Report

HF Thermodynamics Tests: Data Report

A report produced for CEC

C C Kemp and M S Newland

January 2000

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Executive Summary

The risks from industrial releases of Anhydrous Hydrogen Fluoride (AHF) are being studied in the URAHFREP programme of assessment, data acquisition and field trials. This data report describes the results of work package WP5 of URAHFREP on HF thermodynamics.

Given the pivotal role of the thermodynamics on the dispersion of AHF in the environment, the purpose of the work package WP5 was to check the validity of previous data and extend measurements to a wider range of compositions. Butane, which could be released with AHF, was also included in the test matrix to study its influence on the thermodynamics of mixing of HF with air.

The main conclusions of the work are:

1. The reliability of previous work conducted by Schotte has been verified.

2. Measurements have been extended to areas of the HF-water-air system not previously studied.

3. The impact of isobutane has been studied and found only to suppress the extent of temperature increase/decrease generated on mixing HF with humid or dry air.

The implications and discussion of these results in terms of the treatment of HF in code models and impact on risk assessments is addressed in other work packages within the URAHFREP programme.

Contents

1   Introduction

The risks from industrial releases of Anhydrous Hydrogen Fluoride (AHF) are being studied in the URAHFREP programme of assessment, data acquisition and field trials (1). This data report describes the results of work package WP5 of URAHFREP on HF thermodynamics.

The thermodynamics of mixing of AHF with humid air may have a marked effect on its dispersion. This is because a complex mixture of physical and chemical processes can occur which have opposing effects on plume temperature and density. For example, dilution of AHF with air results in dissociation of HF oligomers, which is an endothermic process; however, reaction of HF with water vapour can generate heat. Therefore, the combined effect of important processes must be taken into account in order to predict their influence on dispersion processes. Previous work on HF thermodynamics has been conducted by Schotte (2). His paper includes a review of the molecular process involved, and provides the only available experimental data available to verify theoretical predictions of the thermodynamics of mixing of AHF with humidified air.

Given the pivotal role of thermodynamics on the dispersion of AHF in the environment, the purpose of the work package WP5 was to check the validity of Schotte's data and extend measurements to a wider range of compositions. Butane, which could be released with AHF, was also included in the test matrix to study its influence on thermodynamics of mixing of HF with air.

It should be noted that the tests were intended to examine the equilibrium temperature change on mixing vapour and gas phases, and that it was beyond the scope of these studies to examine the effect of flashing of liquid AHF or butane.

2 WP5 Programme

The programme of work for WP5 was divided into 4 stages:

- Review of requirements to focus experiments on gas mixtures and conditions that would be of most value in terms of validating or enhancing current databases on HF/water/butane/air systems.
- Design and set up of experimental apparatus to provide the necessary data.
- Measurements of HF/water systems: At least five measurements intended to verify the general trend of results obtained in Schotte's tests on dry and humid air.
- Measurements of HF systems including butane: at least 25 measurements to extend the database to wider ranges of components and concentrations.

The matrix of tests was intended to be flexible and was adapted to take account of the results from commissioning and main tests as they became available. For example, the maximum number of measurements per test was established and enabled a significant expansion of the range of conditions and compositions to be studied. It was also possible to conduct more tests than planned, which enabled duplicate runs to be included and less successful runs to be repeated.

3   Experimental

3.1   TEST APPARATUS

The tests were conducted using AEA Technology's existing fluoride handling facilities at Winfrith. AHF was stored in a heated and ventilated room separate from the test apparatus. The AHF was connected to the main facility by a steel and Monel fluoride line incorporating pressure gauge, flow control, bypass and vent, together with a manifold which enabled inert gas purging of the complete system. The fluoride line was connected to the dual fume cupboard in which the thermodynamics experiments were conducted. The extract from the cupboard included acid vapour and particulate filters. Prior to commencing the experimental programme the fluoride line was carefully preconditioned with HF to ensure pacification of surfaces, and air and moisture ingress into the line was minimised by inert gas purging.

The apparatus used to conduct the HF thermodynamics test was designed to be similar to that used successfully by Schotte. The apparatus consisted of 3 main sections:
(i)   a gas and vapour delivery system capable of producing measured flow rates at defined humidities,
(ii)   an atmospheric pressure adiabatic fog chamber in which the gas was mixed with measured flow rates of AHF and the resulting temperature change measured,
(iii)   an exit system to scrub the exhaust gas.

The gas delivery system comprised compressed sources of air and/or butane. These gases were used alone or in some tests mixed together in defined ratios. Their flow rates were controlled using needle valves in combination with calibrated mass flow meters. To humidify the gases to defined levels ($\pm$ 2%, referenced to 20°C), they were passed through a thermostatically set bubbler system containing pure water or saturated solutions of certain salts. The pressure of the gas was also measured prior to its entry into the fog chamber. Similarly, the pressure of the HF line was also monitored and the flow rate controlled and measured using a needle valve and a mass flow meter. In all tests the measured inlet gas pressure was not significantly

above atmospheric, <0.05 bar in both lines except when they became blocked. The HF flow meter was calibrated separately using an acid-base titration of gas absorbed in an alkali bubbler. The temperature of the fume cupboard and the gas lines was controlled to avoid condensation of water vapour or HF, and to ensure that the air and HF inlet temperatures were the same (21 $\pm$ 1°C).

The dimensions of the fog chamber were similar to those of Schotte's, although the method of ensuring adiabatic conditions differed. In Schotte's experiments the fog chamber was enclosed in an ice/water bath that was heated or cooled in order to try to ensure that no heat entered or was lost from the system. In the apparatus used in the current study, the chamber was enclosed in a mirrored evacuated doubled walled flask. This design had the advantage that no manipulation of the external temperature was required in either direction (+10 to –30 °C) from room temperature. However, it did suffer from the possible disadvantage that the

time necessary to reach thermal equilibrium could be much longer. For this reason, the thermal mass of the fog chamber was kept to a minimum and gas flow rates as high as possible (see later). The temperature within the chamber was measured using a fine thermocouple sheathed in Inconel, which was calibrated and periodically checked throughout the test programme. The output from the thermocouple was continuously recorded to help enable the end point of temperature changes to be determined. Before commencing a test, the fog chamber was purged with dry air before test gases were introduced at appropriate concentrations. The general procedure for obtaining the required gas composition during a test was to hold the air and butane flow rate constant (up to ~400 cm^3 min^{-1}) and increase the HF flow in steps.

The exit HF scrubber was a simple column packed with granulated Carbosorb (soda lime), with minimal pressure drop to ensure the fog chamber remained at atmospheric pressure.

A schematic of the apparatus is shown in Figure 1. The initial design had the double wall evacuated vessel as the primary container in which the HF and air were mixed in order to reduce thermal mass. The inner wall of the glass vessel was coated with a variety of materials to prevent reaction with HF. However, none of these were found to be completely successful. Either HF penetrated the coating, causing severe attack on underlying glass, or there was sufficient interaction to cause an increase in fog chamber temperature. In order to overcome this problem, the fog chamber was redesign to include an inner PTFE cell, into which the gases were injected and expelled through sealed tubes. A schematic of the fog chamber is shown in Figure 2a, together with a photograph of the cell without vacuum flask in Figure 2b. The HF inlet was enclosed by the air/butane inlet tube to prevent condensation of pure HF within its length at low chamber temperatures.

3.2   MATERIALS

AHF was liquefied technical grade obtained from Air Products, and was filtered in the vapour inlet line. Air was supplied from compressed air cylinders and filtered for particulate. Liquefied research grade iso-butane was obtained from Air Products.

3.3   TEST MATRIX

Initial tests in the apparatus were conducted under similar conditions used by Schotte. The purpose of these tests was to check the data obtained previously and also to examine whether it was possible to make a series of measurements at different compositions in a single run. The ability to do this depended on a combination of the time taken to reach thermal equilibrium and the degree of retention of any condensed material within the cell. Having successfully obtained this information, the conditions for the remaining tests could be defined.

The full test matrix is shown in Table 1. The tests can be divided into two types depending on the resolution and precision of the data obtained. Tests HF1 to 20 were conducted over very wide concentration ranges, whereas Tests HF21 to 33 were more focused and the data obtained of higher accuracy, in order to resolve small differences in specific areas of the HF-water-butane system. HF34 and 35 examined the HF rich end of the HF-butane system.

4 Results and Discussion

4.1 COMMISSIONING TESTS

A series of commissioning tests was conducted to examine the function of the apparatus in terms of its ability to cope with highly concentrated HF, and the thermal response of the fog chamber to changes in gas temperature. As discussed earlier, the initial design had to be changed due to interaction between HF and the materials of the fog chamber. During these tests the sensitivity of the thermocouple was checked and found to respond quickly to minor temperature changes to inlet gas temperature (and to chemical interaction with the fog chamber walls). The time taken to reach thermal equilibrium was also investigated and it was found necessary to allow a significant length of time before stable measurements were achieved, depending on the size of the temperature change observed (for example, 2-3 hours to for temperature changes of ~10°C).

The time taken to reach thermal equilibrium was also investigated as a function of inlet gas flow rates. High inlet gas flow rates had the advantage of reducing the time needed to change the fog chamber temperature to its final value because of the increased heat exchange. However, increased flow rates could have had the adverse effect of reducing gas residence times in the chamber to the extent that steady state thermodynamic equilibrium was not achieved. In order to ensure that this did not occur in main tests, a series of measurements were conducted at different flow rates into the fog chamber. From these results it was possible to verify that equilibrium could be achieved by choosing from the range of flow rates that generated identical temperature changes.

4.2 MAIN TESTS

Results from the main tests are presented graphically (Figures 3 to 37) in an identical way to that used by Schotte (see Figure 38), together with data point values as requested by code modellers. Composition is given as mole %, where one mole of HF is 20.006 g. As with Schotte's work, main error in the data presented is connected with the composition of the gas-vapour mixture, particularly at low HF concentrations due to the problems associated with flow control and calibration. In comparison, absolute temperature measurement errors (<0.1°C) were not significant.

Data presented in Figures 3 to 22 are from tests conducted over a wide temperature and composition range. The results of these tests are of lower precision than other experiments (as discussed earlier), as less time was allowed for each data point in order to complete the entire run within a reasonable time period (10 hours maximum).

Figures 23 to 35 present data from higher resolution runs that were focused on specific composition ranges, in particular over the exothermic region where there was a much lower temperature difference between different humidity levels.

Later tests involving butane were conducted by reducing from very high HF concentration (test HF 34 and 35), rather than by increasing concentration from zero. It was not always possible to cover the whole range in one experiment because measurements became difficult at low temperature. Under some conditions the temperature approached the dew point of butane (-11.9°C). This was thought to have caused butane to condense in the fog chamber in sufficient quantity, particularly during transient periods, to interfere with the attainment of equilibrium (this was not found to be a problem with other condensable material). For example, test HF 8 is shown in Figure 10 with data points up to 40 % HF. However, once above 20 % HF the temperature began to fluctuate and then did not show the usual trend of slowly increasing temperature with increasing HF. For this reason the data points obtained in tests HF 8, 9 and 11 that were taken around butane's dew point temperature should be treated with caution.

