactor Experimental Program**

```
COMMON/COMA/IFLAG,NCOMP,IN,ICUT
COMMON/COMB/HDG(20),WCSO(10)
IN=1
ICUT=3
C*****READ THE NUMBER OF TESTS TO BE RUN
      READ(IN,200)IFLAG
200   CONTINUE
      IF(IFLAG .EQ. 0) GO TO 300
      CALL HEAD
      CALL MASBAL
      CALL PROANL
      GO TO 200
200   FORMAT(I2)
300   CONTINUE
      STOP
      END
```

```

SUBROUTINE HEAD
COMMON/COMA/IFLAG,NCOMP,IN,IOUT
COMMON/COMB/HDG(20),WCSD(10)
DOUBLE PRECISION ICOMP
10 CONTINUE
C*****READ SUBJECT HEADING
READ(IN,200)(HDG(I),I=1,20)
WRITE(IOUT,250)(HDG(I),I=1,20)
C*****READ NUMBER OF COMPONENTS
READ(IN,210)NCOMP
C*****READ COMPONENT NAMES
DO 20 I=1,NCOMP
READ(IN,220)ICOMP
WRITE(IOUT,260)I,ICOMP
20 CONTINUE
30 CONTINUE
200 FORMAT(20A4)
210 FORMAT(I2)
220 FORMAT(A10)
250 FORMAT(1H1,20X,20A4)
260 FORMAT(' COMPONENT ',I2,' --- ',A10)
300 CONTINUE
RETURN
END

```



```

SUBROUTINE MASBAL
COMMON/COMA/IFLAG, NCOMP, IN, IOUT
COMMON/COMB/HDG(20), WCSO(10)
DIMENSION COMPL(10), WCLI(10), COMPS(10), WCSI(10)
DIMENSION COMPL0(10), WCLO(10), COMPS0(10)
DIMENSION TWCI(10), TWCO(10), PCIFF(10)
C1=454
C2=0.454
C3=100
C4=0.73699875
C5=0.50855002
10 CONTINUE
C*****THE INPUT DATA BEGINS HERE
C*****READ LIQUOR MASS DATA IN
READ(IN,200)VLI,DLI,WSI
IF(WSI .EQ. 0) GO TO 40
20 CONTINUE
WLI=VLI*DLI
TWI=WLI*WSI
FSI=WSI/TWI
30 CONTINUE
READ(IN,205)SCALI
WLRI=C4*(C5*SCALI)
WASIP=WLRI*FSI
WASI=WASIP*C1
WALI=WLRI-WASIP
VALI=(WALI/DLI)*C2
GO TO 50
40 CONTINUE
READ(IN,205)SCALI
WLRI=C4*(C5*SCALI)
VALI=(WLRI/DLI)*C2
50 CONTINUE
C*****READ LIQUID COMPONENTS IN
READ(IN,210)(COMPL(I),I=1,NCOMP)
DO 60 I=1,NCOMP
WCLI(I)=VALI*COMPL(I)
60 CONTINUE
C*****READ SOLID COMPONENTS IN
READ(IN,210)(COMPS(I),I=1,NCOMP)
DO 70 I=1,NCOMP
WCSI(I)=WASI*(COMPS(I)/C3)
TWCI(I)=WCLI(I)+WCSI(I)
70 CONTINUE
C*****WRITE INPUT DATA
WRITE(IOUT,255)
WRITE(IOUT,256)(I,I=1,NCOMP)
WRITE(IOUT,257)
WRITE(IOUT,250)(WCLI(I),I=1,NCOMP)
WRITE(IOUT,260)(WCSI(I),I=1,NCOMP)
WRITE(IOUT,270)(TWCI(I),I=1,NCOMP)

