# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



| 1. REPORT DATE *(DD-MM-YYYY)* | 2. REPORT TYPE | 3. DATES COVERED *(From - To)* |
|---|---|---|
| | Technical Papers | |

**4. TITLE AND SUBTITLE**

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**

**5d. PROJECT NUMBER**
2303

**5e. TASK NUMBER**
M2C8

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

**8. PERFORMING ORGANIZATION REPORT**

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSOR/MONITOR'S NUMBER(S)**

**12. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release; distribution unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

1121 033

**15. SUBJECT TERMS**

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | Leilani Richardson |
| Unclassified | Unclassified | Unclassified | A | | 19b. TELEPHONE NUMBER *(include area code)* (661) 275-5015 |



62 separate items are enclosed

2303P02 TP-FY99-0110

✓ Spreadsheet
✓ DTS

Let me know which #'s are right. OK
See other page

MEMORANDUM FOR PRR (~~Contractor~~/In-House Publication)

1 June 1999

FROM: PROI (TI) (STINFO)

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-FY99-0110**
Fajardo and Tam, "High Resolution Infrared Absorption Spectroscopy of Molecular Dopants in Cryogenic Solid Parahydrogen"

**Poster Session HEDM CONFERENCE** **(Public Release)**

HIGH ENERGY DENSITY MATTER CONTRACTORS CONFERENCE
Cocoa Beach, FL 8-11 June 1999

# High Resolution Infrared Absorption Spectroscopy of Molecular Dopants in Cryogenic Solid Parahydrogen

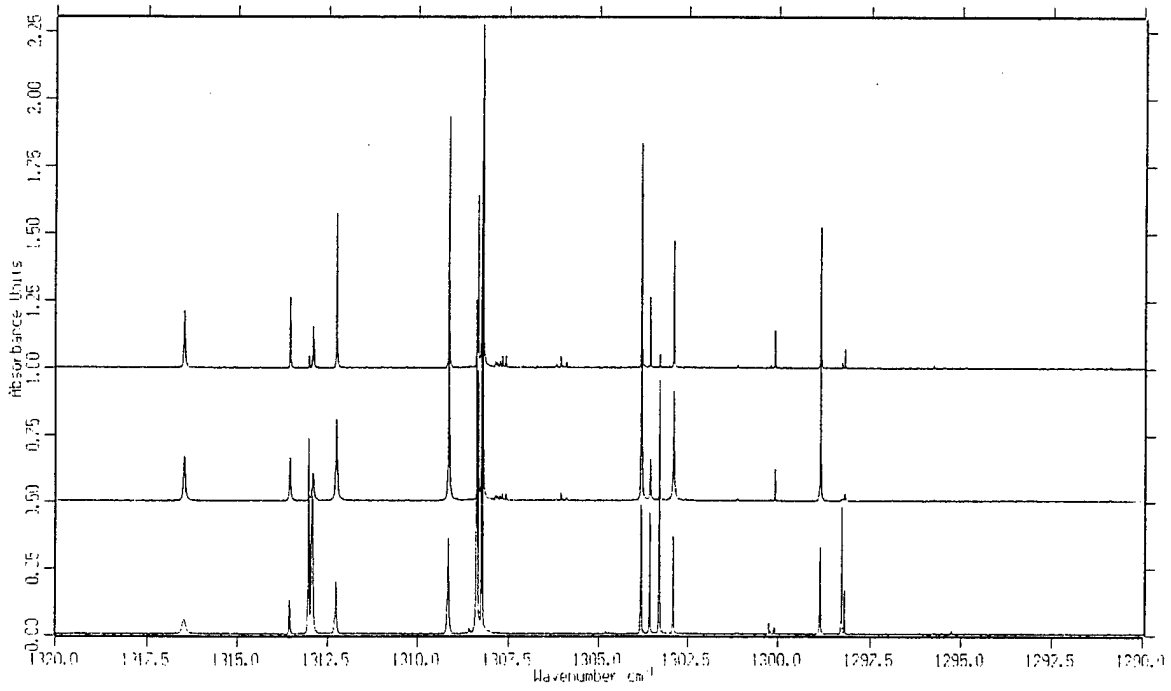
Mario E. Fajardo and Simon Tam
US Air Force Research Laboratory, Propulsion Directorate
(AFRL/PRSP Bldg. 8451, Edwards AFB, CA 93524-7680) mario_fajardo@ple.af.mil

Premature claims of successful energy storage in cryogenic solids date back to the National Bureau of Standards' Free Radicals program. Such errors typically result from reliance on unsupplemented calorimetric data, which shed little light on the mechanism of energy storage, *i.e.* chemical identities of the energetic species and microscopic structures within the trapping medium. **Only spectroscopic measurements provide the species and structure specific information required for directed incremental progress towards higher stored energy densities.**

In HEDM program funded studies, Oka and co-workers pioneered the use of high resolution spectroscopic techniques in solid parahydrogen ($pH_2$). Our rapid vapor deposition sample preparation technique now enables us to trap virtually any volatilizable species in solid $pH_2$. We present results of high resolution infrared absorption experiments on $pH_2$ solids doped with isolated molecules and small clusters.



## 13 PPM $CH_4/pH_2$ d≈3mm




st27011.8 annealed T=2.4K
st27011.4 annealing T=4.8K
st27011.2 as deposited T=2.4K resolution = 0.0075 $cm^{-1}$

## OBJECTIVE

Develop infrared (IR) absorption spectroscopic diagnostics for HEDM doped cryogenic parahydrogen ($pH_2$) solids.

## APPROACH

Collect high resolution IR spectra of $pH_2$ solids doped with non-energetic species: prototypical diatomic, triatomic, linear polyatomic, symmetric top, and spherical top dopant molecules.

Model data as "matrix-perturbed" gas phase spectra, if possible. Develop new spectroscopic models in collaboration with AFRL/Edwards Theory group, as necessary.

## SUMMARY

Many, but not all, molecular dopants exhibit very sharp (~0.01 $cm^{-1}$ FWHM) IR absorption lines in solid $pH_2$, providing an extremely detailed window into trapping site structures and dynamics.

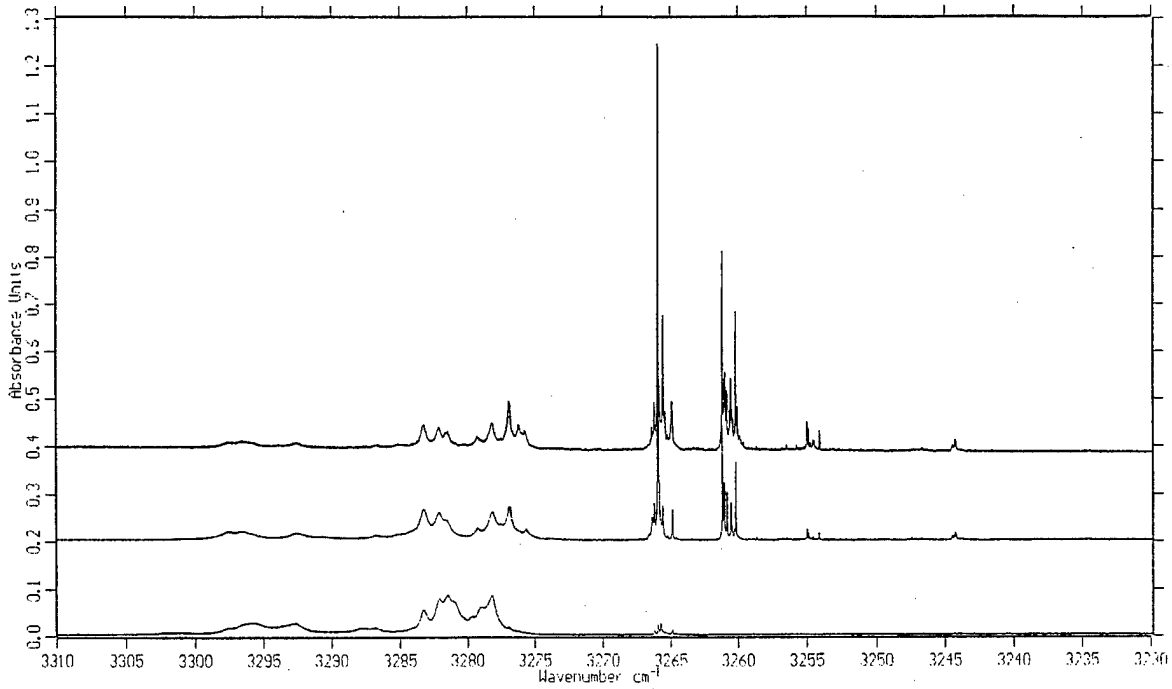
Model for spherical top molecules trapped in single substitutional sites in fcc and hcp solid $pH_2$ developed in collaboration with Prof. T. Momose of Kyoto U. is completely successful in explaining spectra of $CH_4/pH_2$ system. Model of trapped diatomic molecules forthcoming.

## FUTURE DIRECTIONS

Develop model for dopants trapped in multi-substitutional vacancies.

Include effects of lattice relaxation via quantum Monte Carlo methods.

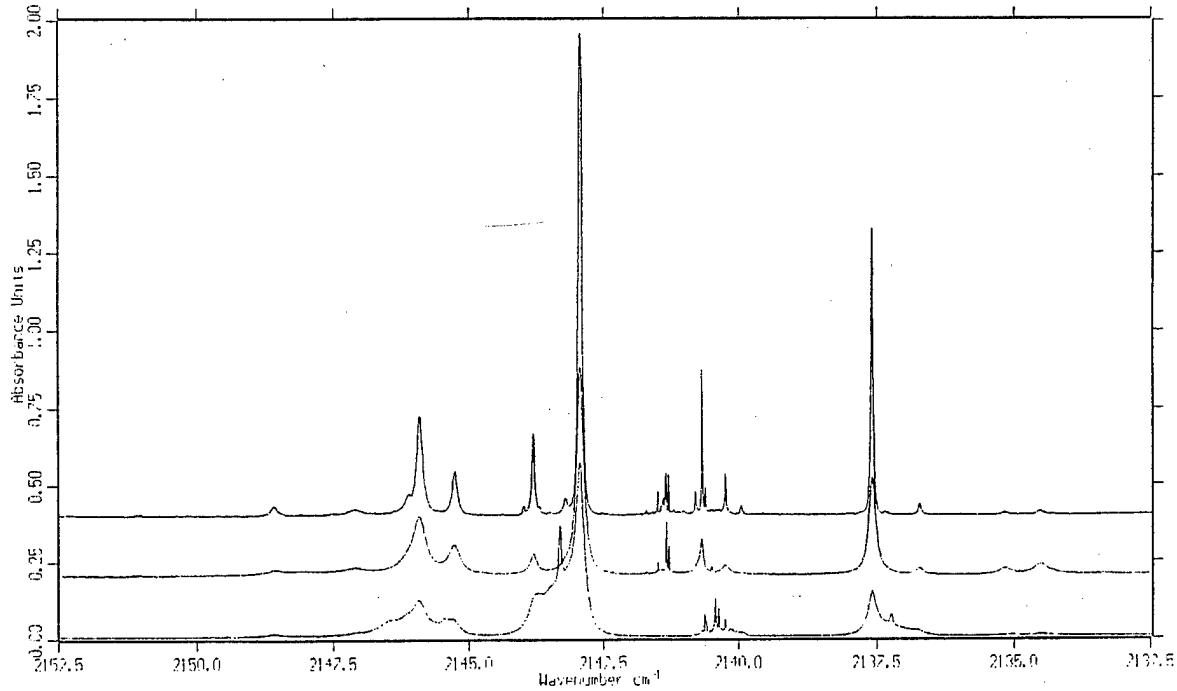
# 9 ~~PPM~~ ppm $C_2H_2/pH_2$ d≈3mm




st28034.13 annealed T=2.4K
st28034.7 annealing T=4.8K
st28034.5 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