The results generate the same pattern of endothermic and exothermic behaviour observed by Schotte and good agreement was found between the two sets of data (see Figure 38 where Schotte's data is provided for comparison). This is particularly true of tests with dry air. There are some differences between comparable tests conducted with humid air. However, this is mostly likely due to the fact that Schotte's test were conducted at ~25-26°C, whereas in this study the inlet gas temperature was lower (20-22°C). Therefore, absolute water vapour pressures were

lower in this study (although relative humidities were equivalent) and temperature increase due to hydration of HF would be less, as observed. The degree of association of HF would also be slightly different at the two temperatures.

Schotte's tests were limited to HF concentration of less than ~20%, but in this study it has been able to extend measurements to cover up to pure HF. As expected, the data confirm a steady decrease in temperature change, as HF concentration was increased past the level of minimum temperature, ultimately reaching zero on approaching 100% HF. This general behaviour was found with all combinations of HF with air, humidity level and butane, although the absolute temperatures and their rate of change with HF concentration were different.

The effect of butane appears to be that of an inert diluent. No change in the pattern of exo/endothermic behaviour was observed, only the size of the temperature change was reduced, in agreement with the relatively large heat capacity of butane compared with that of air. This would imply that chemical interaction between butane and humid or dry HF is not a significant process in terms of their thermodynamics of mixing. However, condensation of butane, which was not studied in this work, could have a significant effect if the temperature decrease was sufficient to enable it to occur.

5   Conclusions

An experimental task has been successfully completed on the thermodynamics of mixing of AHF with air and butane. This work had the objective of obtaining information to verify previously obtained data and extending measurements to unexamined composition ranges of HF-butane-water-air system. The data obtained will be used to reduce uncertainties in models to predict the dispersion of HF into the environment following an accidental release. The main conclusions of the work are:

1. The reliability of previous work conducted by Schotte has been verified.

2. Measurements have been extended to areas of the HF-water-air system not previously studied.

3. The impact of isobutane has been studied and found only to suppress the extent of temperature increase/decrease generated on mixing HF with humid or dry air.

The implications and discussion of these results in terms of the treatment of HF in code models and impact on risk assessments is addressed in other work packages within the UHFRAP programme.

6 References

1. Understanding the Dispersion of Industrial Releases of Anhydrous Hydrogen Fluoride and the Associated Risks to the Environment and People (URAHFREP), CEC 4th framework project PL971152.

2. W. Schotte, Ind. Eng. Chem. Res. 1987, 26, 300.

7   Tables and Figures

Table 1. HF Thermodynamics – Experimental Test Matrix

Expt. No.	Experimental Conditions			Comments
	% Air	% Isobutane	% Humidity	
HF01	100	-	-	Experiment aborted after early due to HF leak in fog chamber
HF02	100	-	-	Repeat of HF01 – starting from end point of previous experiment
HF03	100	-	100	
HF04	100	-	50 (?)	Incorrect temperature control of bubbler – humidity possibly as high as 80%
HF05	100	-	60	
HF06	100	-	80	
HF07	100	-	-	Repeat of HF01 & HF02
HF08	75	25	-	Experiment stopped early - temperature fluctuations at –12 °C (isobutane boiling point)
HF09	50	50	-	Experiment stopped early as HF08
HF10	100	-	50	Repeat of HF04
HF11	25	75	-	Experiment stopped as HF08 & HF09
HF12	-	100	-	
HF13	75	25	50	
HF14	50	50	50	
HF15	25	75	50	
HF16	-	100	50	Difficulty in maintaining steady HF flow due to 'sticky' valve
HF17	75	25	100	
HF18	50	50	100	Fluctuation in temperatures during the early part of the experiment

Table 1(con'd). HF Thermodynamics – Experimental Test Matrix

Expt. No.	Experimental Conditions			Comments
	% Air	% Isobutane	% Humidity	
HF19	25	75	100	
HF20	-	100	100	
HF21	100	-	100	Low HF fraction. Experiment stopped due to blocked HF inlet pipe (results invalid)
HF22	50	50	100	Low HF fraction. Unreliable flow after HF surge, experiment stopped early
HF23	100	-	100	Low HF fraction. Blocked inlet pipe, experiment stopped early
HF24	-	100	100	Low HF fraction. Larger bore inlet tube fitted to stop blocking.
HF25	100	-	100	Low HF fraction. Repeat of HF21 & HF23
HF26	-	100	100	Low HF fraction. Repeat of HF24. Experiment stopped early due to sticking HF valve
HF27	100	-	-	Low HF fraction. Repeat of HF07
HF28	50	50	-	Low HF fraction. Repeat of HF09
HF29	100	-	50	Low HF fraction. Repeat of HF10
HF30	50	50	50	Low HF fraction. Repeat of HF14. Fluctuation in temperature although following a general trend
HF31	50	50	50	Low HF fraction. Repeat of HF30. Fluctuation in temperature although following a general trend
HF32	-	100	-	Low HF fraction. Repeat of HF12
HF33	-	100	50	Low HF fraction. Repeat of HF16
HF34	100	-	-	High HF fraction
HF35	-	100	-	High HF fraction

Note: Humidity referenced to 20°C.

Figure 1. Schematic of apparatus

Figure 1. Schematic of apparatus
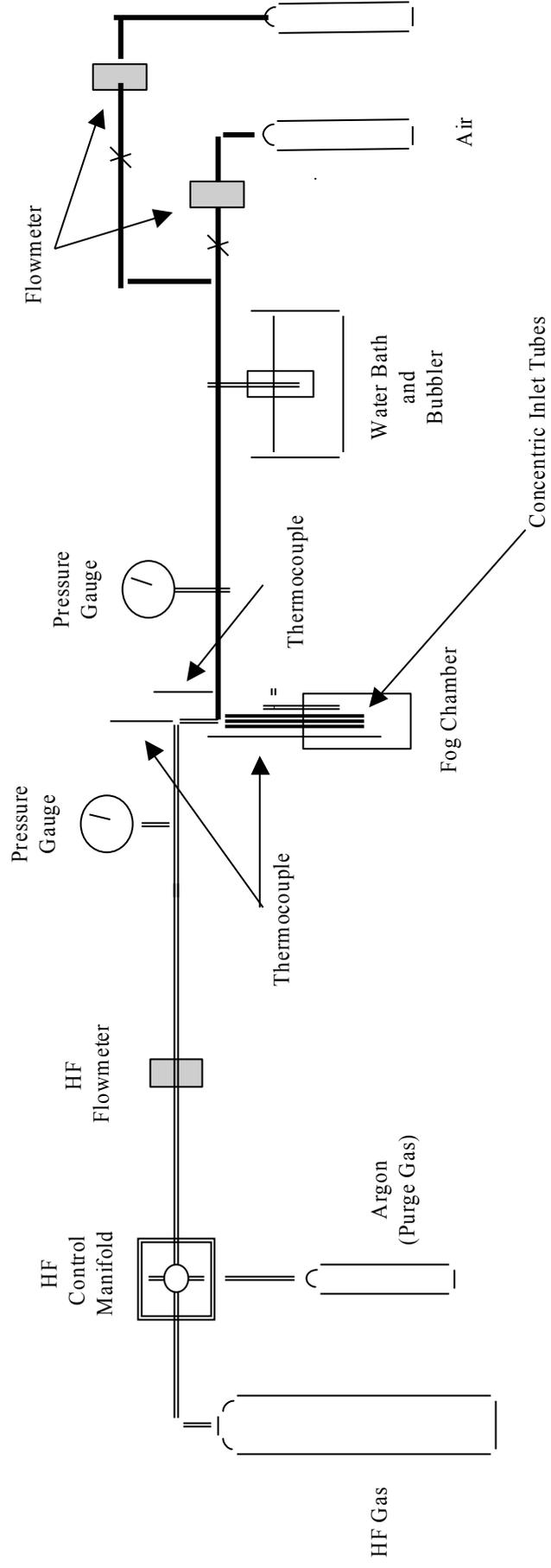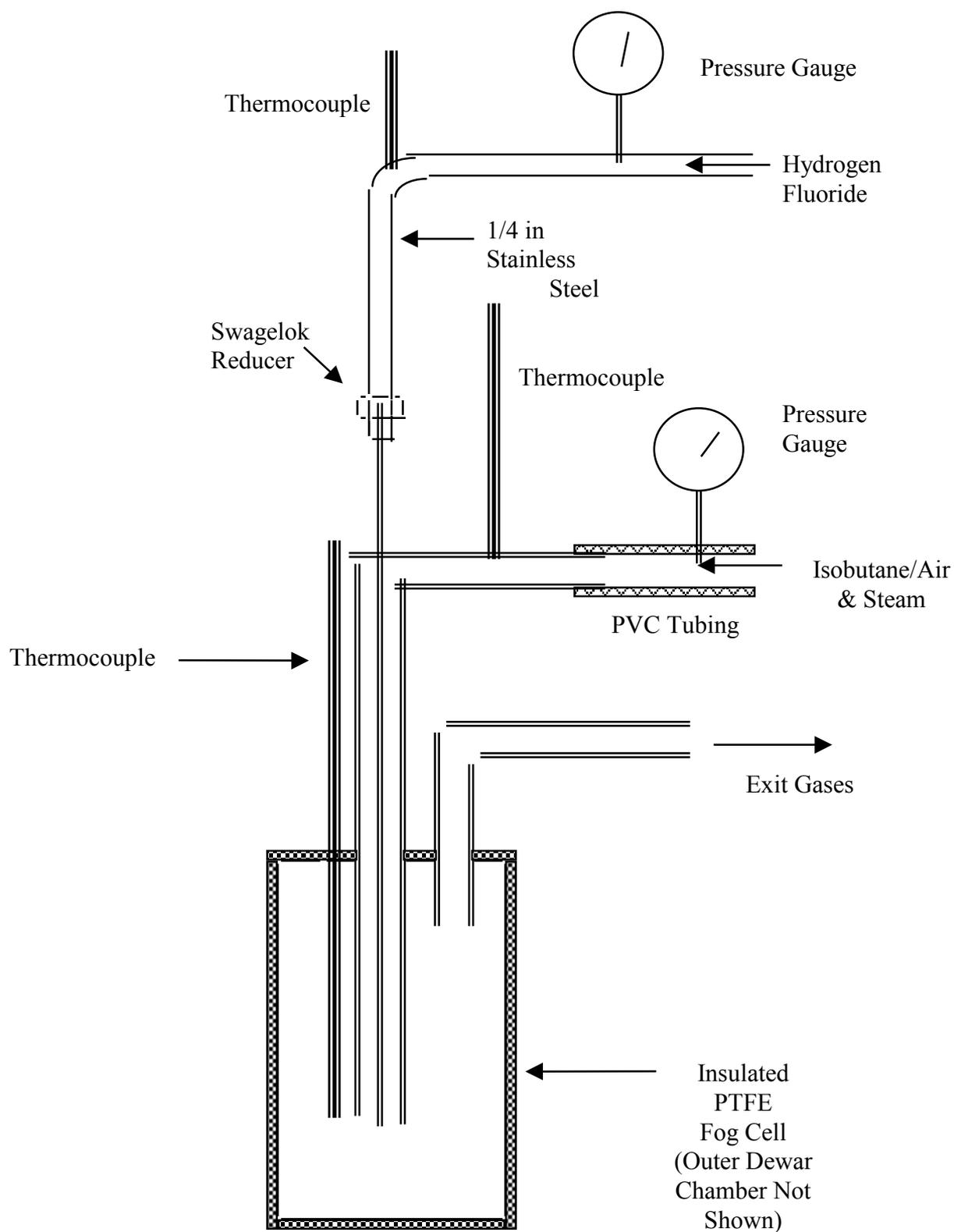
Figure 2a. Schematic of Fog Chamber