```

```

80    CONTINUE
C*****THE OUTPUT DATA BEGINS HERE
C*****READ LIQUOR MASS DATA OUT
      READ(IN,200)VLO,DLO,WSO
      WLO=VLO*DLO
      TWO=WLO+WSO
      FSO=WSO/TWO
90    CONTINUE
      READ(IN,205)SCALO
      WLRO=C4+(C5*SCALO)
      WASOP=WLRO*FSO
      WASO=WASOP*C1
      WALO=WLRO-WASOP
      VALO=(WALO/DLO)*C2
100   CONTINUE
C*****READ LIQUID COMPONENTS OUT
      READ(IN,210)(COMPL0(I),I=1,NCOMP)
      DO 110 I=1,NCOMP
      WCLO(I)=VALO*COMPL0(I)
110   CONTINUE
C*****READ SOLID COMPONENTS OUT
      READ(IN,210)(COMPS0(I),I=1,NCOMP)
      DO 120 I=1,NCOMP
      WCSO(I)=WASO*(COMPS0(I)/C3)
      TWCO(I)=WCLO(I)+WCSO(I)
120   CONTINUE
C*****WRITE OUTPUT DATA
      WRITE(IOUT,258)
      WRITE(IOUT,250)(WCLO(I),I=1,NCOMP)
      WRITE(IOUT,260)(WCSO(I),I=1,NCOMP)
      WRITE(IOUT,270)(TWCO(I),I=1,NCOMP)
130   CONTINUE
C*****CALCULATE DIFFERENCE BETWEEN INPUT AND OUTPUT
      DO 140 I=1,NCOMP
      PDIFF(I)=((TWCI(I)-TWCO(I))/TWCI(I))*C3
140   CONTINUE
C*****WRITE PERCENT DIFFERENCE
      WRITE(IOUT,275)
      WRITE(IOUT,280)(PDIFF(I),I=1,NCOMP)
200   FORMAT(F6.1,1X,F5.3,1X,F5.2)
205   FORMAT(F5.2)
210   FORMAT(10(F6.3,1X))
250   FORMAT(' LIQUID   I ',2X,10(F6.2,1X))
255   FORMAT('/',20X,' MATERIAL BALANCE')
257   FORMAT('/',16X,' MASS IN (GRAMS PER MINUTE)')
256   FORMAT('/',10X,10(5X,I2))
258   FORMAT('/',15X,' MASS OUT (GRAMS PER MINUTE)')
260   FORMAT(' SOLIDS   I ',2X,10(F6.2,1X))
270   FORMAT(' TOTAL     I ',2X,10(F6.2,1X))
275   FORMAT('/',18X,' DIFFERENCE (PERCENT)')
280   FORMAT(' DIFF      I ',2X,10(F6.2,1X))

```

300 CONTINUE
RETURN
END

```

SUBROUTINE PROANL
COMMON/COMA/IFLAG, NCOMP, IN, IOUT
COMMON/COMB/HDG(2), WCSO(10)
DIMENSION R(10), SR(10), CMW(10)
C1=34.06
C2=-14.37968480
C3= 1.50702004
C4=- 0.04659467
C5= 0.00065751
C6=- 0.00000315
C***** WRITE REACTION COEFFICIENT FOR PROCESS
DO 10 I=1, NCOMP
R(I)=WCSO(I)
10 CONTINUE
WRITE(IOUT, 250)
WRITE(IOUT, 252)
WRITE(IOUT, 255)
WRITE(IOUT, 258)
WRITE(IOUT, 260) (R(I), I=1, NCOMP)
20 CONTINUE
C***** CALCULATE AND WRITE SELECTIVITY
SCU=R(2)/R(1)
SZN=R(3)/R(1)
30 CONTINUE
WRITE(IOUT, 265)
WRITE(IOUT, 270) SCU
WRITE(IOUT, 280) SZN
40 CONTINUE
C***** CALCULATE THE AMOUNT OF H2S REACTING
READ(IN, 200) SGI
TWGI=C2+(C3*SGI)+(C4*(SGI**2))+(C5*(SGI**3))+(C6*(SGI**4))
WGI=0.98*TWGI
READ(IN, 210) (CMW(I), I=1, NCOMP)
DO 50 I=1, NCOMP
A1=C1/CMW(I)
B1=R(I)
SR(I)=A1*B1
50 CONTINUE
TSR=SR(1)+SR(2)+SR(3)
FHS=TSR/WGI
60 CONTINUE
C***** WRITE FRACTION OF GAS REACTING
WRITE(IOUT, 285)
WRITE(IOUT, 290) FHS
70 CONTINUE
IFLAG=IFLAG-1
200 FORMAT(F5, 2)
210 FORMAT(3(F5, 2, 1X))
250 FORMAT(/, 20X, 'PROCESS ANALYSIS')
252 FORMAT(10X, 'USING THE REACTION COEFFICIENT (R) FOR')
255 FORMAT(10X, 'THE STEADY STATE MASS BALANCE EQUATION')