ST28034.5

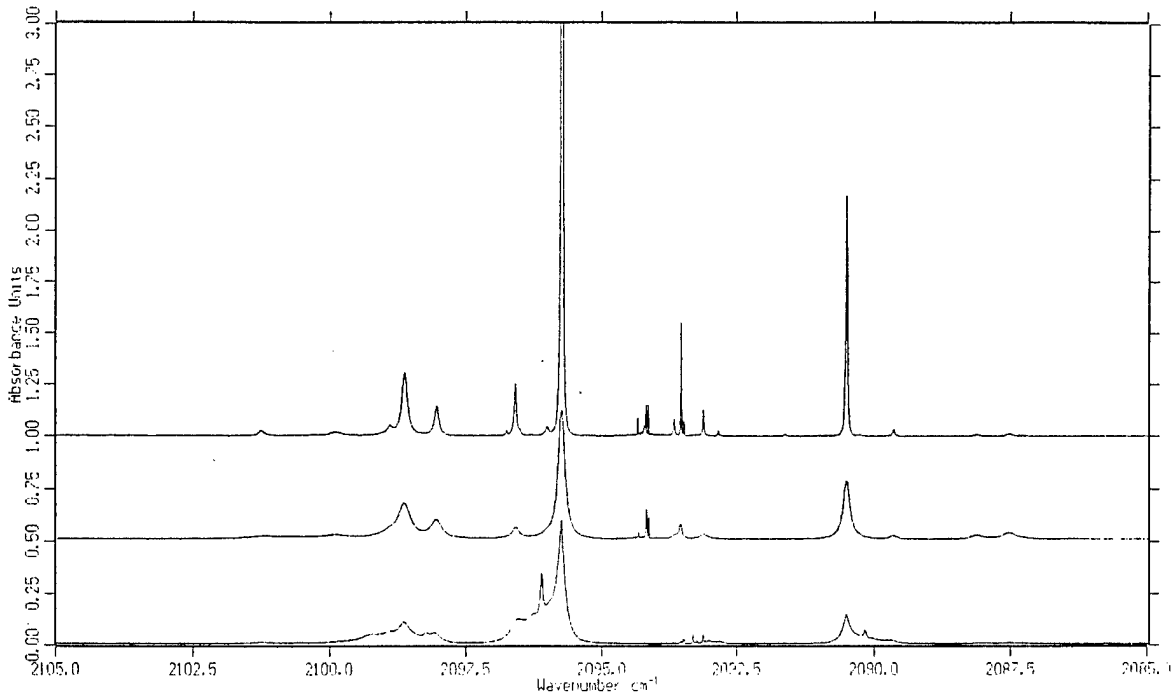
# 13 ~~PPM~~ ppm $CO/pH_2$ d≈3mm




st27017.18 annealed T=2.4K
st27017.14 annealing T=4.8K
st27017.10 as deposited T=2.4K resolution = 0.0075 $cm^{-1}$

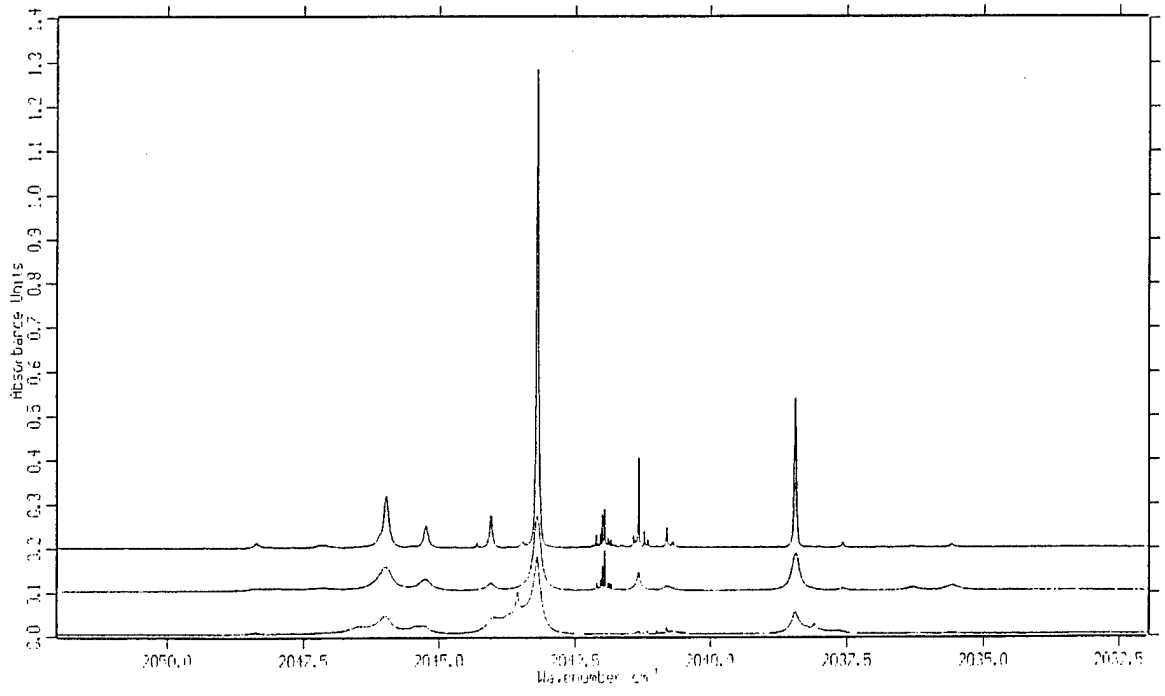
ST27017.10

# $^{13}C^{16}O/pH_2$ d≈3mm



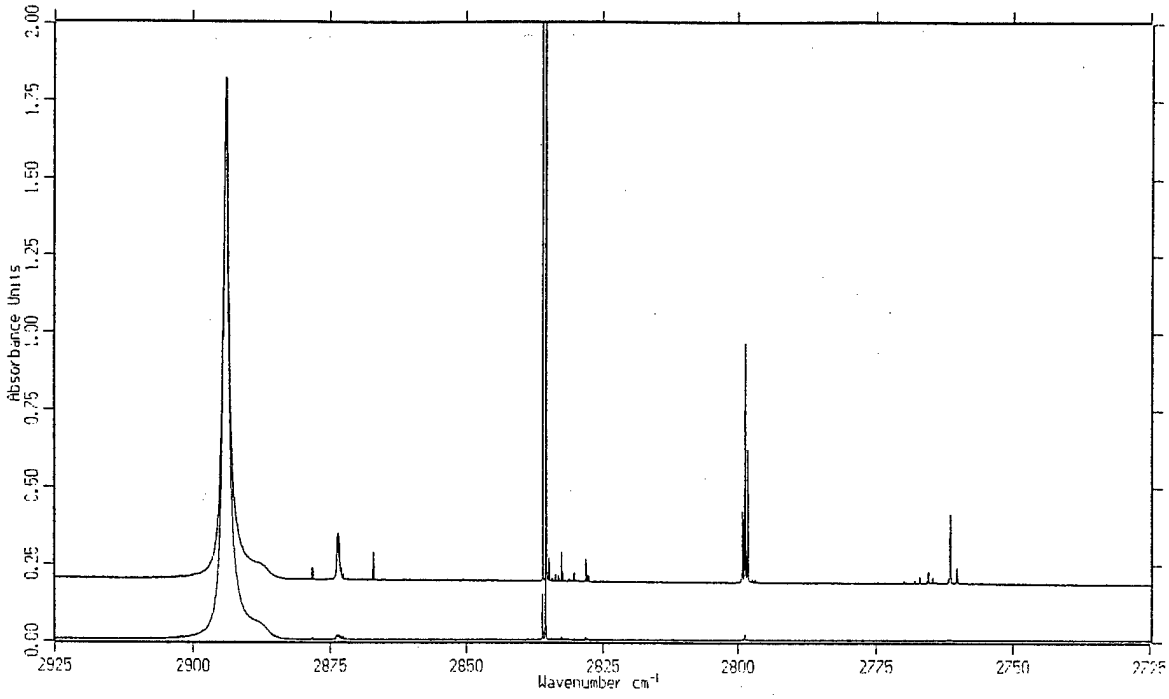

st28082.6 annealed T=2.4K
st28082.4 annealing T=4.8K
st28082.2 as deposited T=2.4K 11 PPM $^{13}CO/pH_2$ resolution = 0.005 $cm^{-1}$

# $^{13}C^{18}O/pH_2$ d≈3mm




st28085.5 annealed T=2.4K
st28085.3 annealing T=4.8K
st28085.1 as deposited T=2.4K 29 PPM $^{13}CO/pH_2$ resolution = 0.005 $cm^{-1}$

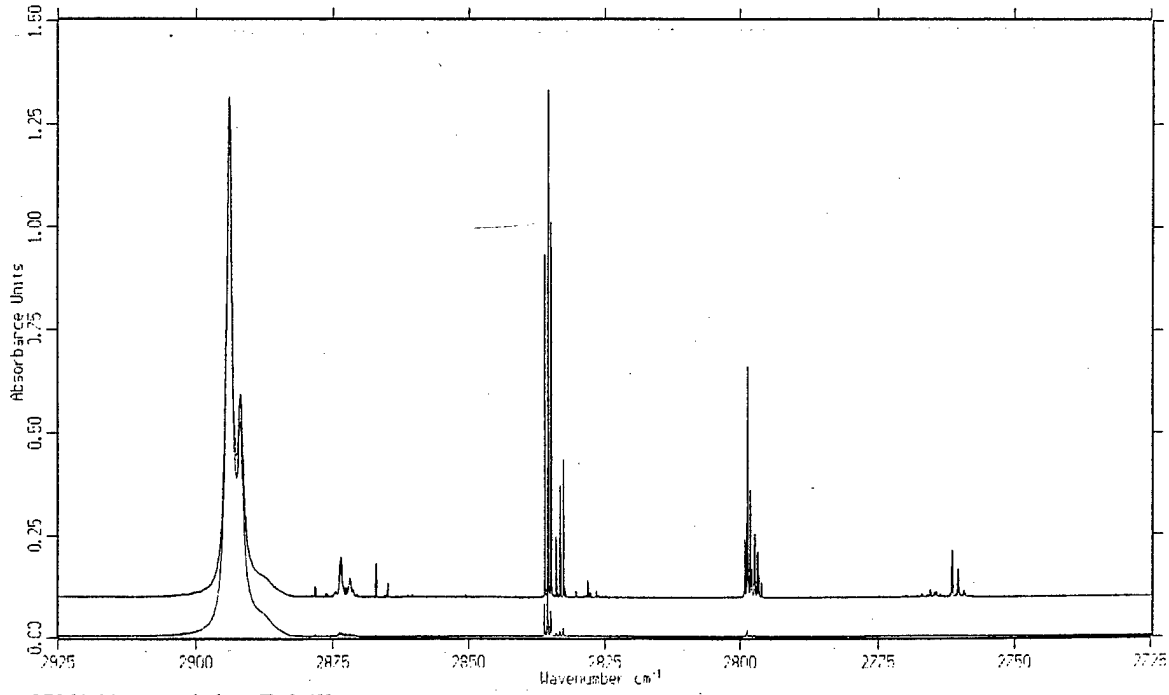
# 90 ~~PPM~~ ppm $H^{35}Cl/pH_2$ d≈3mm




st27079.11 annealed T=2.4K
st27079.7 as deposited T=2.4K
resolution = 0.005 $cm^{-1}$