Figure 2b. PTFE Cell Without Vacuum Flask

Figure 3. Expt. HF01 - Pure Air
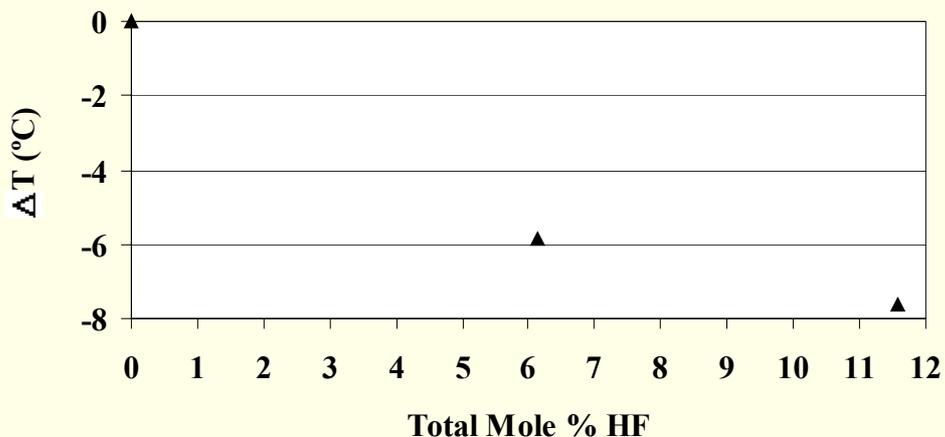
Note comments in Test Matrix (Table 1.)

Mole % HF	T/Change
0	0
6.15	(-5.85)
11.58	(-7.6)

Figure 4. Expt. HF02 - Pure Air
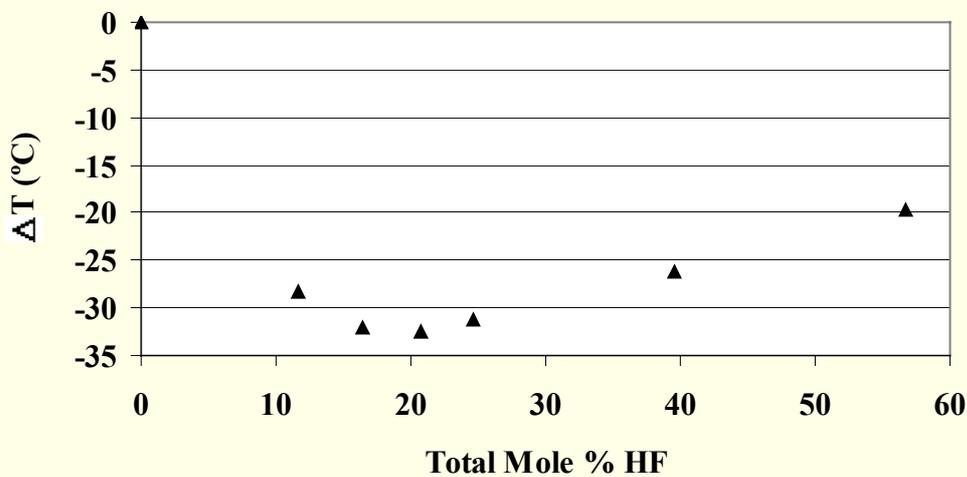
Mole % HF	T/Change
0	0
11.58	-28.2
16.42	-32.1
20.76	-32.45
24.67	-31.3
39.58	-26.1

56.7   -19.6

Figure 5. Expt. HF03 - Pure Air
100% Humidity
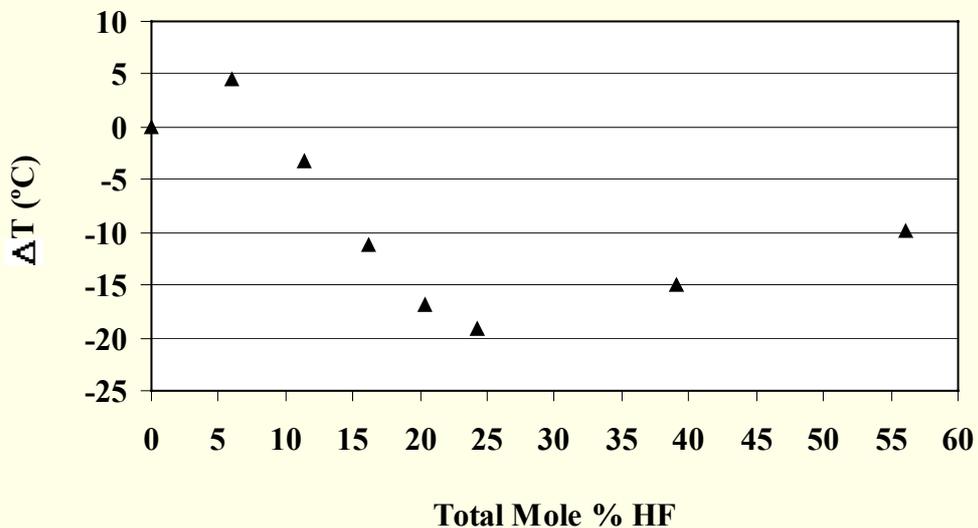
Mole % HF	Temp Change
0	0
6.02	4.5
11.36	-3.3
16.12	-11.1
20.4	-16.85
24.26	-19.15
38.99	-15.05
56.15	-9.95

**Figure 6. Expt. HF04 - Pure Air
~80% Humidity**
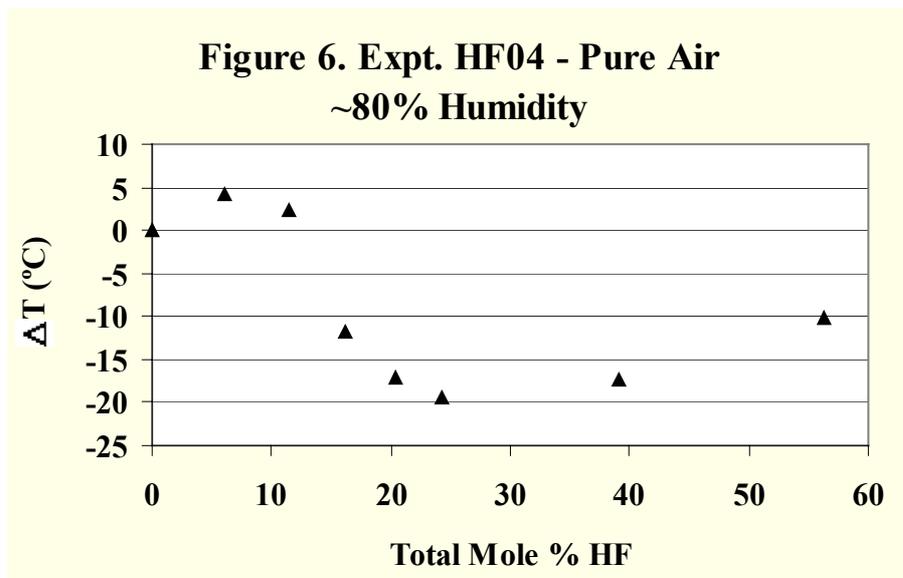
Mole % HF	T/Change
0	0
6.04	4.3
11.4	2.3
16.17	-11.85
20.46	-17.2
24.33	-19.4
39.14	-17.3
56.26	-10.15

**Figure 7. Expt. HF05 - Pure Air
60% Humidity**
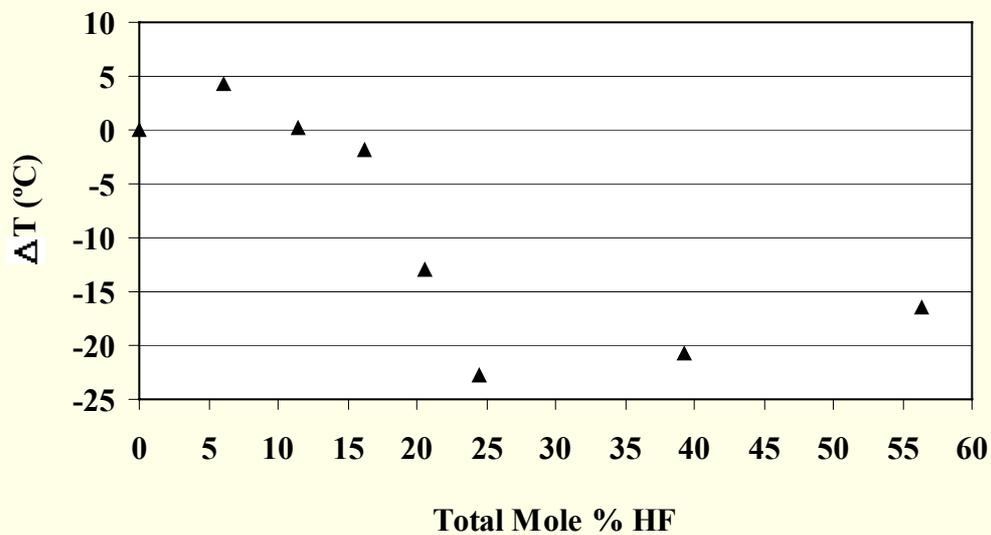
Mole % HF	Temp Change
0	0
6.07	4.2
11.44	0.1
16.24	-1.9
20.54	-13.05
24.54	-22.85
39.25	-20.65
56.37	-16.55

Figure 8. Expt. HF06 - Pure Air
80% Humidity
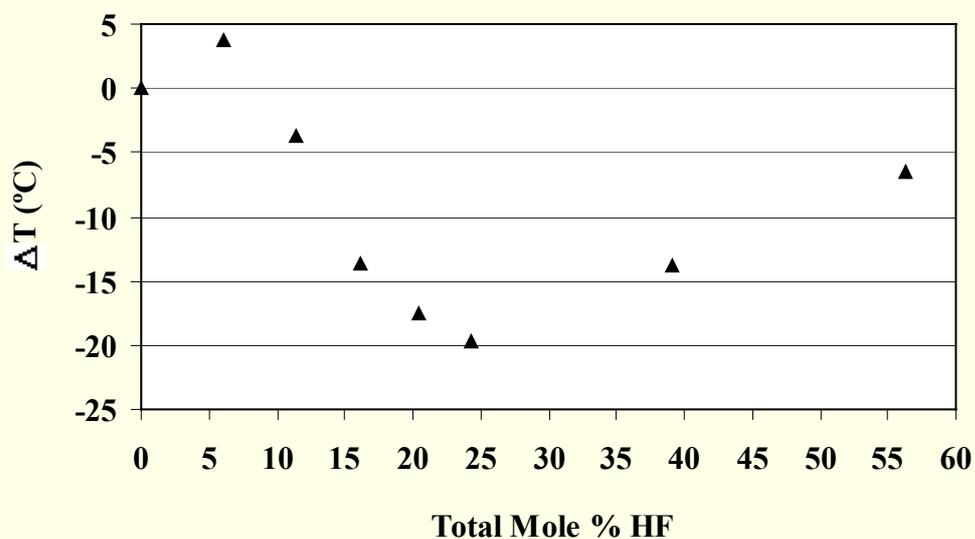
Mole % HF	Temp Change
0	0
6.04	3.75
11.4	-3.7
16.17	-13.7
20.46	-17.6
24.33	-19.7
39.14	-13.75
56.26	-6.5