```

```
258 FORMAT(/,20X,'IN-OUT-REACTION=0')
260 FORMAT(/,' R      ! ',2X,3(F6,2,1X))
265 FORMAT(/,10X,'TO OBTAIN SELECTIVITY.')
```

270 FORMAT(' RCU/RNI : ',2X,F6,2)

280 FORMAT(' REN/RNI : ',2X,F6,2)

285 FORMAT(/,10X,'FRACTION OF H2S REACTING!')

290 FORMAT(' FH2S ! ',2X,F6,3)

300 CONTINUE

RETURN

END

Ø1
MIXING TUBE LENGTH TEST 3.75 INCHES

Ø3

NICKEL

COPPER

ZINC

0000.0 1.150 0.000

36.00

48.000 01.040 01.050

00.000 00.000 00.000

0890.0 1.150 2.900

36.00

48.000 00.001 00.540

05.600 31.800 15.200

59.00

58.71 63.54 65.37

1 MIXING TUBE LENGTH TEST 3.75 INCHES
 COMPONENT 1 77 NICKEL
 COMPONENT 2 77 COPPER
 COMPONENT 3 77 ZINC

MATERIAL BALANCE

	1	2	3
	MASS IN (GRAMS PER MINUTE)		
LIQUID	360.89	7.82	7.89
SOLIDS	0.00	0.00	0.00
TOTAL	360.89	7.82	7.89
	MASS OUT (GRAMS PER MINUTE)		
LIQUID	359.87	0.01	4.05
SOLIDS	1.37	7.77	3.71
TOTAL	361.24	7.78	7.76
	DIFFERENCE (PERCENT)		
DIFF	-0.10	0.55	1.68

PROCESS ANALYSIS
 USING THE REACTION COEFFICIENT (R) FOR
 THE STEADY STATE MASS BALANCE EQUATION

IN-OUT-REACTIONS

R	1	1.37	7.77	3.71
---	---	------	------	------

TO OBTAIN SELECTIVITY,

RCU/RNI	1	5.68
RZN/RNI	1	2.71

FRACTION OF H₂S REACTING

FH ₂ S	1	0.764
-------------------	---	-------

APPENDIX I - Set of Equations, Based on Mass and Reaction Balances, for the Liquid Jet-Gas Eductor Reactor Experimental Program.

EQUATIONS

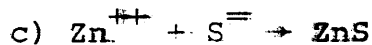
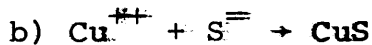
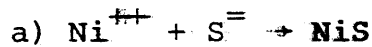
VARIABLES

OVERALL MASS BALANCE

$$1) U_1 \rho_1 + U_2 \rho_2 - U_3 \rho_3 = 0$$

$$\begin{array}{lll} 1) F_1 & 2) \rho_1 & 3) F_2 \\ 4) \rho_2 & 5) F_3 & 6) \rho_3 \end{array}$$