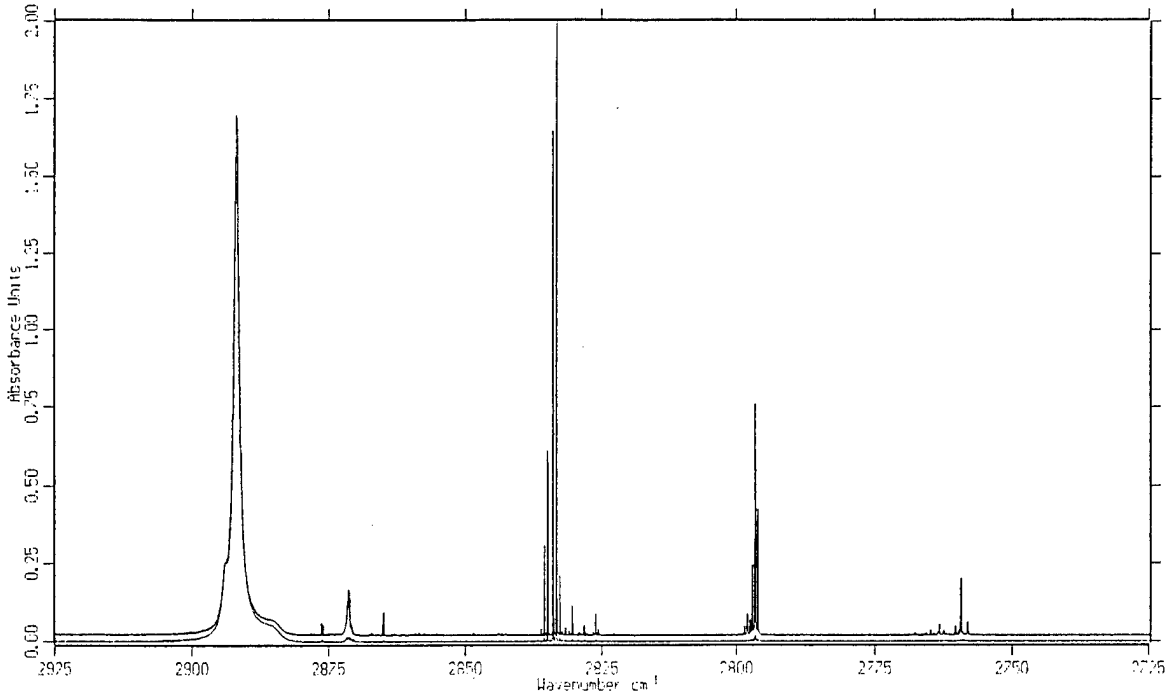
ST27079.7

# 88 ~~PPM~~ ppm $HCl/pH_2$ d≈3mm




st27061.11 annealed T=2.4K
st27061.7 as deposited T=2.4K
resolution = 0.0075 $cm^{-1}$

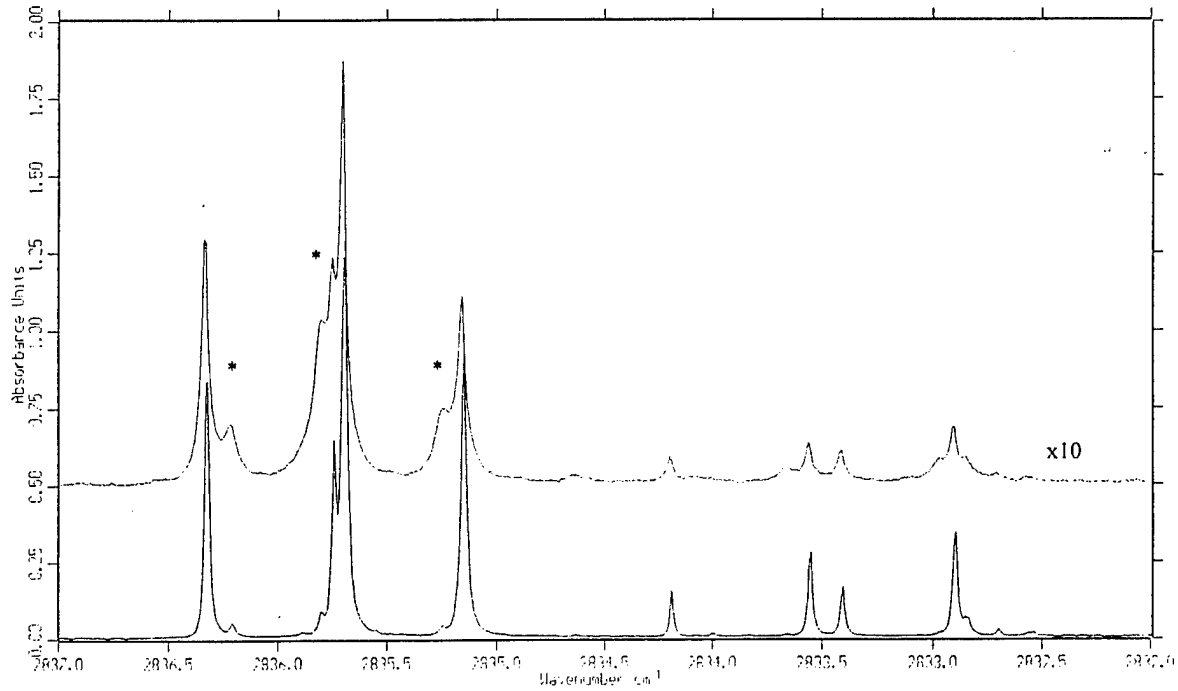
# 94 ~~PPM~~ PPm $H^{37}Cl/pH_2$ d≈3mm




st27103.6 annealed T=2.4K
st27103.2 as deposited T=2.4K
resolution = 0.005 $cm^{-1}$

ST27103.2

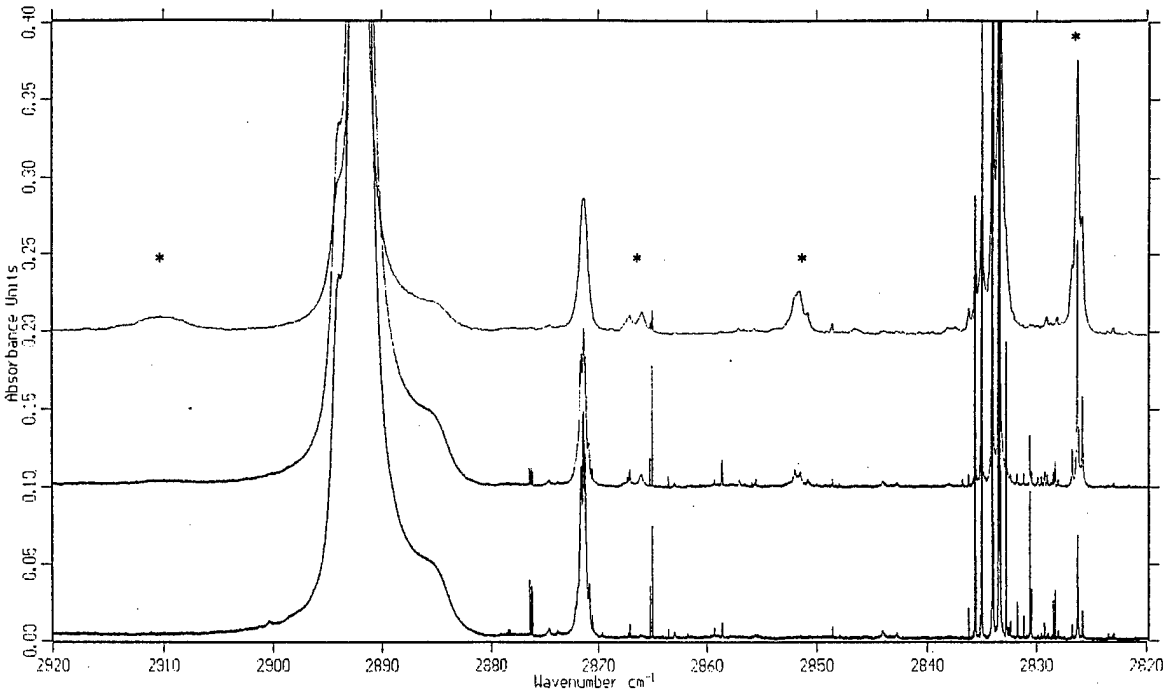
# irreversible T dependences




88 PPM $HCl/pH_2$ d≈3mm
st27061.7 as deposited T=2.4K
st27061.11 annealed T=2.4K

ST27061.11

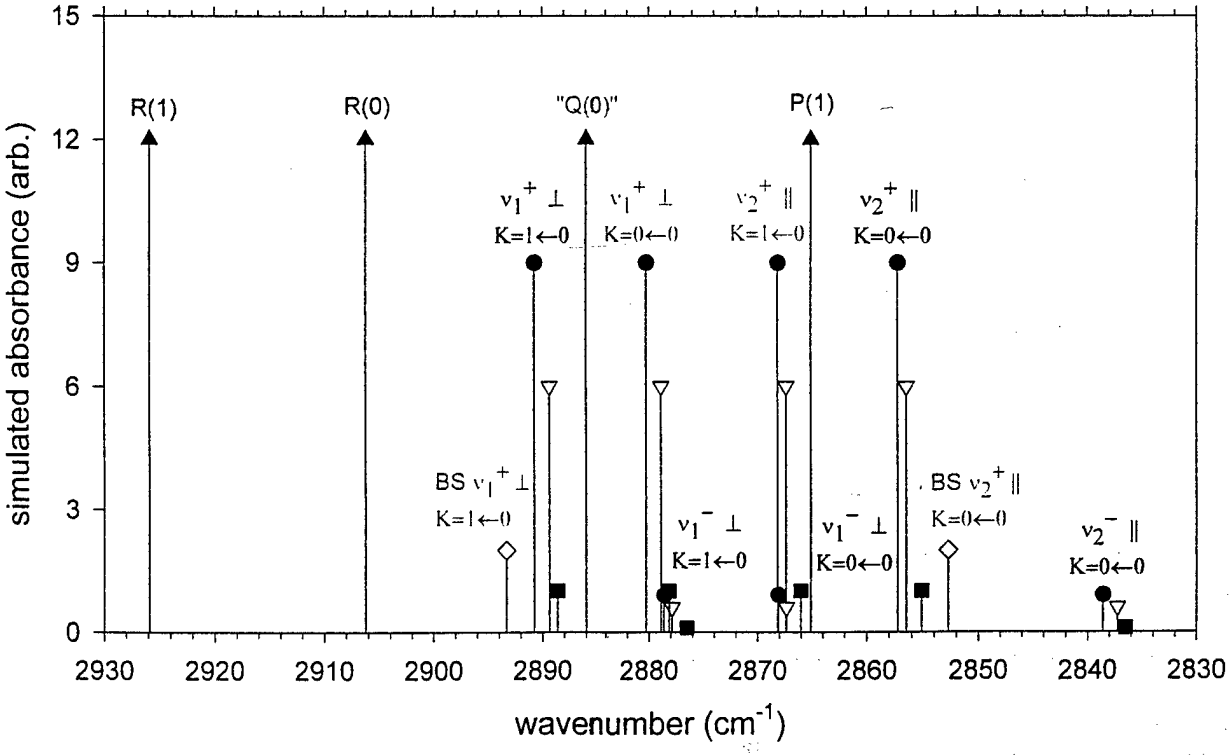
# reversible T dependences



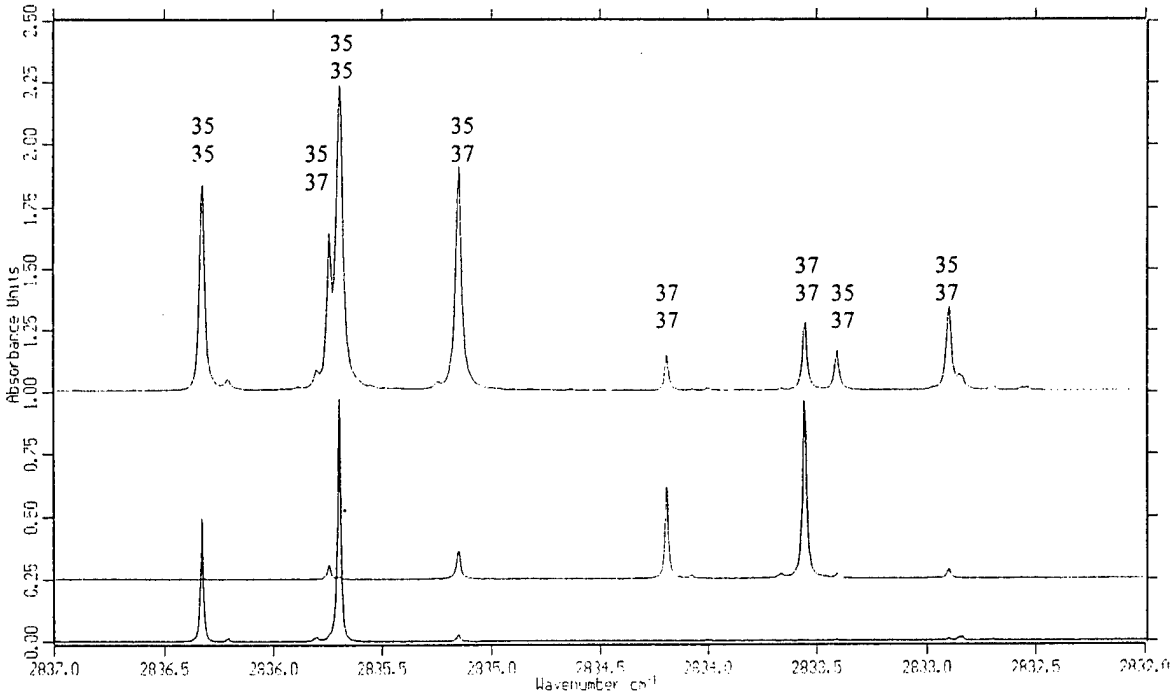

st27103.13 evaporating T≈10K 94 PPM $H^{37}Cl$
st27103.4 annealing T=4.8K
st27061.11 annealed T=2.4K