Figure 9. Expt. HF07 - Pure Air
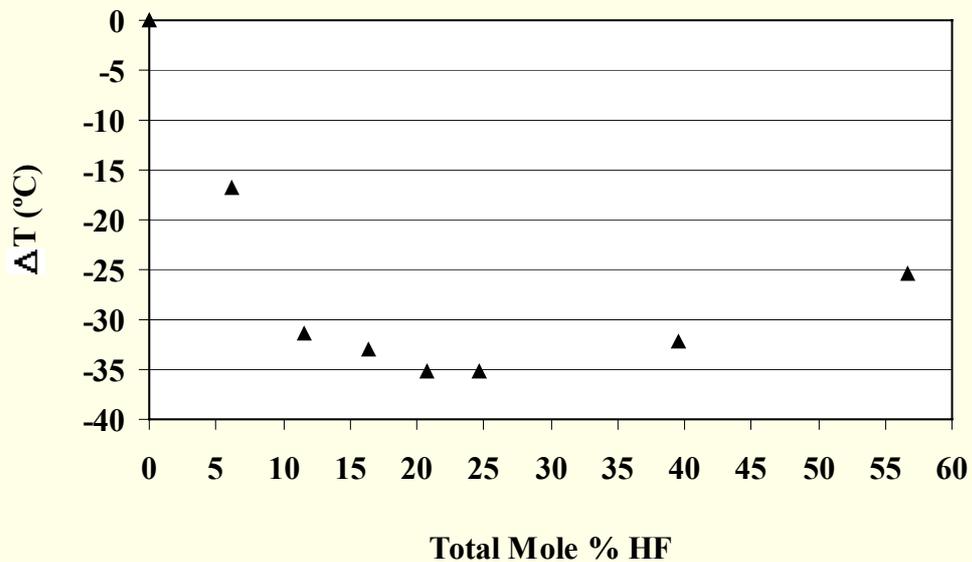
Mole % HF	Temp Change
0	0
6.14	-16.7
11.58	-31.4
16.42	-33
20.76	-35.15
24.67	-35.25
39.58	-32.15
56.71	-25.4

Figure 10. Expt. HF08 - 75 Air/25 Butane
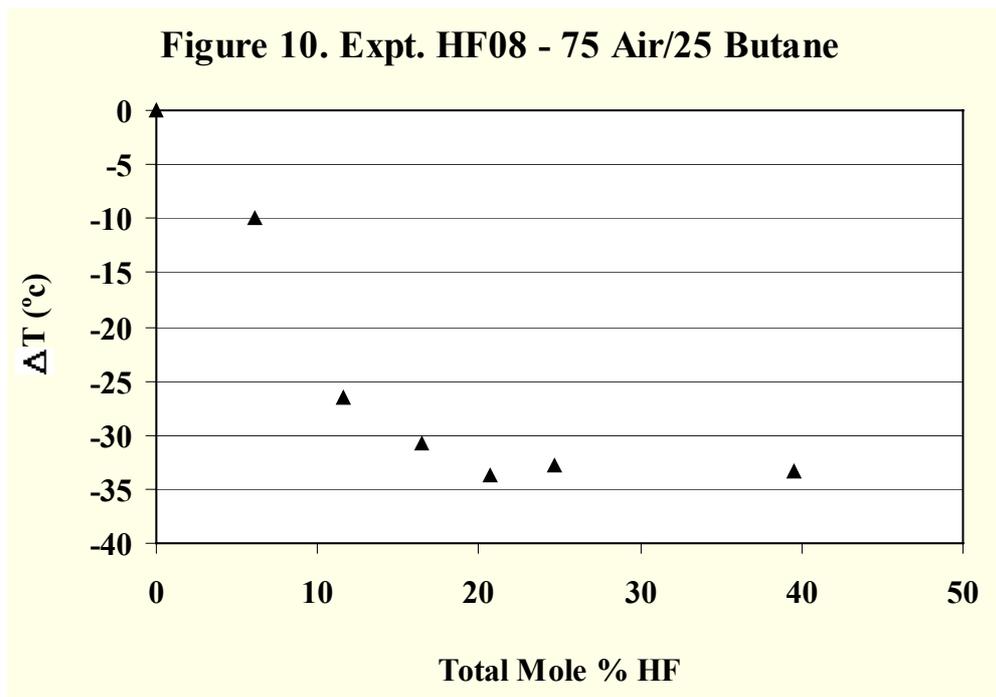
Note comments in Test Matrix (Table 1.) and in main text.

Mole % HF	Temp Change
0	0
6.14	-9.95
11.58	-26.55
16.42	-30.7
20.76	-33.75
24.67	-32.75
39.58	-33.45

Figure 11. Expt. HF09 - 50 Air/50 Butane
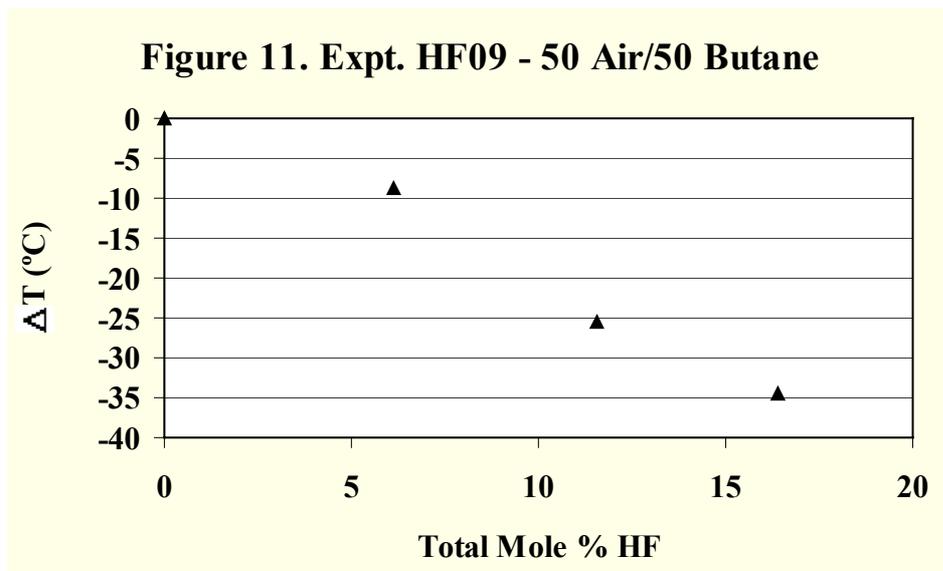
Note comments in Test Matrix (Table 1.) and in main text.

Mole %	T/Change
0	0
6.14	-8.85
11.58	-25.5
16.42	-34.4

**Figure 12. Expt. HF10 - Pure Air
50% Humidity**
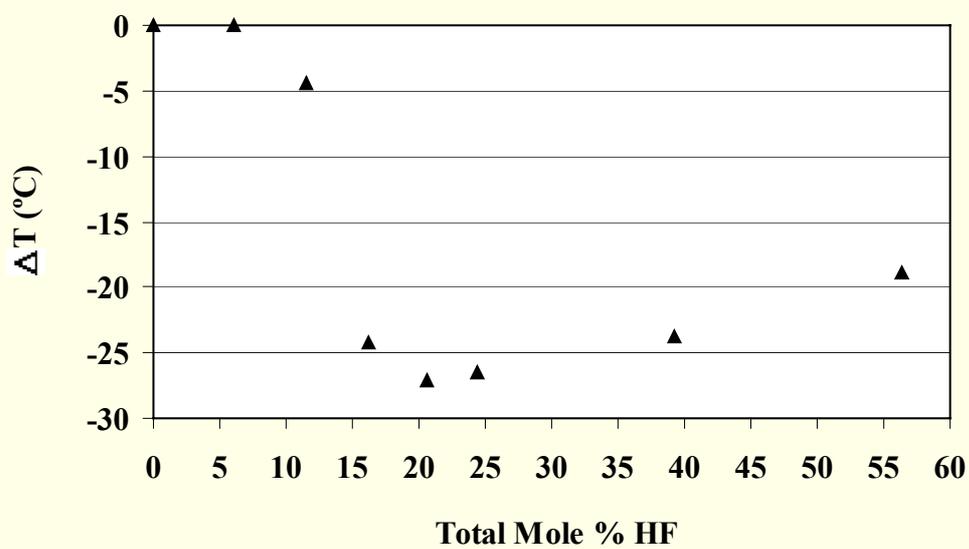
Mole % HF	Temp Change
0	0
6.08	0
11.46	-4.45
16.26	-24.15
20.57	-27.1
24.46	-26.55
39.3	-23.7
56.43	-18.9

Figure 13. Expt. HF11 - 25 Air/75 Butane
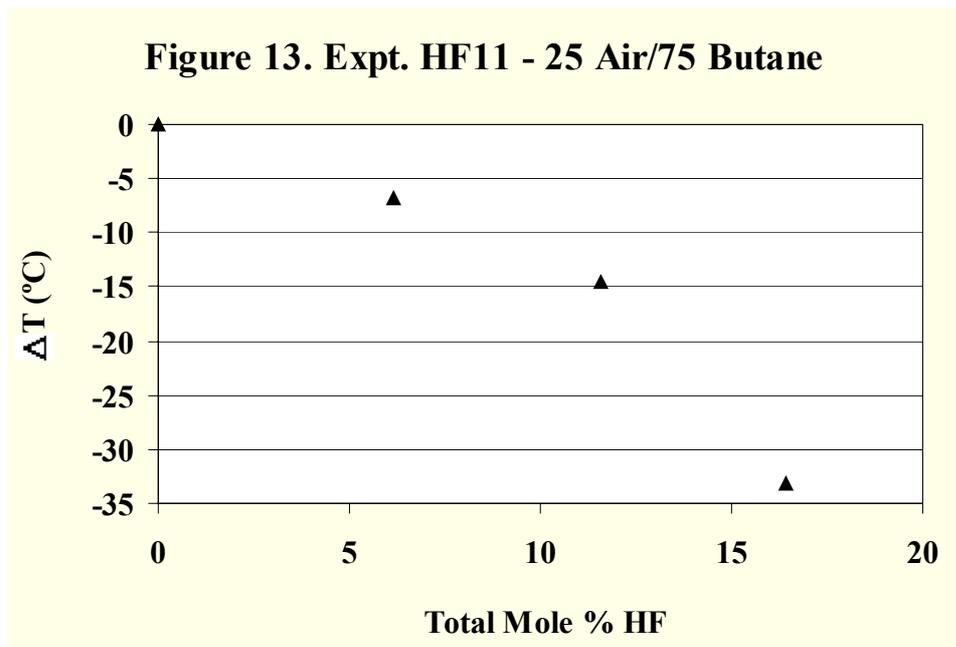
Note comments in Test Matrix (Table 1.) and main text.