REACTIONS



COMPONENT BALANCE

$$1 = Ni \quad 2 = Cu \quad 3 = Zn \quad 4 = S$$

$$5 = NiS \quad 6 = CuS \quad 7 = ZnS$$

$$2) U_1 C_{11} - U_3 C_{31} - R_1 = 0$$

$$7) C_{11} \quad 8) C_{31} \quad 9) R_1$$

$$3) U_1 C_{12} - U_3 C_{32} - R_2 = 0$$

$$10) C_{12} \quad 11) C_{32} \quad 12) R_2$$

$$4) U_1 C_{13} - U_3 C_{33} - R_3 = 0$$

$$13) C_{13} \quad 14) C_{33} \quad 15) R_3$$

$$5) U_2 C_{24} - U_3 C_{34} - (R_1 + R_2 + R_3) = 0$$

$$16) C_{24} \quad 17) C_{34}$$

$$6) U_3 C_{35} + R_1 = 0$$

$$18) C_{35}$$

$$7) U_3 C_{36} + R_2 = 0$$

$$19) C_{36}$$

$$8) U_3 C_{37} + R_3 = 0$$

$$20) C_{37}$$

REACTION RATE EXPRESSION

$$9) R_1 = f_1(C_{11}, T, pH, C_{12}/C_{13}, Dn, Lmt, Lgn) = 0$$

$$\begin{array}{lll} 21) T & 22) pH & 23) Dn \\ 24) Lmt & 25) Lgn & \end{array}$$

$$10) R_2 - F_2 (C_{12}, T, PH, C_{12}/C_{13}, Dn, Lmt, Lgn) = 0$$

$$11) R_3 - F_3 (C_{13}, T, PH, C_{12}/C_{13}, Dn, Lmt, Lgn) = 0$$

CONSTRAINTS OR OBJECTIVE FUNCTIONS

$$12) S_1 - C_{36}/C_{35} = 0$$

$$26) S_1$$

$$13) S_2 - C_{37}/C_{35} = 0$$

$$27) S_2$$

$$14) f - 1 + F_3 C_{34} / F_2 C_{24} = 0$$

$$28) f$$

()

APPENDIX 4

Box Wilson Data Sheet Used in the
Liquid Jet Gas Eductor Experimental Program

APPENDIX 5 - Sample Calculations for the Box Wilson Work Sheet.

With reference to the Box Wilson work sheet the following discussion explains the calculation procedure.

The test is set up by determining the variables to be studied in order to obtain a specific program objective. The independent variables are recorded in columns A to G. A base level and the amount of variation (unit) are recorded for each variable. The high levels and low levels are calculated as the base level \pm the units.

Rows 7 to 14 are filled in by placing the high level values in the shaded area and low level values in the non-shaded area. The samples are randomly run and the outcome is recorded in column H.

The data is analyzed by the Yates method. That is columns J to L are filled in by dividing rows 7 to 14 into pairs and adding the two numbers of each pair to get the first four values of the new column and subtracting the two numbers of each pair to get the last four values of the new column.

Example:	<u>H</u>	<u>J</u>
	7	7+8
	8	9+10
	9	11+12
	10	13+14
	11	7-8
	12	9-10
	13	11-12
	14	13-14

The values in column L are divided by eight to obtain values for the M column. These values define the effects of the factors listed in the N column.

For the objective of this project the ordering of variables was based on the magnitude of the absolute value of the effects.

Example of Ordering:

1	A	Dn-	18.2
2	E	U1-	7.0
3	D	Lgn+	5.8
4	G	Pb-	3.1
5	C	Lmt+	1.6
6	B	Ln-	1.4
7	F	Eg+	0.6

The significance of the order was related to the average value. Therefore for the nozzle diameter, Dn, the values 18.2 is compared to 28.8, implying the nozzle diameter was very significant to the pressure drop across the reactor. However, the value of the excess gas, 0.6, was relatively insignificant to the pressure drop.