ST27103.4

## gas phase HCl and $(HCl)_2$ transitions



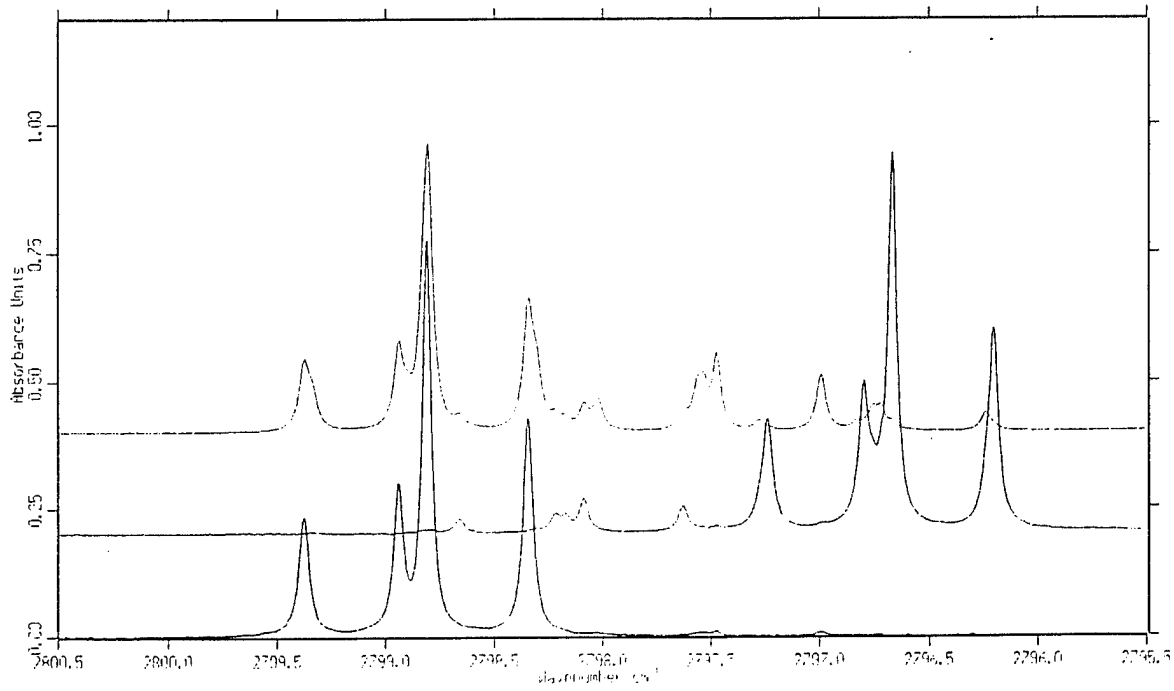
# $(HCl)_2$ $\nu_2^+$ region




st27061.11 annealed T=2.4K 88 PPM HCl
st27097.6 annealed T=2.4K 33 PPM $H^{37}Cl$
st27073.17 annealed T=2.4K 30 PPM $H^{35}Cl$

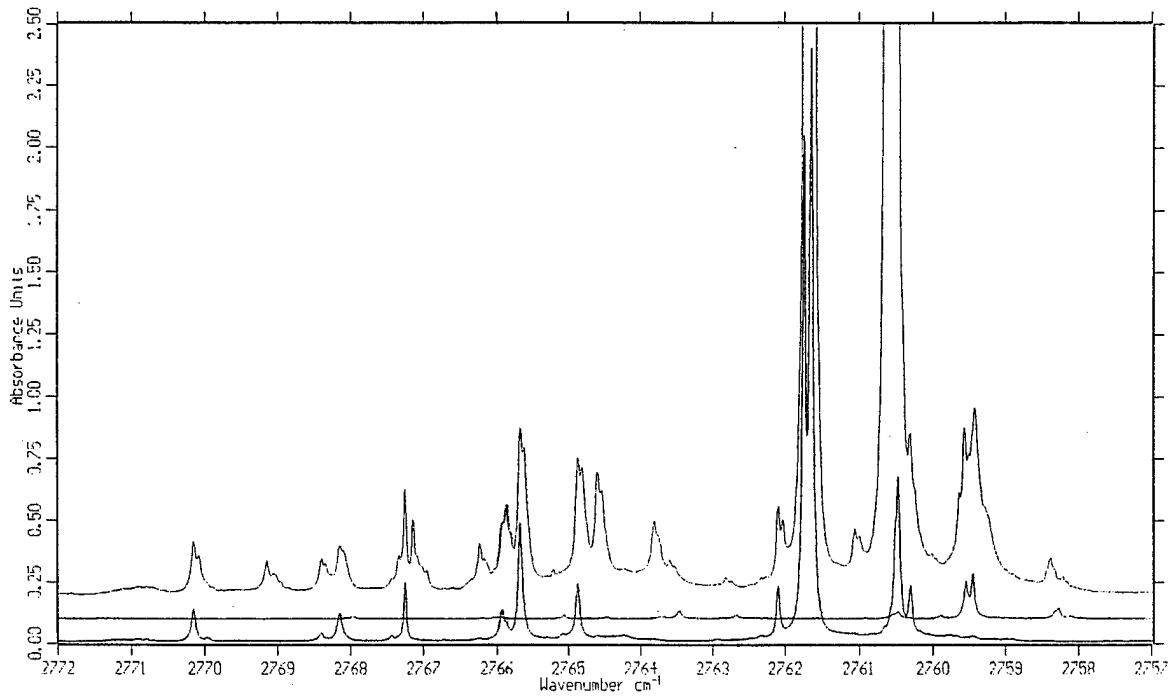
ST27073.17

# $(HCl)_3$




st27061.11 annealed T=2.4K 88 PPM HCl
st27103.6 annealed T=2.4K 94 PPM $H^{37}Cl$
st27079.11 annealed T=2.4K 90 PPM $H^{35}Cl$

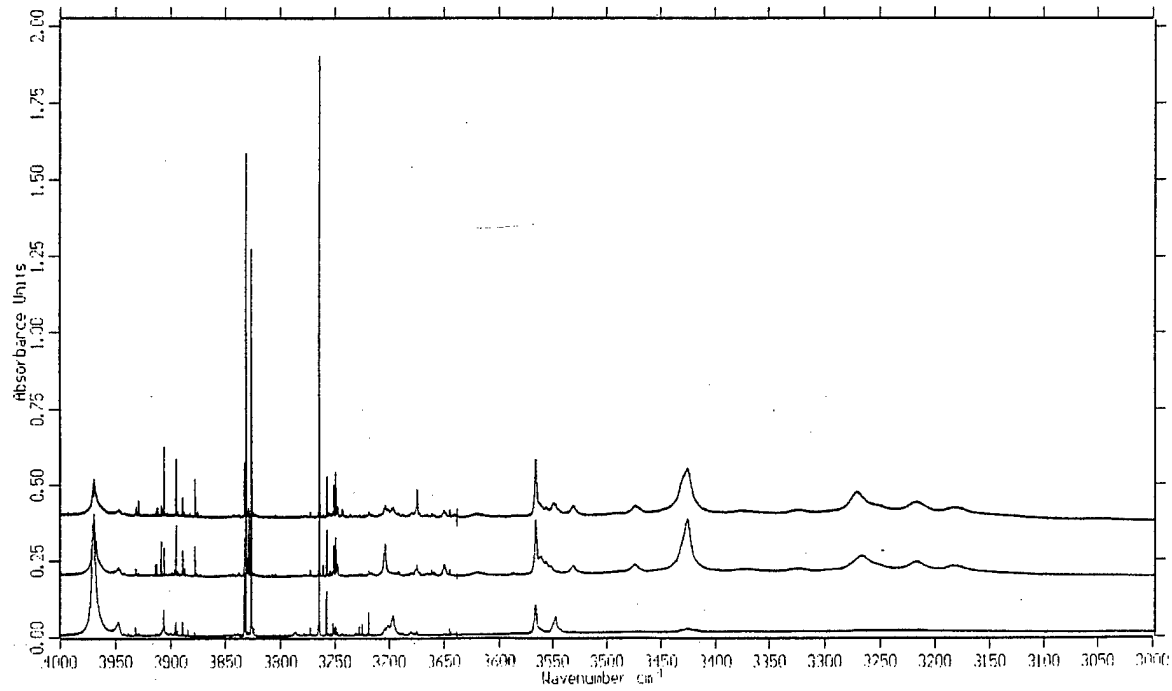
# $(HCl)_4$




st27067.10 annealed T=2.4K 494 PPM HCl
st27103.6 annealed T=2.4K 94 PPM $H^{37}Cl$
st27085.9 annealed T=2.4K 284 PPM $H^{35}Cl$

ST27103.6

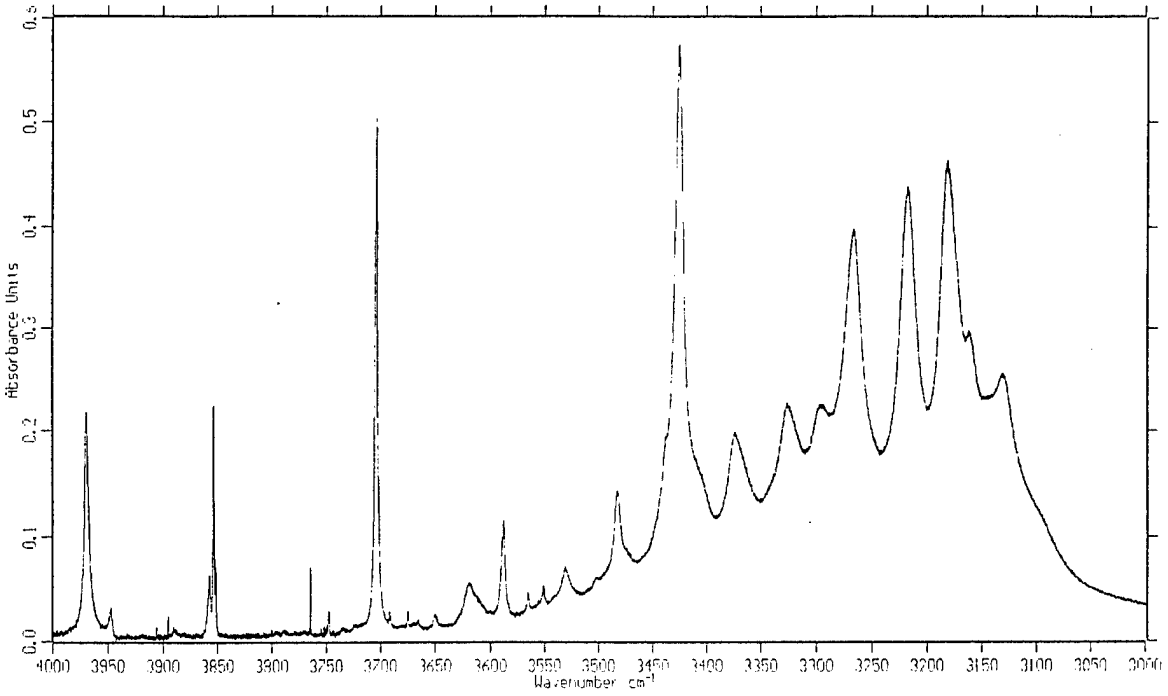
# 123 ~~PPM~~ ppm $HF/pH_2$ d≈3mm




st27115.15 annealed T=2.4K
st27115.13 annealing T=4.8K
st271215.9 as deposited T=2.4K