Mole %	T/Change
0	0
6.14	-6.9
11.58	-14.5
16.42	-33.2

Figure 14. Expt. HF12 - Pure Butane
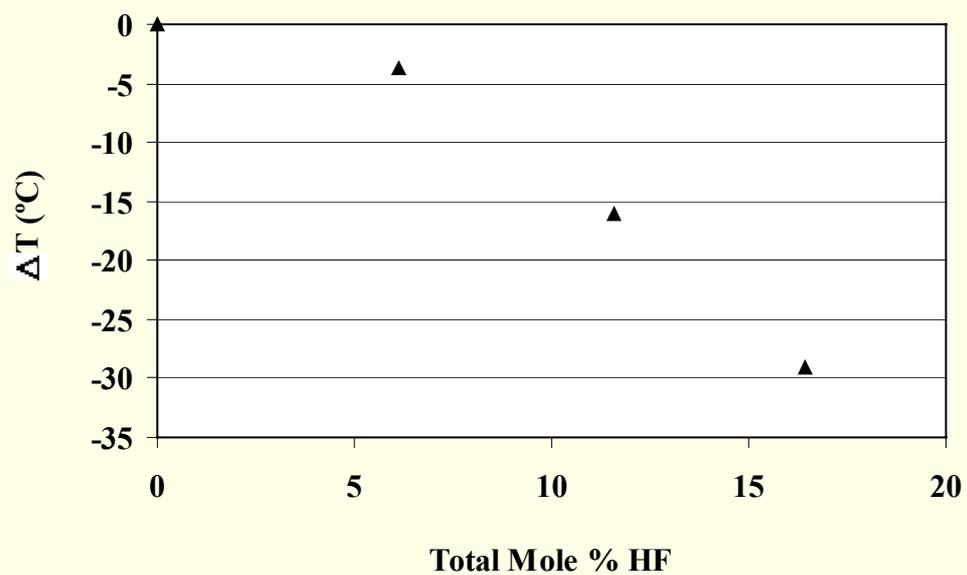
Mole % HF	Temp Change
0	0
6.14	-3.75
11.58	-16.05
16.42	-29.05

Figure 15. Expt. HF13 - 75 Air/25 Butane 50% Humidity
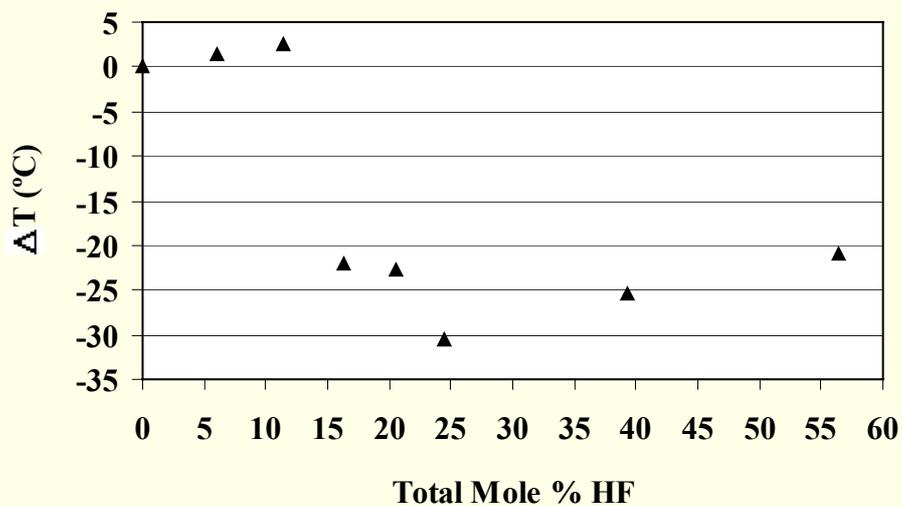
Mole %	T/Change
0	0
6.08	1.4
11.47	2.65
16.27	-22.1
20.57	-22.65
24.46	-30.45
39.3	-25.35
56.43	-20.9

Figure 16. Expt. HF14 - 50 Air/50 Butane
50% Humidity
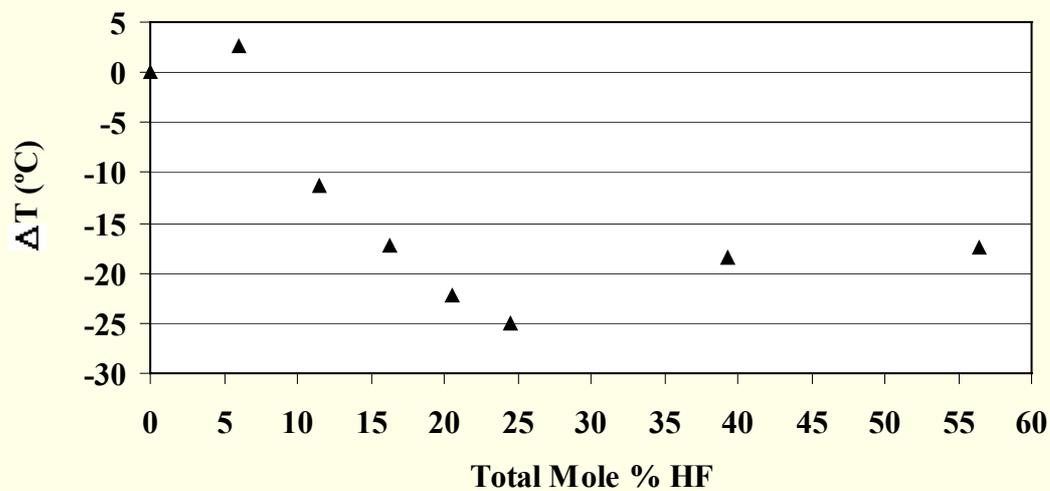
Mole %	T/Change
0	0
6.08	2.55
11.47	-11.3
16.27	-17.25
20.57	-22.15
24.46	-25
39.3	-18.4
56.43	-17.5

Figure 17. Expt. HF15 - 25 Air/75 Butane 50% Humidity
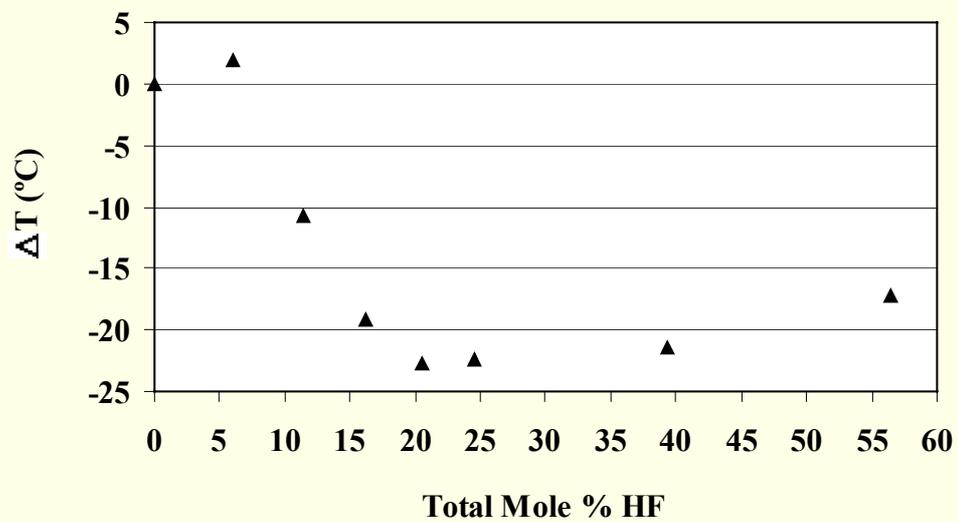
Mole %	T/Change
0	0
6.08	1.9
11.47	-10.7
16.27	-19.2
20.57	-22.65
24.46	-22.4
39.3	-21.5
56.43	-17.2

Figure 18. Expt. HF16 - Pure Butane
50% Humidity
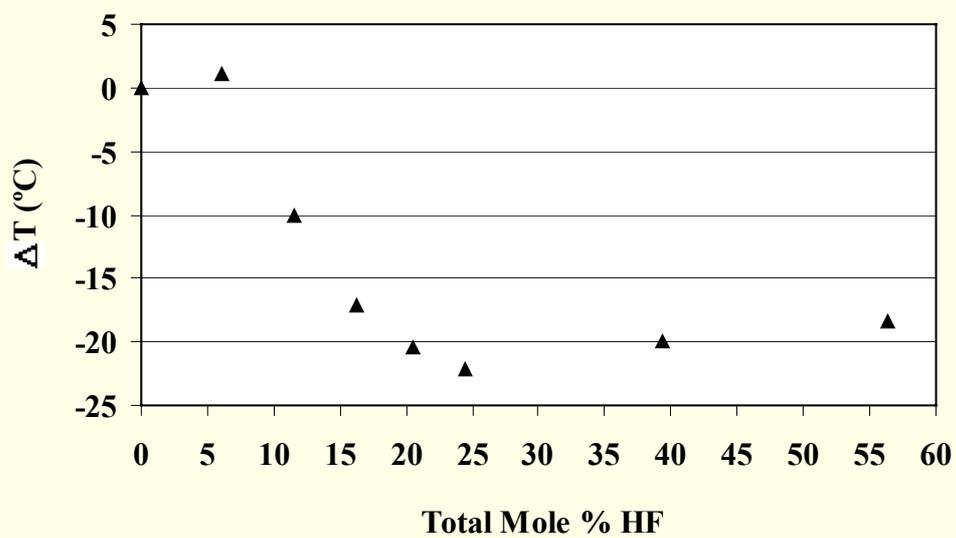
Mole % HF	Temp Change
0	0
6.08	1.1
11.47	-10.05
16.27	-17.15
20.57	-20.4
24.46	-22.25
39.3	-20
56.43	-18.4