APPENDIX 6

Table 6A

Response Variables for the Box-Wilson Study of
Independent Variables Affecting the Gas-Liquid
Mixing of the Liquid Jet-Gas Eductor Reactor

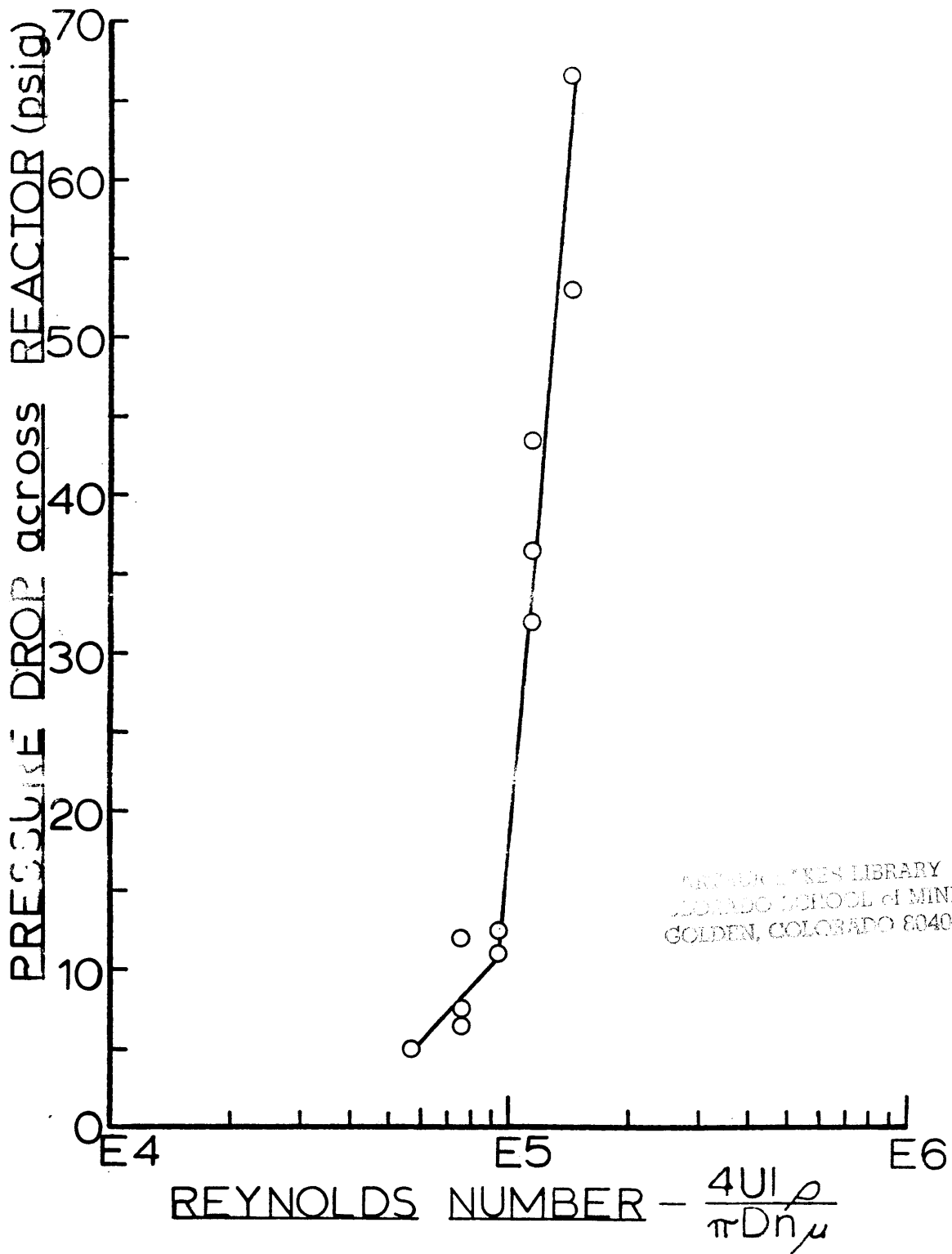
Test	Response Variables				
	$S_{Cu/Ni}$	$S_{Zn/Ni}$	F_{Zn}	F_{H_2S}	ΔP
1	22.33	0.72	0.034	0.508	36.5
2	7.92	2.58	0.299	0.509	12.5
3	3.43	1.58	0.470	0.896	11.5
4	11.00	0.95	0.122	0.721	32.0
5	10.45	6.58	0.629	0.757	6.5
6	8.91	2.77	0.247	0.482	53.0
7	2.98	1.43	0.649	0.997	66.5
8	5.15	1.64	0.310	0.657	9.0