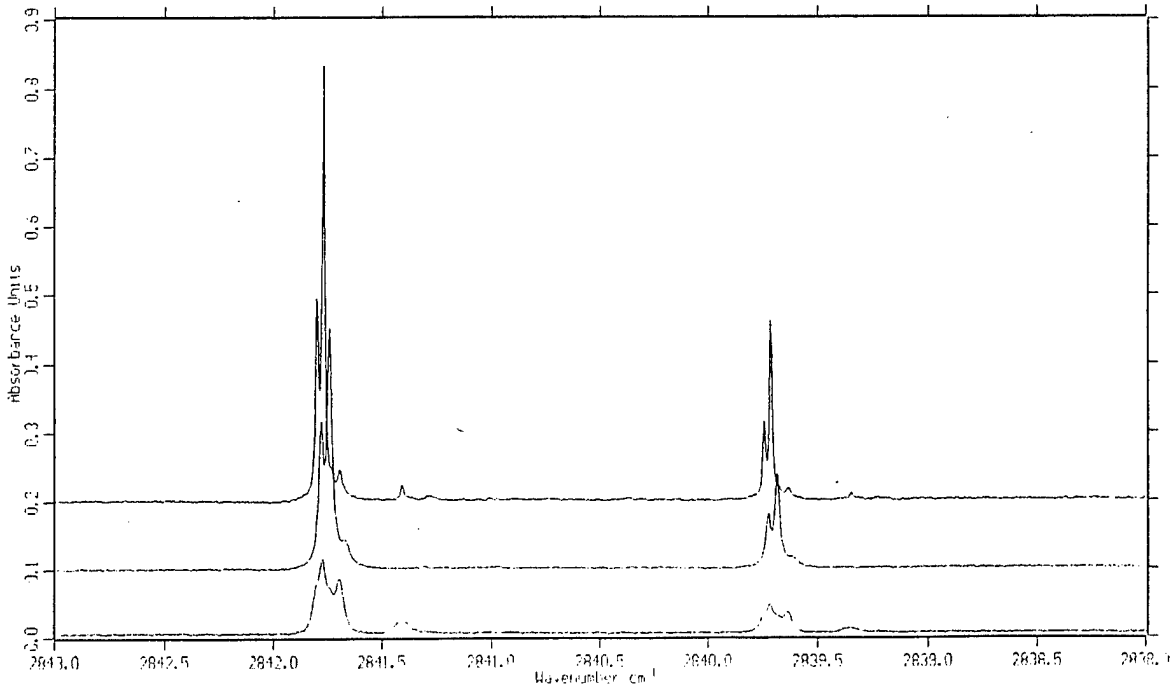
resolution = 0.005 $cm^{-1}$

# $(HF)_n/pH_2$



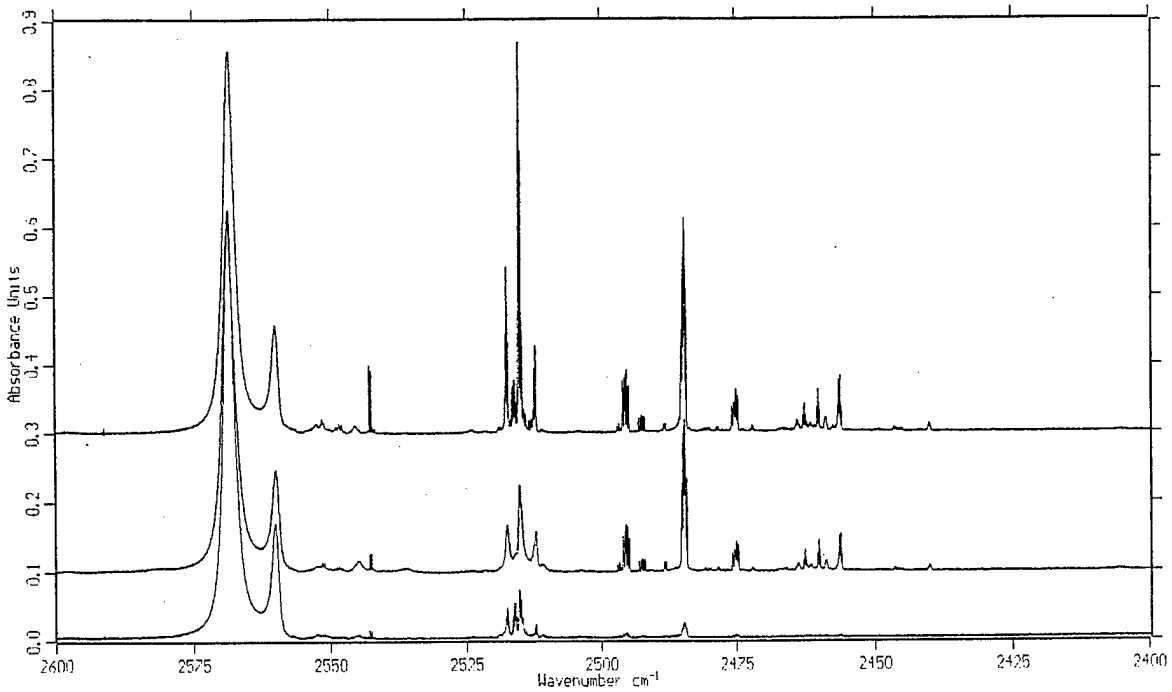

st27133.15 sample burnoff T~10K 268 PPM HF/$pH_2$ resolution = 0.1 $cm^{-1}$

# HF-HCl/$pH_2$




st27115.15 annealed T=2.4K
st27115.13 annealing T=4.8K
st27115.9 as deposited T=2.4K 123 PPM HF/$pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

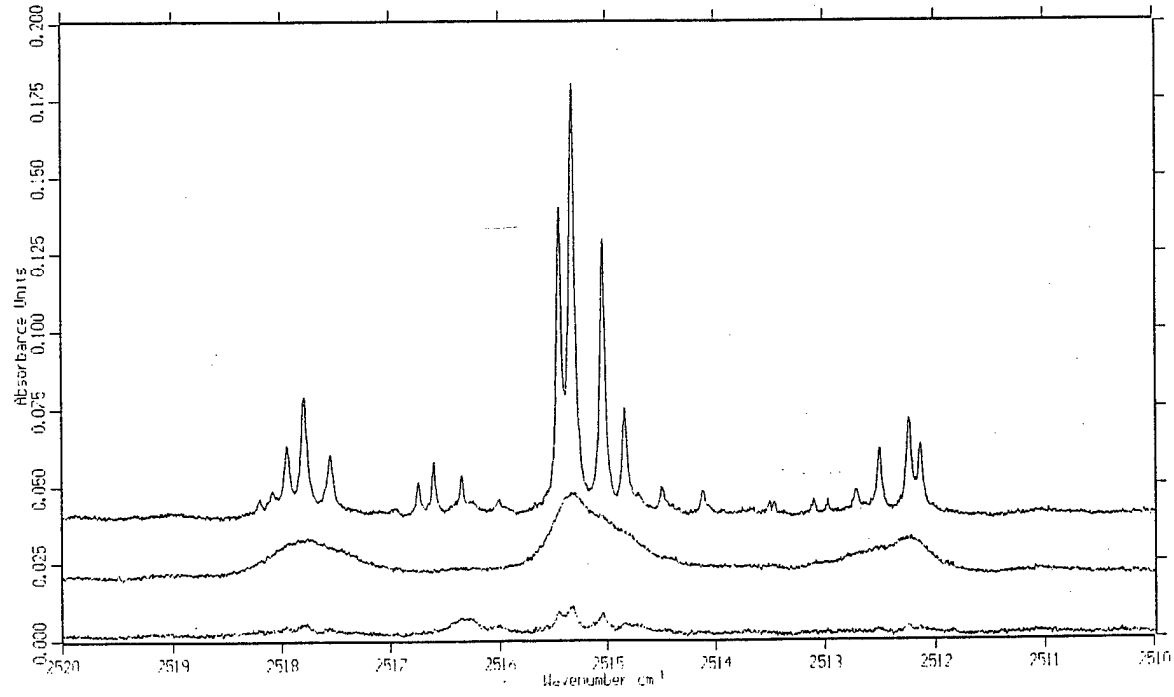
# 260 ~~PPM~~ ppm $HBr/pH_2$ d≈3mm




st27145.9 annealed T=2.4K
st27145.7 annealing T=4.8K
st27145.5 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

ST27145.5

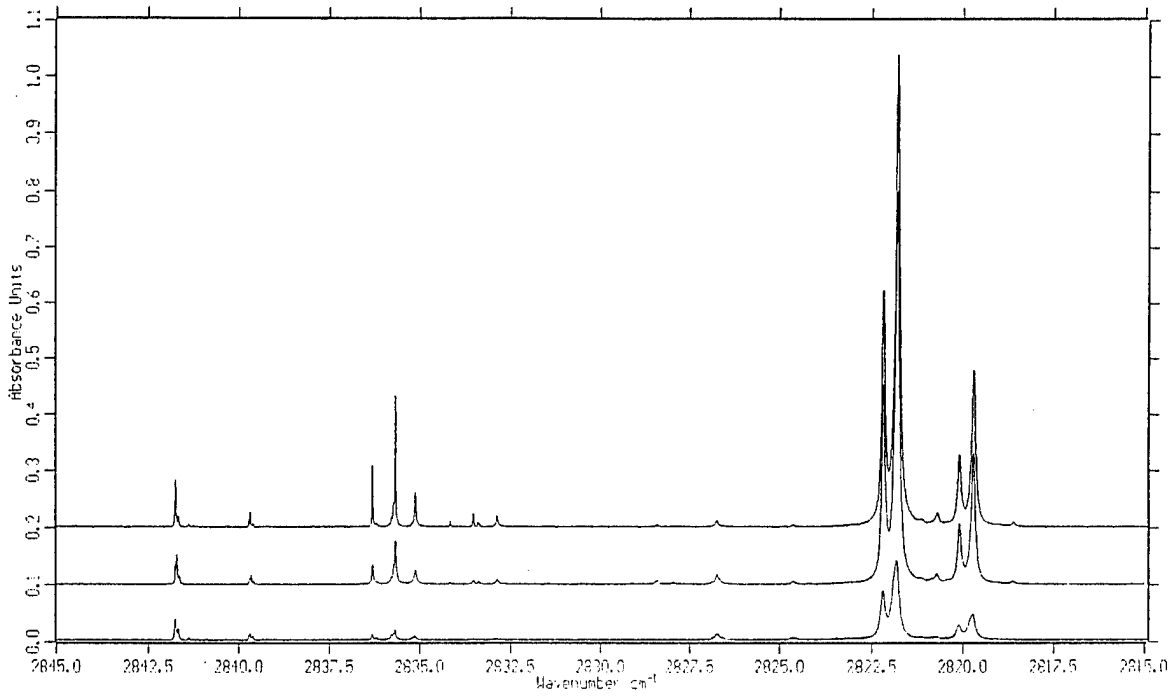
# $(HBr)_2/pH_2$




st27140.9 annealed T=2.4K
st27140.7 annealing T=4.8K
st27140.5 as deposited T=2.4K 80 PPM $HBr/pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