**Figure 19. Expt. HF17 - 75 Air/25 Butane
100% Humidity**
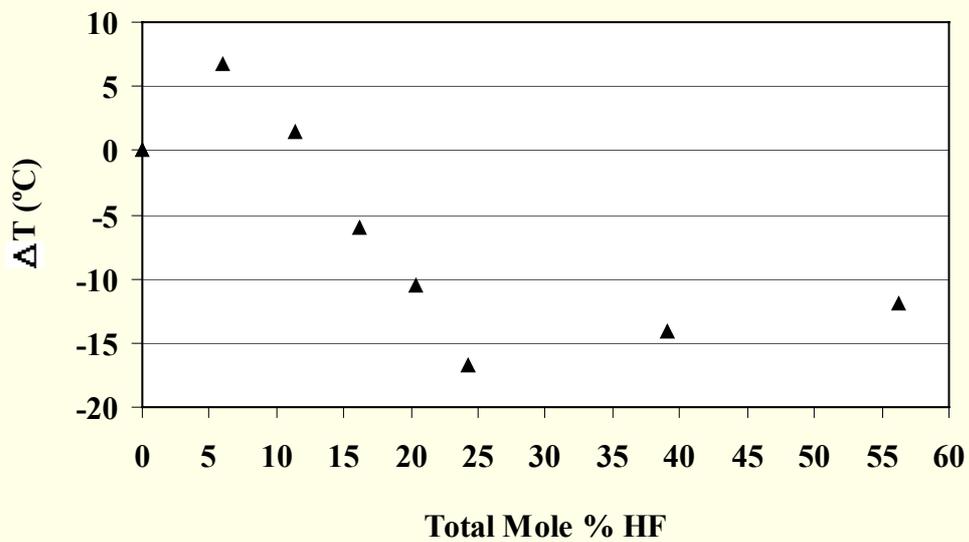
Mole % HF	Temp Change
0	0
6.02	6.7
11.37	1.4
16.11	-6
20.39	-10.5
24.25	-16.8
39.09	-14.05
56.21	-11.85

Figure 20. Expt. HF18 - 50 Air/50 Butane 100% Humidity
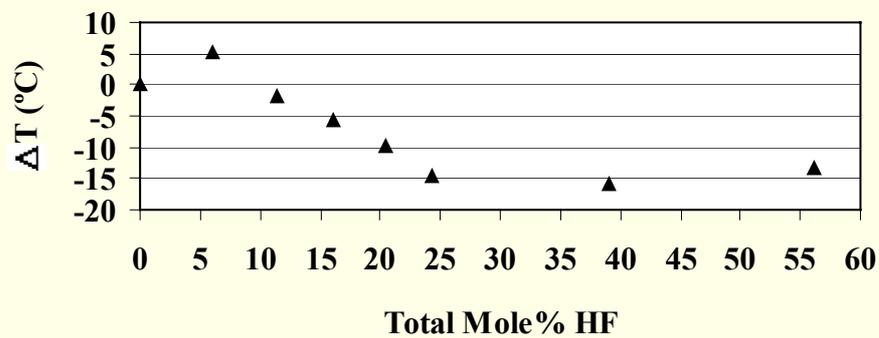
Mole %	T/Change
0	0
6.02	5.2
11.35	-1.75
16.11	-5.55
20.39	-9.7
24.25	-14.5
39.03	-15.95
56.15	-13.35

Figure 21. Expt. HF19 - 25 Air/75 Butane 100% Humidity
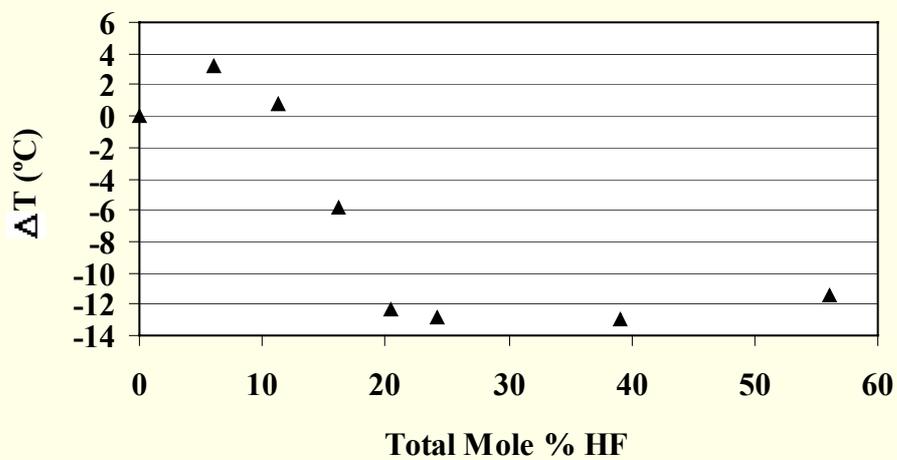
Mole %	T/Change
0	0
6.02	3.25
11.35	0.75
16.11	-5.9
20.39	-12.35
24.25	-12.9
39.03	-12.95
56.15	-11.45

Figure 22. Expt. HF20 - Pure Butane 100%Humidity
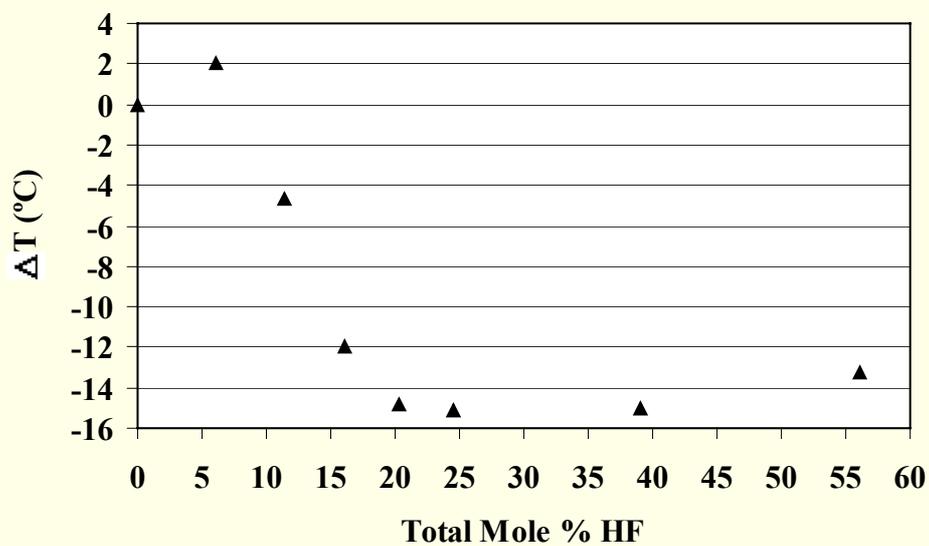
Mole % HF	Temp Change
0	0
6.02	2.05
11.35	-4.65
16.11	-12
20.39	-14.85
24.48	-15.1
39.03	-15
56.15	-13.2

Figure 23. Expt. HF21 - Pure Air 100% Humidity
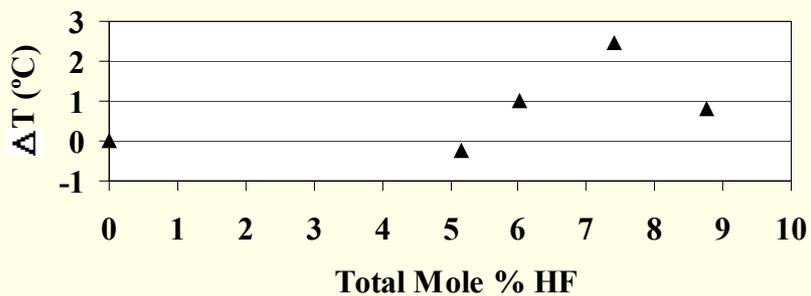
Note comments in Test Matrix (Table 1.)

Mole %	T/Change
0	0
5.16	-0.25
6.02	1
7.41	2.45
8.76	0.8

Figure 24. Expt. HF22 - 50 Air/50 Butane 100% Humidity
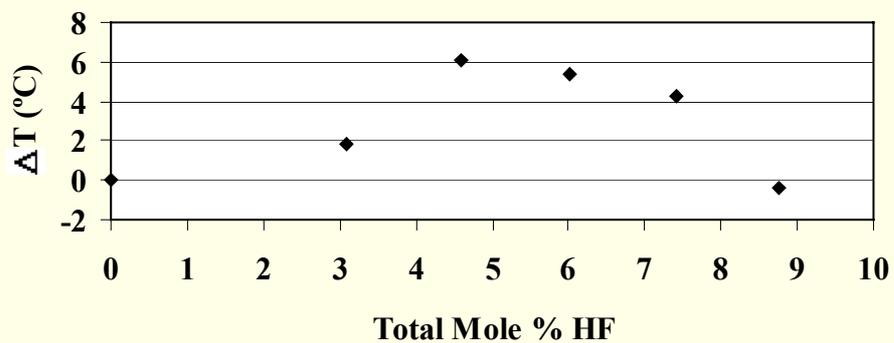
Mole %	T/Change
0	0
3.1	1.85
4.58	6.1
6.02	5.4
7.41	4.3
8.76	-0.35

Figure 25. Expt. HF23 - Pure Air 100% Humidity
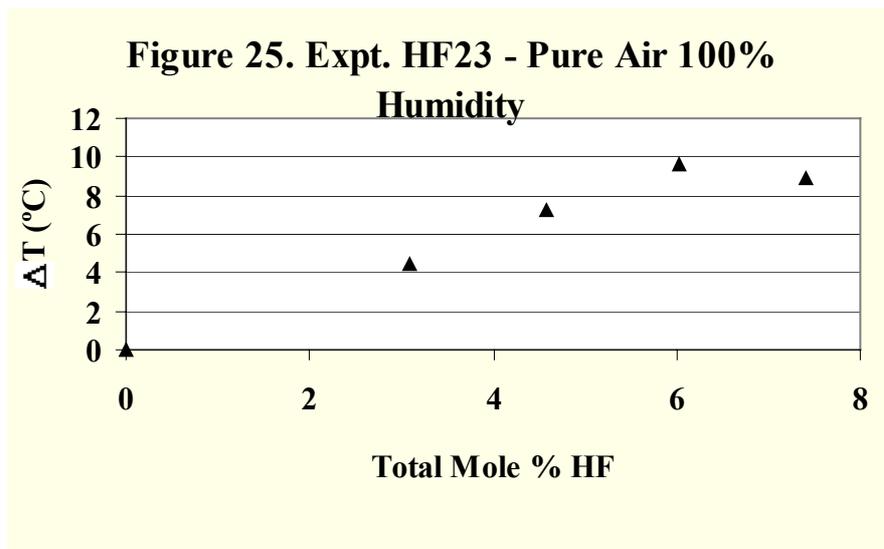
Mole %	T/Change
0	0
3.1	4.45
4.58	7.25
6.02	9.65
7.41	8.9

Figure 26. Expt. HF24 - Pure Butane
100% Humidity
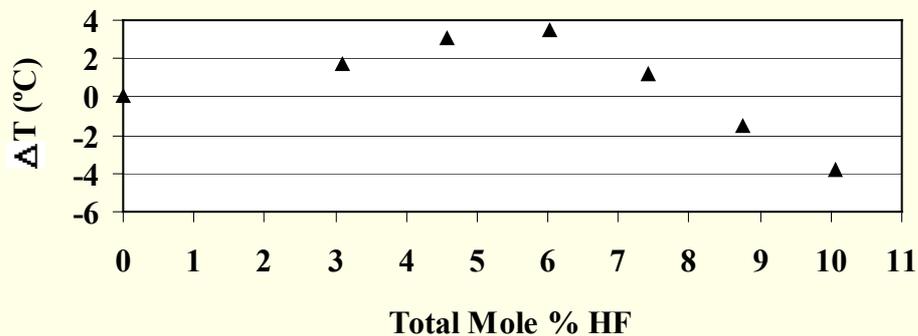
Mole %	T/Change
0	0
3.1	1.7
4.58	3.1
6.02	3.5
7.41	1.15
8.76	-1.5
10.07	-3.85