Table 6B

Effects Calculated from the Box Wilson Data
Sheet for the Liquid Jet-Gas Eductor Study

Independent Variables	$S_{Cu/Ni}$	$S_{Zn/Ni}$	F_{Zn}	F_{H_2S}	ΔP
AVERAGE	9.02	2.28	0.345	0.647	28.8
Dn	-2.30	0.76	0.086	0.048	-18.2
Ln	-0.78	-0.30	-0.100	-0.095	-1.4
Lmt	-3.38	-0.88	0.043	0.083	1.6
Lgn	-2.15	0.82	0.114	0.039	5.8
Ul	-3.20	-0.14	0.071	0.026	7.0
Eg	-0.93	0.60	0.080	0.021	0.6
Pb	-0.57	0.69	0.022	0.017	-3.1

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APPENDIX 7: Pressure Drop across the reactor as a function of the Reynolds Number.

APPENDIX 8

Table 8A

Reactor Design Data and Process Design Data
as a Function of Mixing Tube Length

Lmt	S _{Cu/Ni}	S _{Zn/Ni}	f _{Zn}	ΔP	f _{H₂S}
2.5	13.41	3.12	0.317	7.0	0.648
3.75	5.68	2.71	0.478	7.0	0.764
5.0	5.07	2.47	0.512	7.5	0.904

Table 8B

Reactor Design Data and Process Design Data
as a Function of Nozzle Diameter

Dn	S _{Cu/Ni}	S _{Zn/Ni}	f _{Zn}	ΔP	f _{H₂S}
0.125	5.85	3.65	0.645	43.5	0.759
0.1875	7.48	3.65	0.487	7.5	0.718
0.250	15.38	6.46	0.389	5.0	0.613

Table 8C

Reactor Design Data and Process Design Data
as a Function of Gas Nozzle Length

Lgn	S _{Cu/Ni}	S _{Zn/Ni}	f _{Zn}	ΔP	f _{H₂S}
Out	6.14	2.14	0.389	8.5	0.857
Mid 0.25	6.47	2.15	0.372	8.5	0.843
In	10.67	0.80	0.093	7.5	0.672

APPENDIX 9

Table 9A

Reactor Design Data as a Function of Temperature

Temperature	$S_{\text{Cu/Ni}}$	$S_{\text{Zn/Ni}}$	f_{Zn}	$f_{\text{H}_2\text{S}}$
23°C	8.15	1.27	0.181	0.643
36°C	4.59	1.12	0.279	0.780
55°C	2.76	0.09	0.035	0.733
65°C	2.73	0.05	0.024	0.852

Table 9B

Reactor Design Data as a Function of pH

pH	$S_{\text{Cu/Ni}}$	$S_{\text{Zn/Ni}}$	f_{Zn}	$f_{\text{H}_2\text{S}}$
1.95	10.00	0.67	0.069	0.541
3.25	6.57	5.48	0.799	0.774
3.45	6.00	4.70	0.874	0.835
4.30	3.74	3.45	0.860	0.701

Table 9C

Reactor Design Data as a Function of
Copper to Zinc Ratio of the Feed Solution

Cu:Zn	$S_{\text{Cu/Ni}}$	$S_{\text{Zn/Ni}}$	f_{Zn}	$f_{\text{H}_2\text{S}}$
1:0.64	26.80	1.45	0.087	0.480
1:0.72	10.70	0.15	0.022	0.561
1:0.82	11.27	0.39	0.052	0.622
1:1.0	4.95	1.97	0.452	0.918