ST27140.5

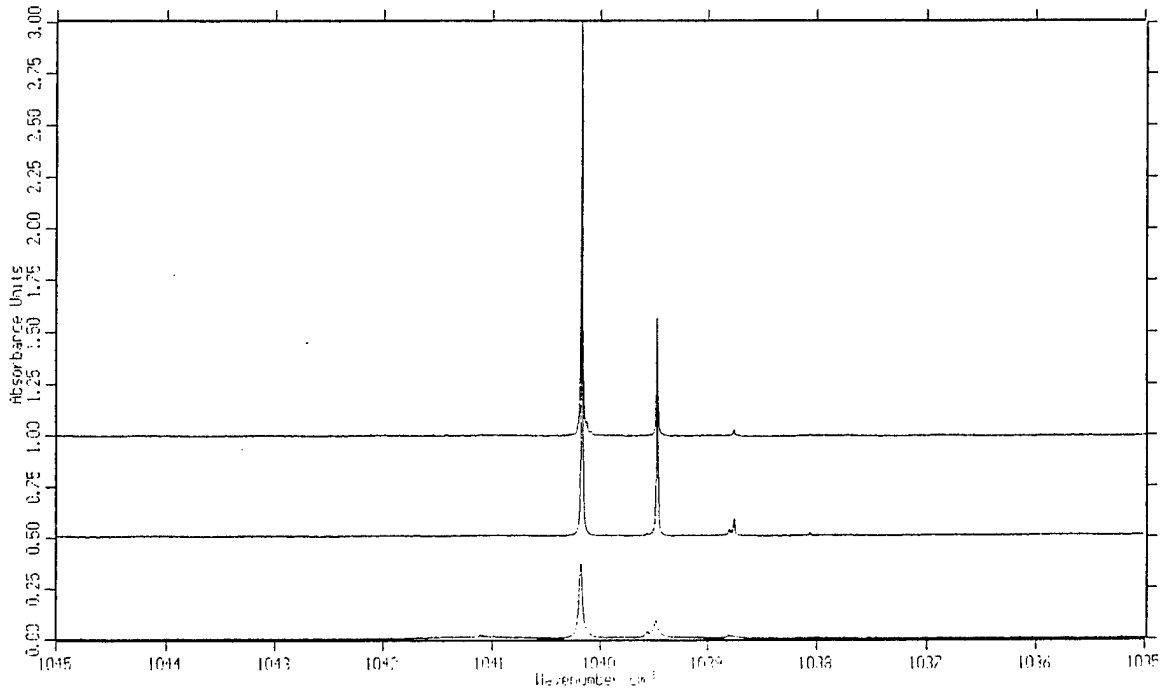
# $HCl-(HF, HCl, HBr)/pH_2$




st27145.9 annealed T=2.4K
st27145.7 annealing T=4.8K
st27145.5 as deposited T=2.4K 260 PPM $HBr/pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

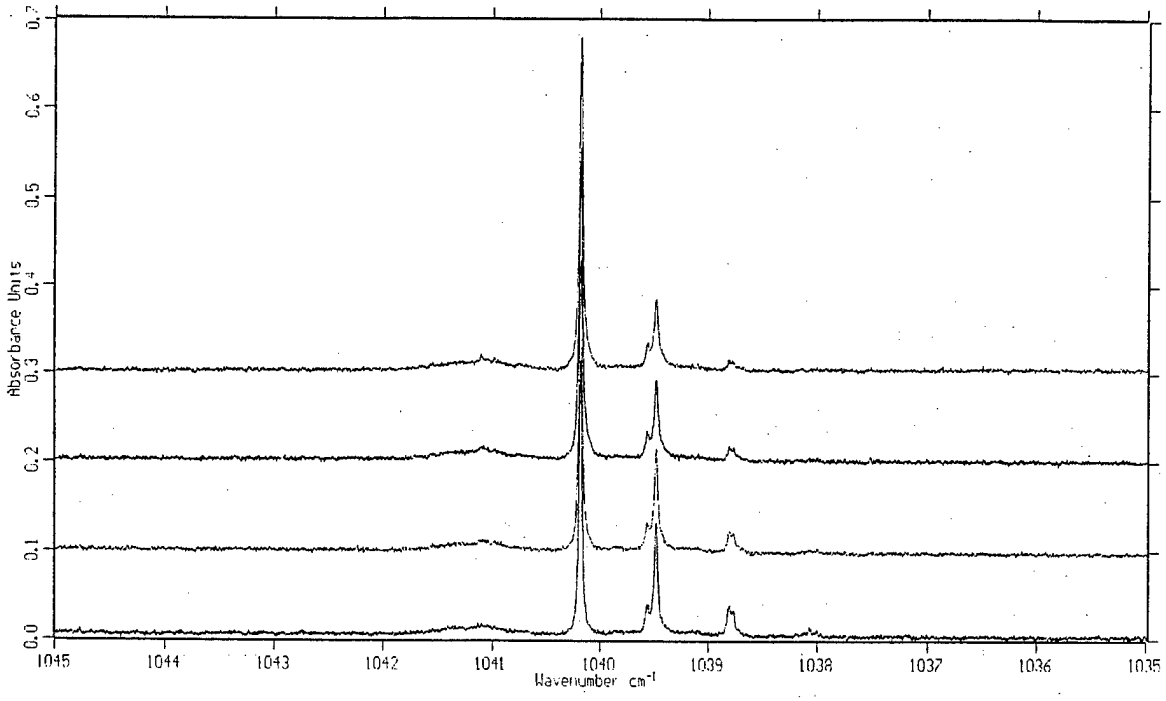
ST27145.5

# 2.4 PPM $CH_3F/pH_2$ d≈3mm




st28060.15 annealed T=2.4K
st28060.11 annealing T=4.8K
st28060.6+7 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

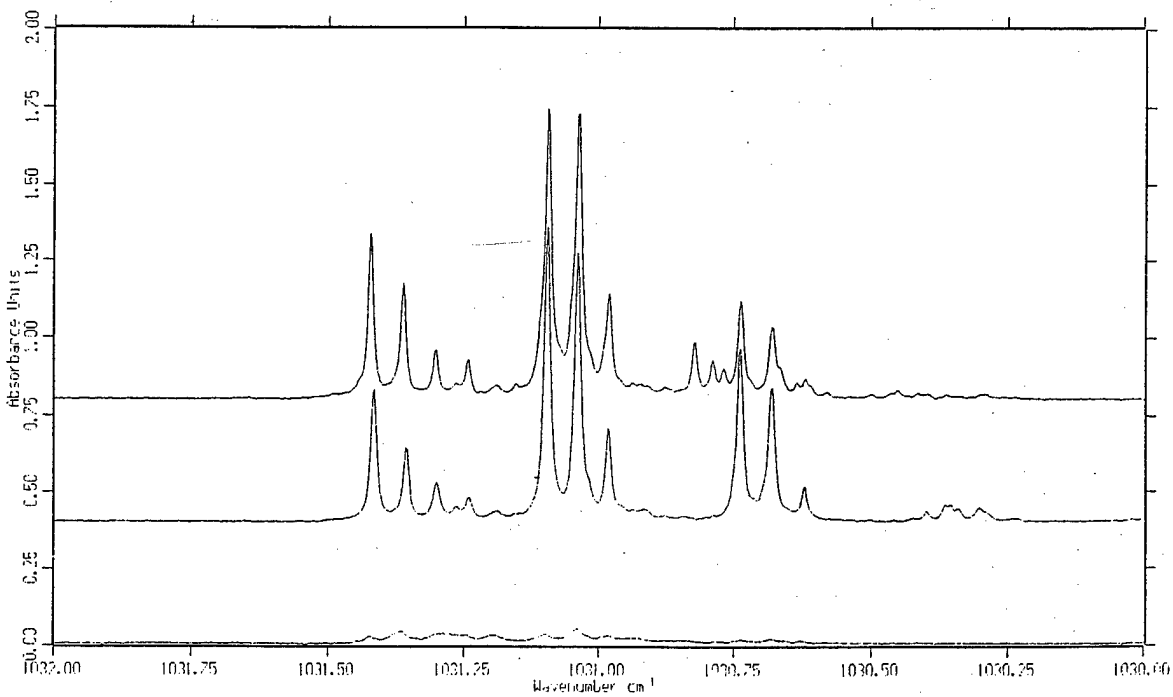
# $^1H$ Spin Relaxation in $CH_3F/pH_2$




st28060.7 after 100 min T=2.4K st28060.3 after 30 min T=2.4K
st28060.6 after 70 min T=2.4K st28060.2 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

ST28060.2

# $(CH_3F)_2/pH_2$




st28044.11 annealed T=2.4K
st28044.7 annealing T=4.8K
st28044.3 as deposited T=2.4K 30 PPM $CH_3F/pH_2$ resolution = 0.005 $cm^{-1}$

# SUPPLEMENTAL MATERIALS

**for the poster:**

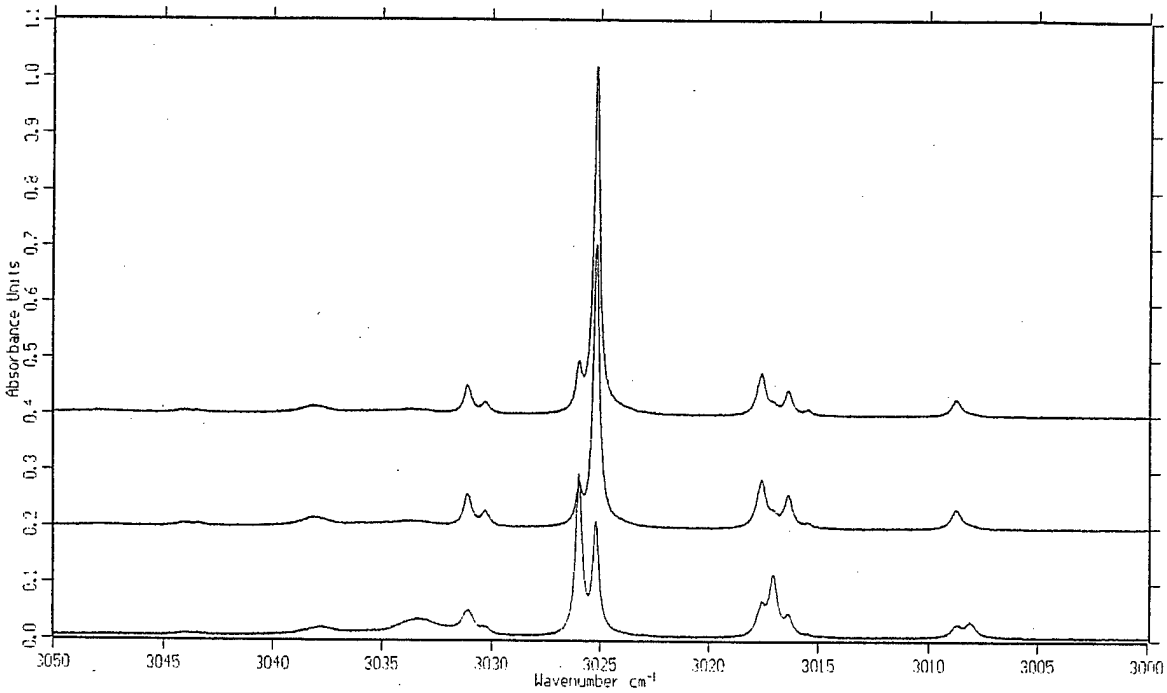
HIGH ENERGY DENSITY MATTER CONTRACTORS CONFERENCE
Cocoa Beach, FL 8-11 June 1999

## High Resolution Infrared Absorption Spectroscopy of Molecular Dopants in Cryogenic Solid Parahydrogen

Mario E. Fajardo and Simon Tam
US Air Force Research Laboratory, Propulsion Directorate
(AFRL/PRSP Bldg. 8451, Edwards AFB, CA 93524-7680) mario_fajardo@ple.af.mil

Consisting of spectra of NON-ENERGETIC species trapped in solid hydrogen at low concentrations. These data encompass prototypical diatomic (CO, HCl, HF, HBr), triatomic ($CO_2$, $N_2O$, $H_2O$), linear polyatomic ($C_2H_2$), symmetric top ($NH_3$, $CH_3F$), and spherical top ($CH_4$) molecular dopants. The basic research activity of understanding these spectra will aid in the future characterization of HEDM cryosolid propellants.