**Figure 27. Expt. HF25 - Pure Air
100% Humidity**
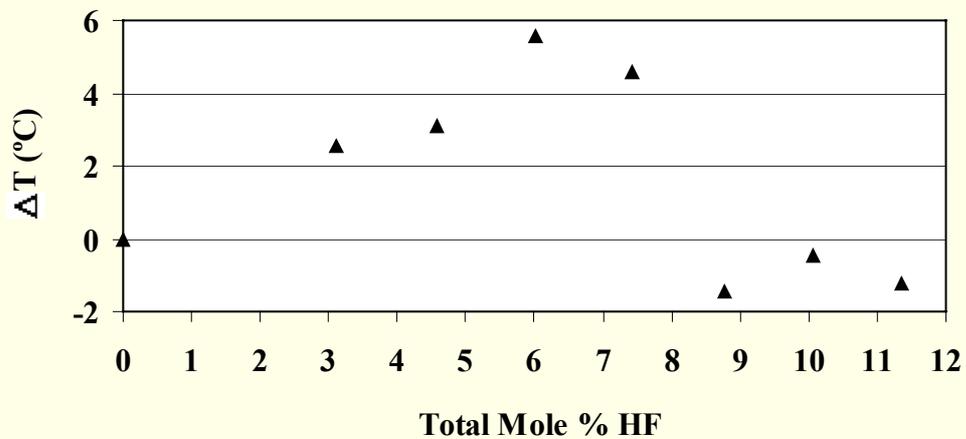
Mole %	T/Change
0	0
3.1	2.55
4.58	3.1
6.02	5.55
7.41	4.55
8.76	-1.45
10.07	-0.45
11.35	-1.25

Figure 28. Expt. HF26 - Pure Butane 100% Humidity
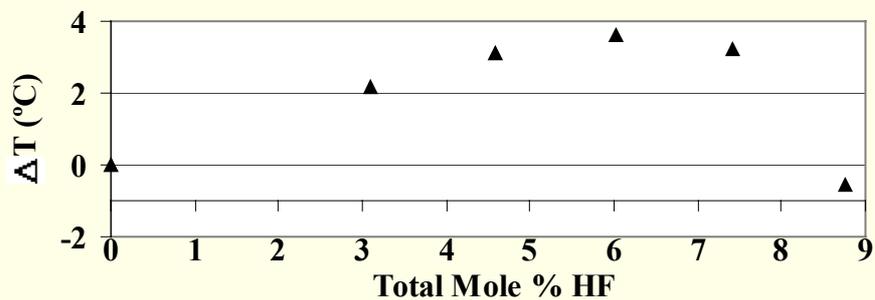
Mole %	T/Change
0	0
3.1	2.15
4.58	3.1
6.02	3.6
7.41	3.2
8.76	-0.55

Figure 29. Expt. HF27 - Pure Air
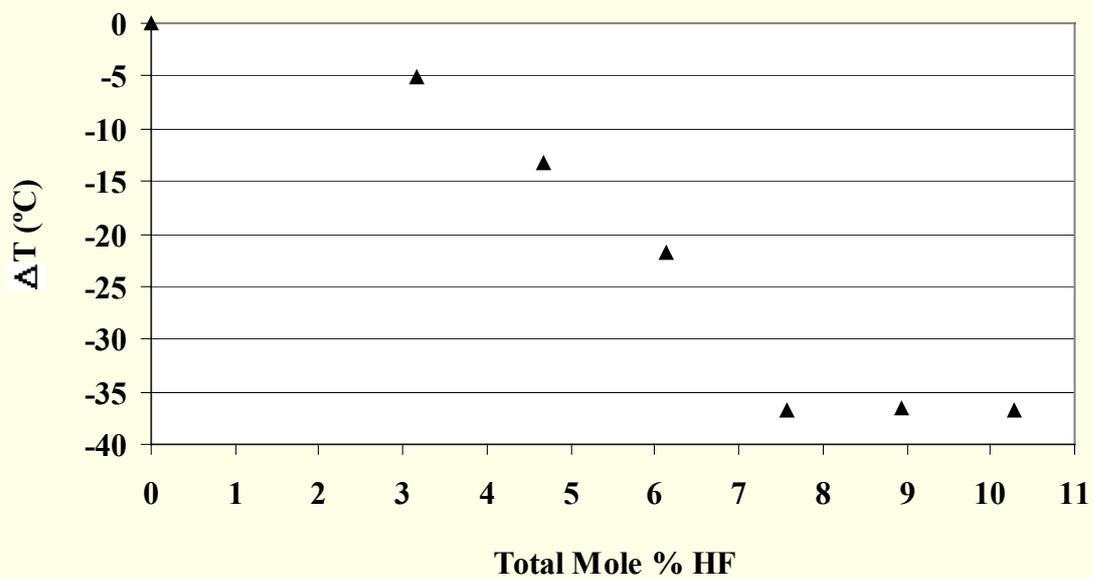
Mole %	T/Change
0	0
3.17	-5.1
4.68	-13.3
6.14	-21.85
7.57	-36.8
8.95	-36.55
10.28	-36.7

Figure 30. Expt. HF28 - 50 Air/50 Butane
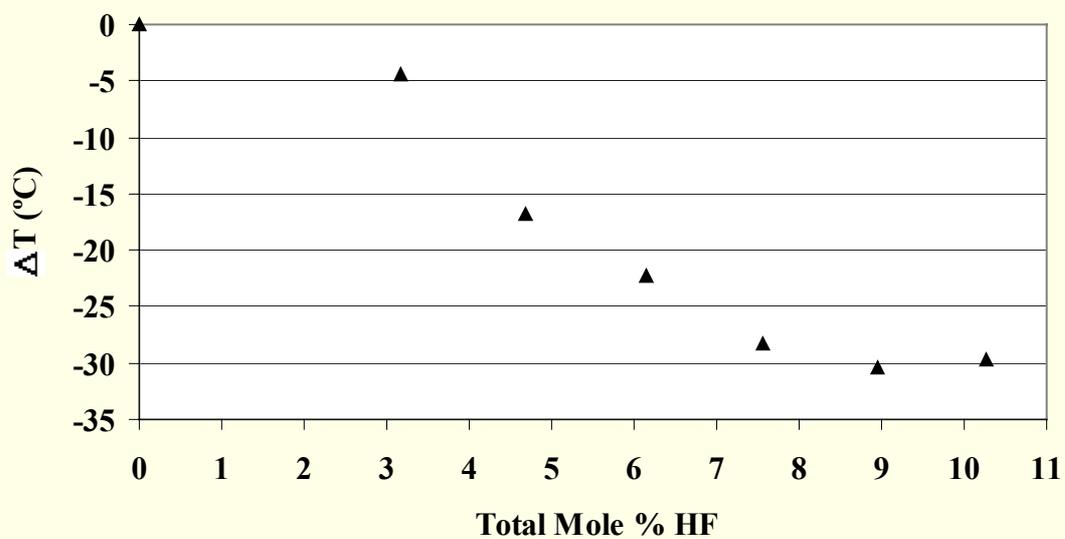
Mole %	T/Change
0	0
3.17	-4.35
4.68	-16.85
6.14	-22.35
7.57	-28.25
8.95	-30.4
10.28	-29.7

Figure 31. Expt. HF29 - Pure Air
50% Humidity
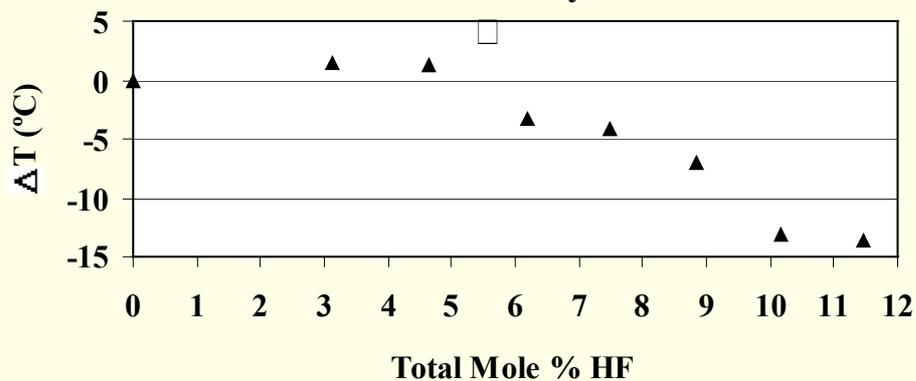
Mole %	T/Change
0	0
3.14	1.45
4.63	1.25
6.18	-3.25
7.49	-4.2
8.85	-7.05
10.18	-13.15
11.47	-13.7

Figure 32. Expt. HF30 - 50 Air/50 Butane 50% Humidity
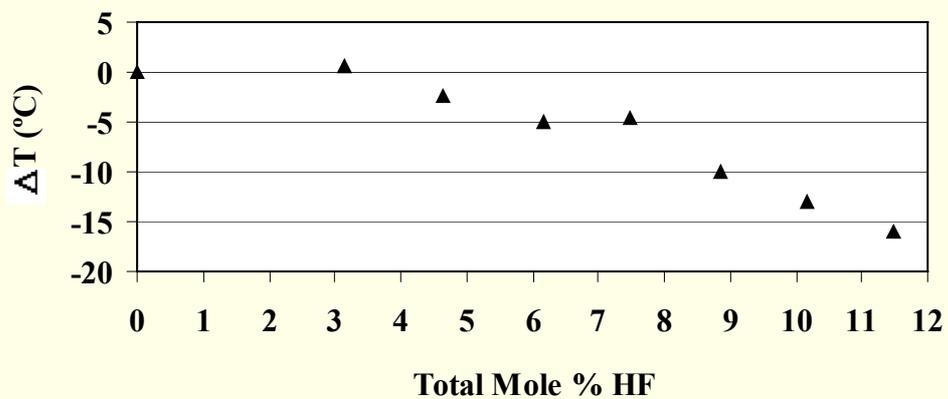
Mole %	T/Change
0	0
3.14	0.6
4.63	-2.3
6.18	-4.9
7.49	-4.5
8.85	-10.05
10.18	-12.95
11.47	-16

Figure 33. Expt. HF31 - 50 Air/50 Butane 50% Humidity
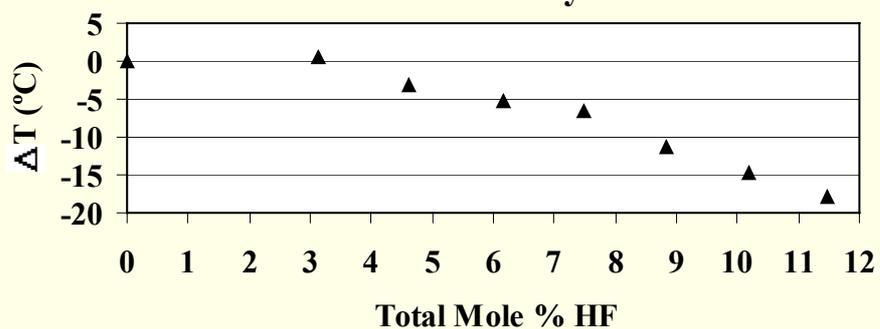
Mole %	T/Change
0	0
3.14	0.6
4.63	-3.1
6.18	-5.35
7.49	-6.7
8.85	-11.35
10.18	-14.75
11.47	-17.8