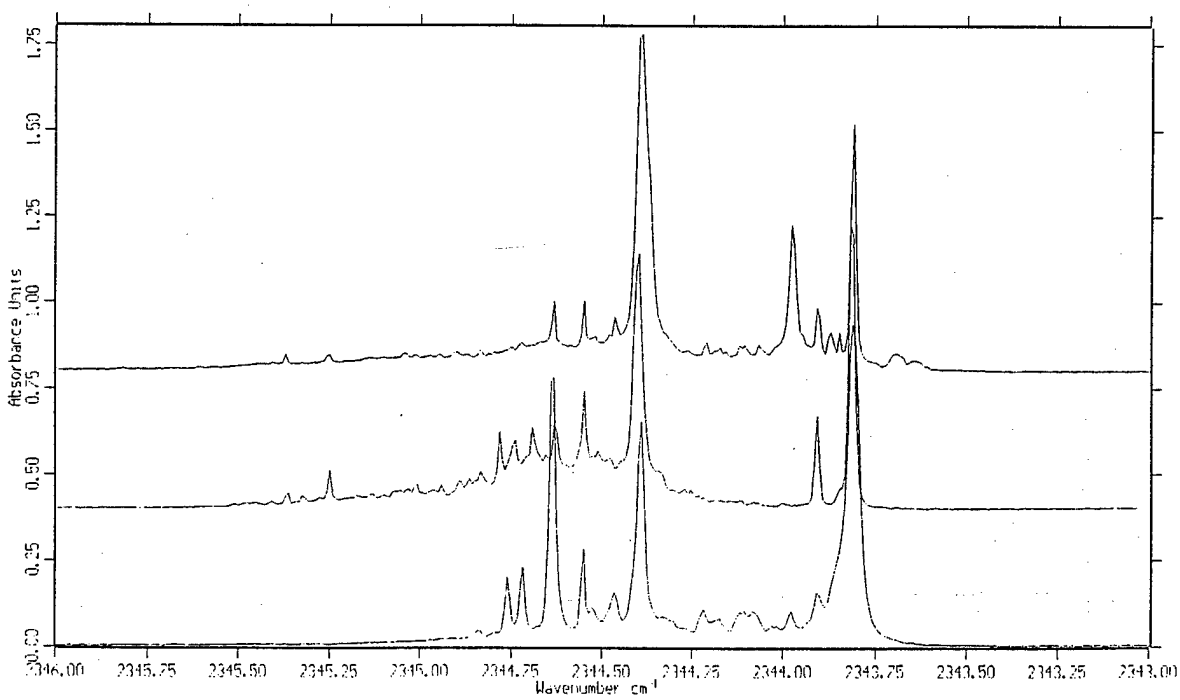
# 13 ~~PPM~~ ppm $CH_4/pH_2$ d≈3mm




st27011.8 annealed T=2.4K
st27011.4 annealing T=4.8K
st27011.2 as deposited T=2.4K resolution = 0.0075 $cm^{-1}$

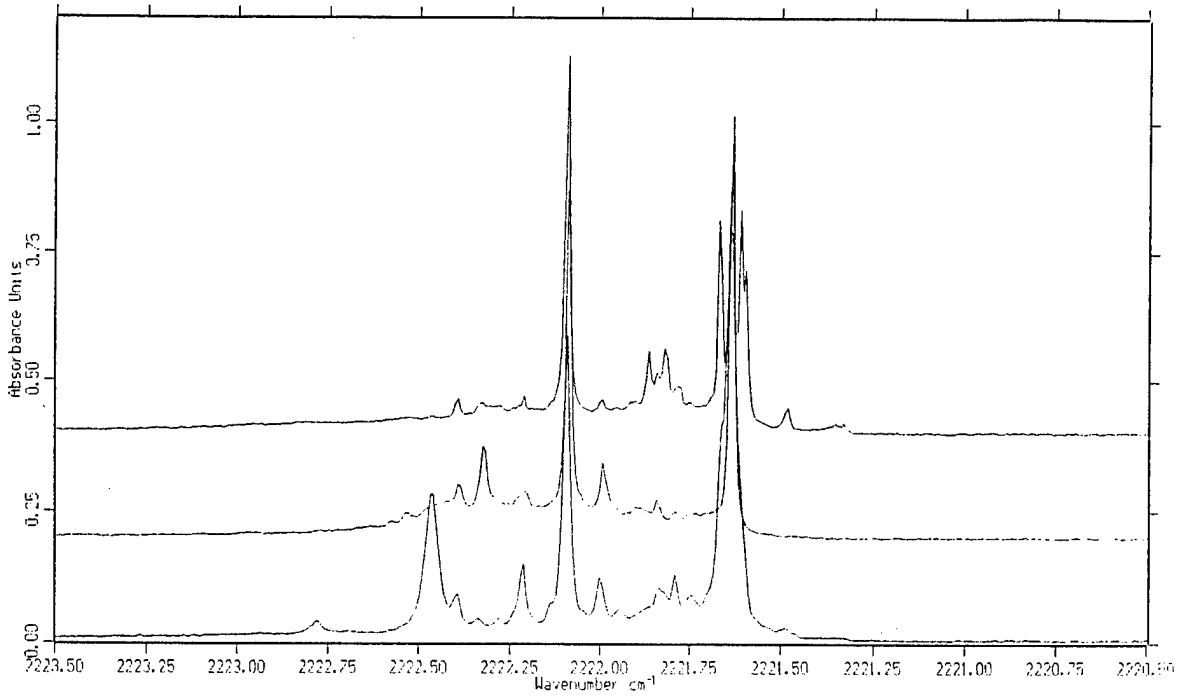
ST27011.2

# 1 ~~PPM~~ ppm $CO_2/pH_2$ d≈3mm




st27025.11 annealed T=2.4K
st27025.9 annealing T=4.8K
st27025.7 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

# 1 ppm ~~PPM~~ $N_2O/pH_2$ d≈3mm

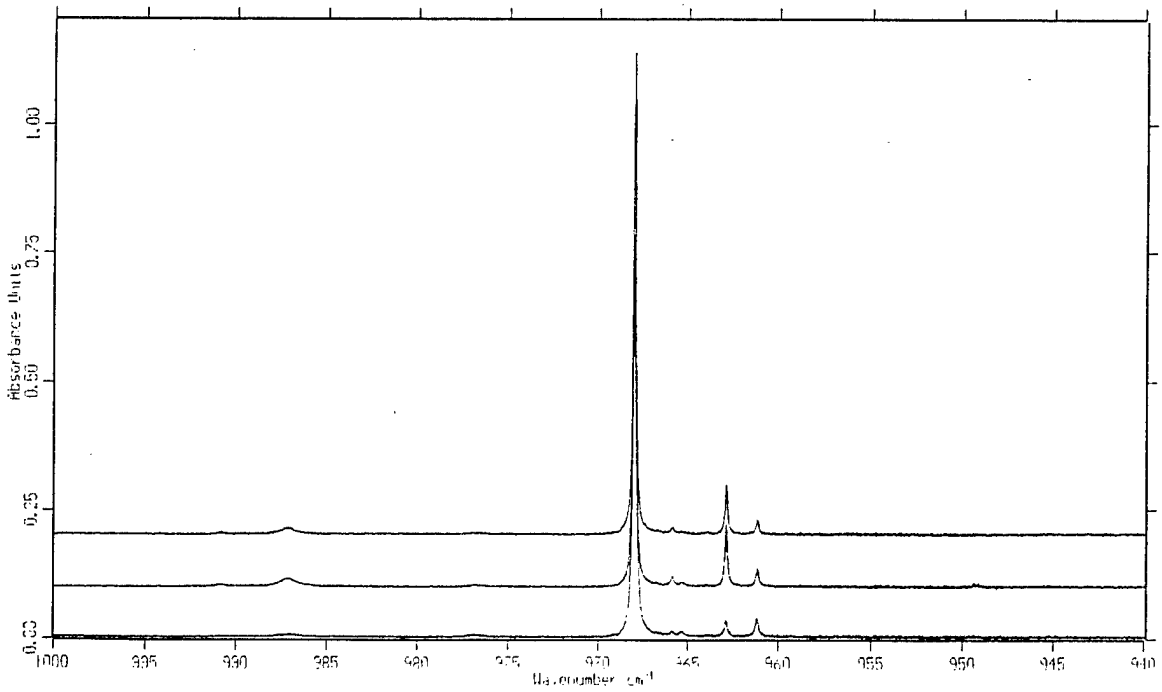



st27025.14 annealed T=2.4K
st27025.12 annealing T=4.8K
st27025.6 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

31

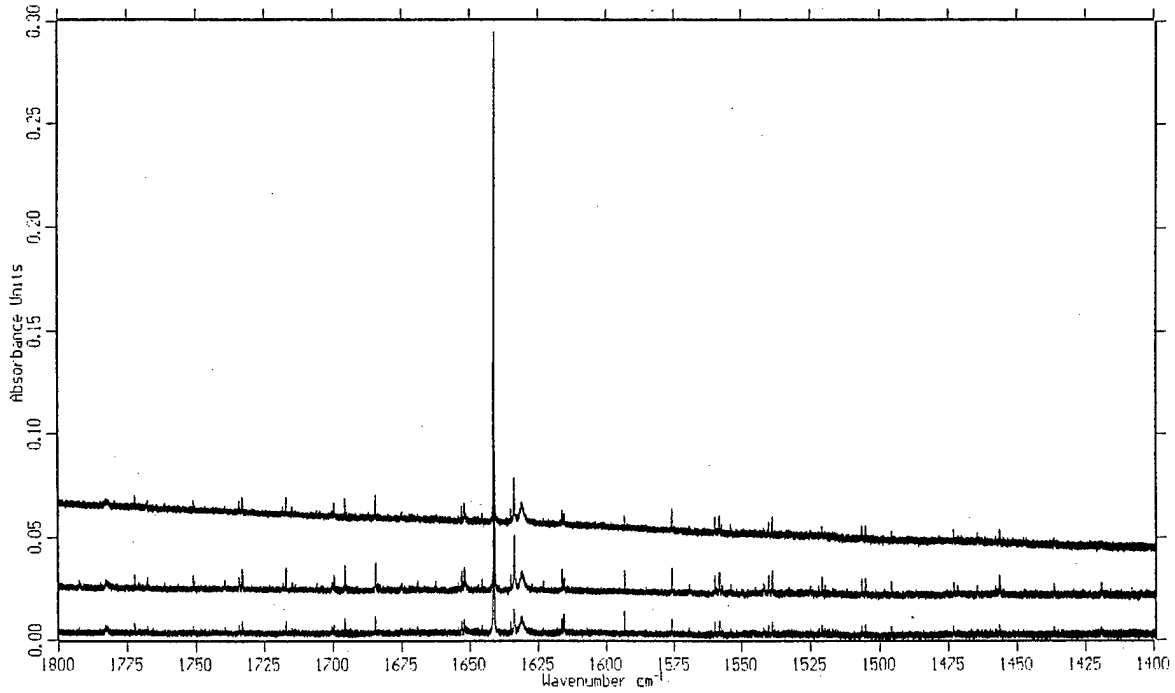
ST27031.c

# 4 ppm ~~PPM~~ $NH_3/pH_2$ d≈3mm




st27036.12 annealed T=2.4K
st27036.10 annealing T=4.8K
st27036.8 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

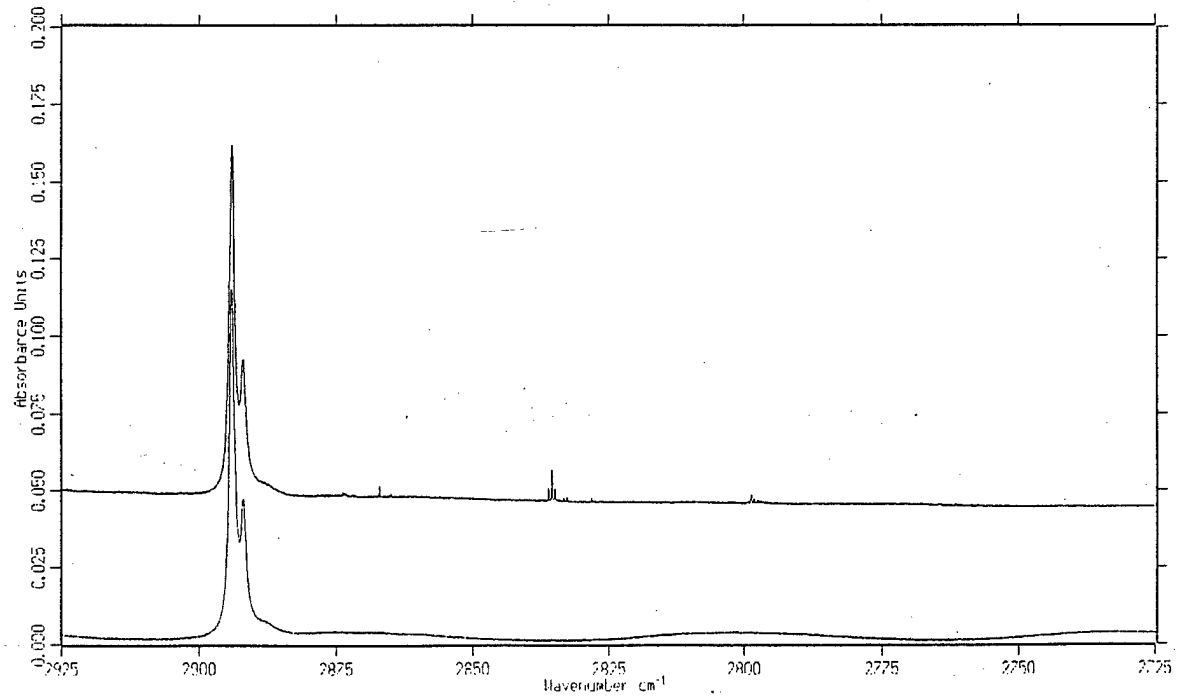
# 4 ~~PPM~~ ppm $NH_3/pH_2$ d≈3mm




st27036.12 annealed T=2.4K
st27036.10 annealing T=4.8K
st27036.8 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