Figure 34. Expt. HF32 - Pure Butane
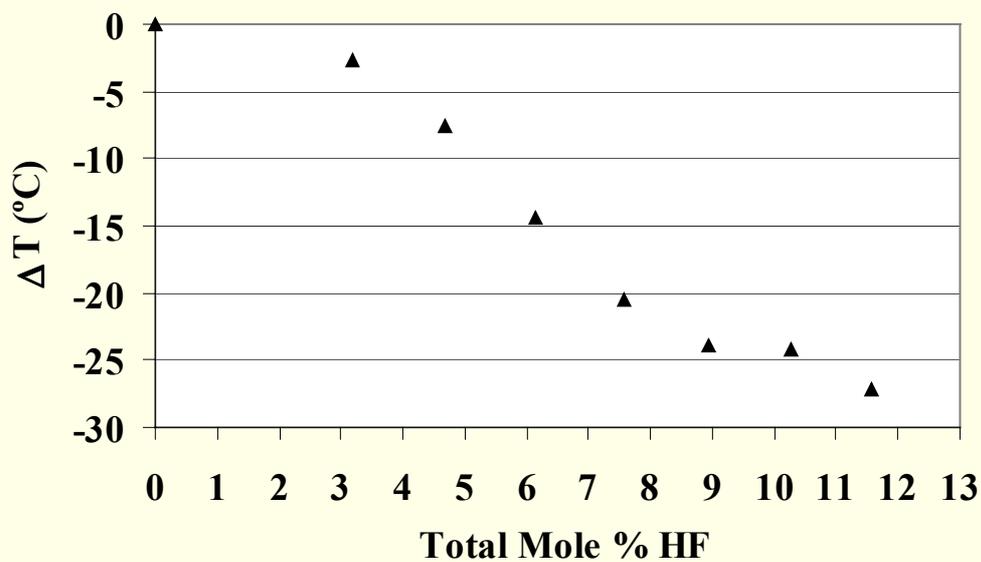
Mole %	T/Change
0	0
3.17	-2.65
4.68	-7.55
6.14	-14.35
7.57	-20.45
8.95	-23.85
10.28	-24.2
11.58	-27.2

**Figure 35. Expt. HF33 - Pure Butane
50% Humidity**
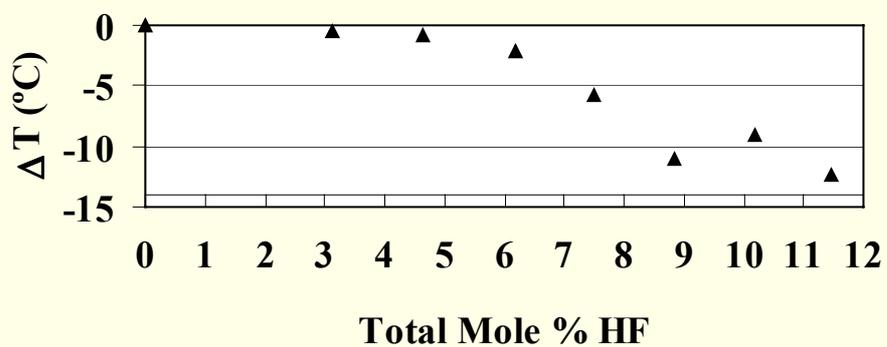
Mole %	T/Change
0	0
3.14	-0.55
4.63	-0.9
6.18	-2.2
7.49	-5.85
8.85	-11
10.18	-9.1
11.47	-12.4

Figure 36. Expt. HF34 - Pure Air
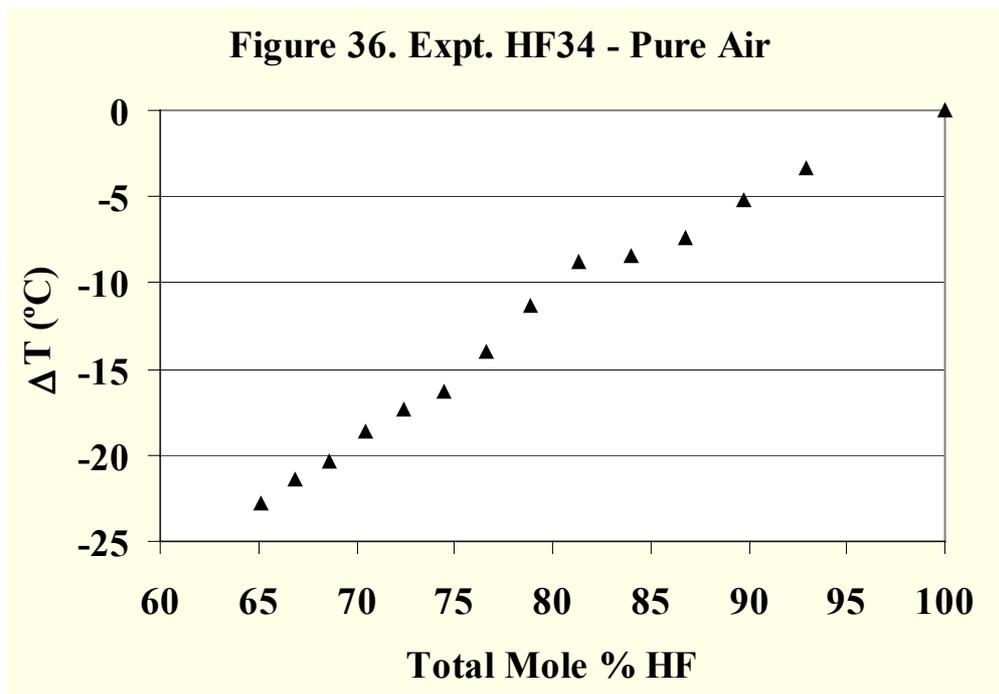
Mole % HF	Temp Change
100	0
92.91	-3.4
89.73	-5.25
86.75	-7.35
83.97	-8.5
81.37	-8.8
78.92	-11.3
76.61	-14
74.43	-16.35
72.38	-17.4
70.43	-18.6
68.59	-20.4
66.84	-21.4
65.17	-22.75

Figure 37. Expt. HF35 - Pure Butane
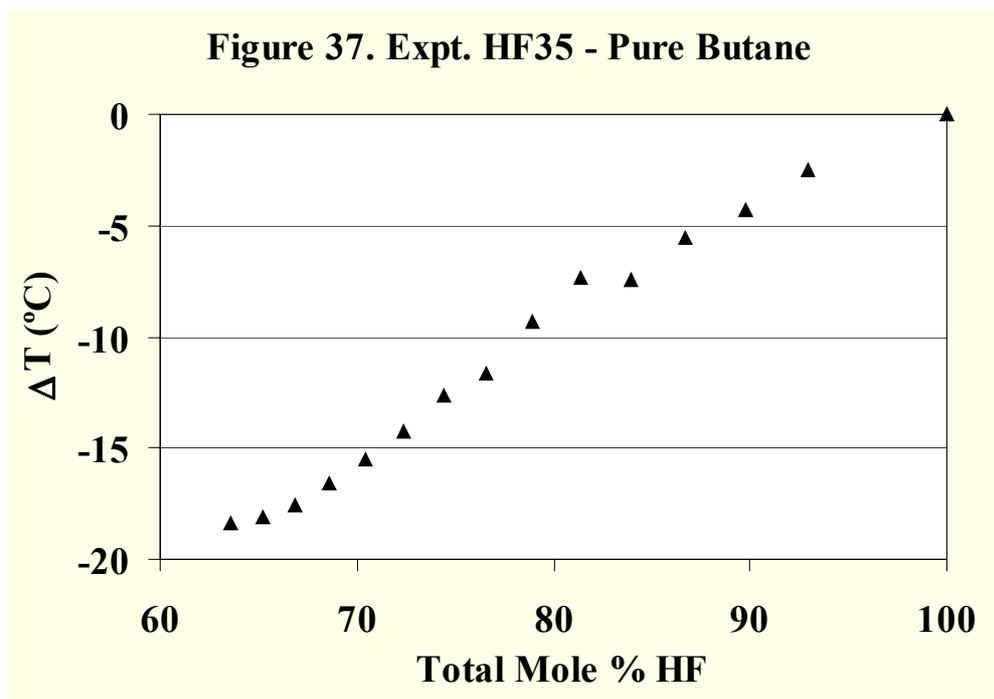
Mole % HF	Temp Change
100	0
92.91	-2.55
89.73	-4.3
86.75	-5.6
83.97	-7.4
81.37	-7.35
78.92	-9.35
76.61	-11.65
74.43	-12.65
72.38	-14.3
70.43	-15.5
68.59	-16.55
66.84	-17.55
65.17	-18.1
63.59	-18.35

Figure 38. AEA Results and Data from Schotte's Paper on HF Mixing with Dry and Humid Air
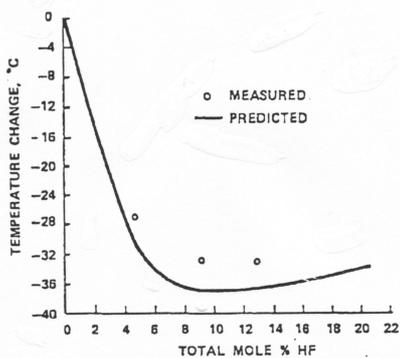

Figure 2. Temperature change during mixing of HF and dry air at 26 °C.

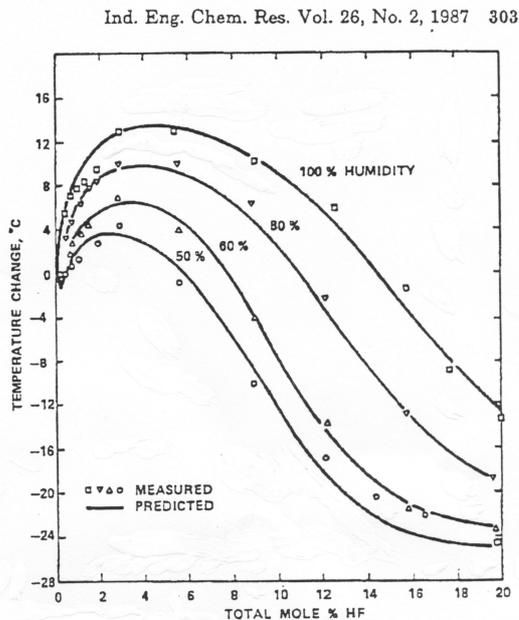Ind. Eng. Chem. Res. Vol. 26, No. 2, 1987 303

Figure 3. Temperature change during mixing of HF and moist air at 25-26 °C.