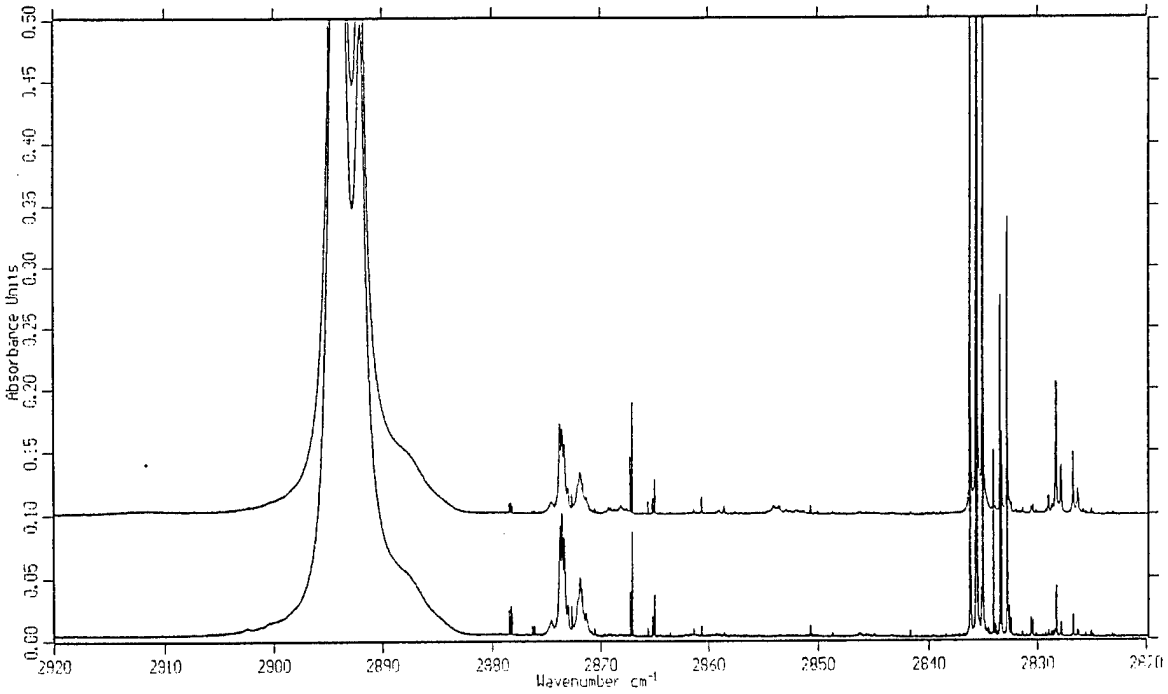
ST27036.8

# 8 ~~PPM~~ ppm HCl/$pH_2$ d≈3mm




st27055.11 annealed T=2.4K
st27055.4 as deposited T=2.4K
resolution = 0.05 $cm^{-1}$

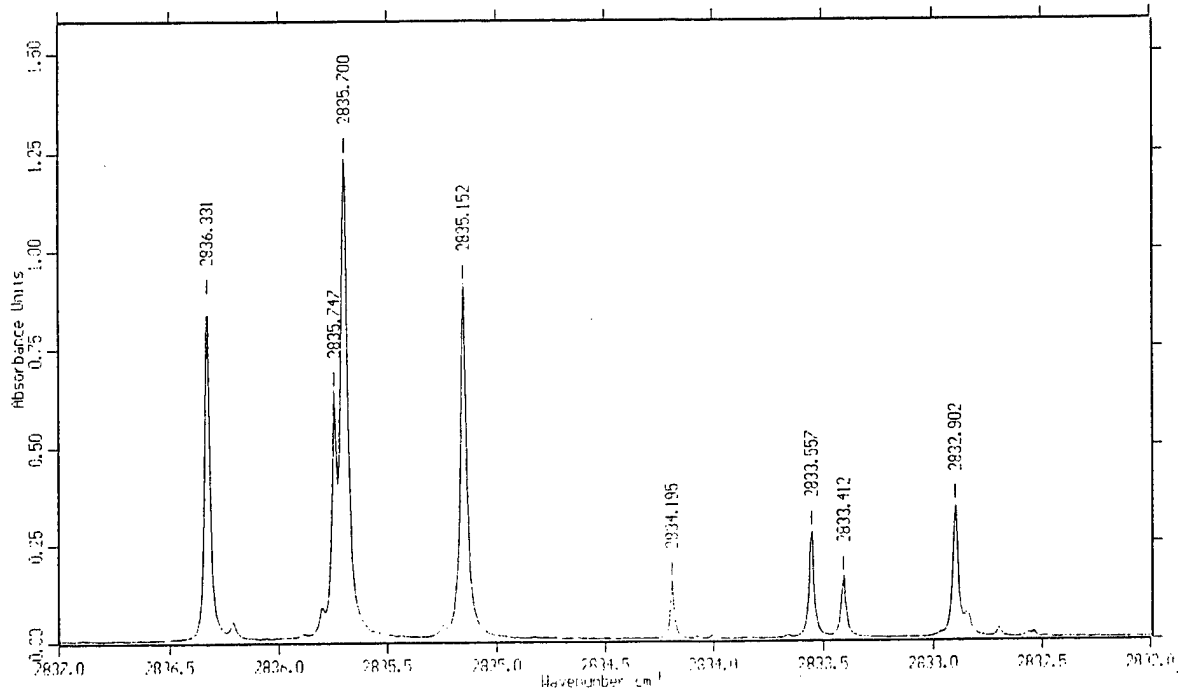
# reversible T dependences




88 PPM HCl
st27061.9 annealing T=4.8K
st27061.11 annealed T=2.4K

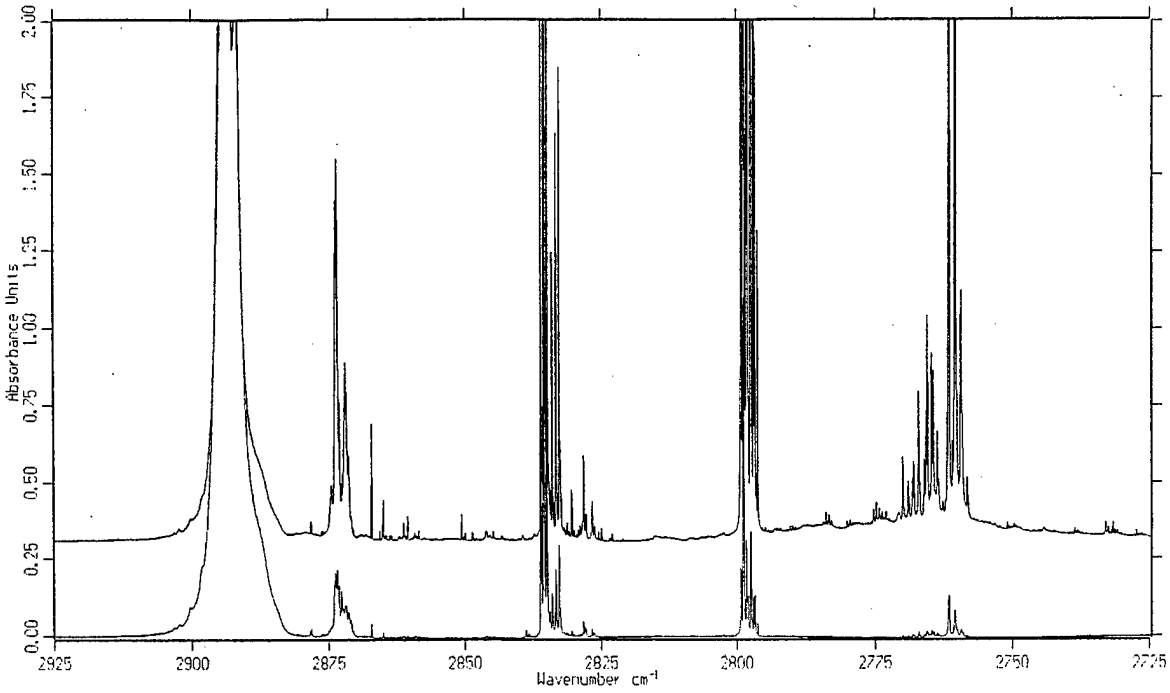
ST27061.9

# $(HCl)_2$ $\nu_2^+$ region




st27061.11 annealed T=2.4K 88 PPM HCl

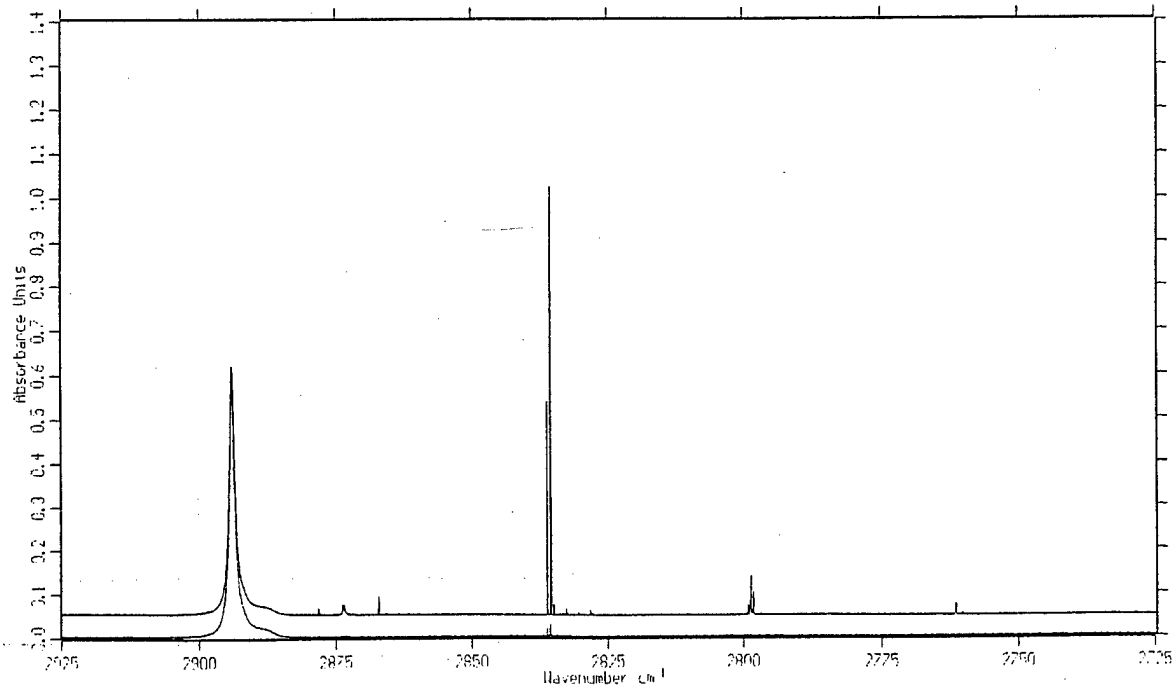
# 494 ~~PPM~~ ppm $HCl/pH_2$ d≈3mm




st27067.10 annealed T=2.4K
st27067.6 as deposited T=2.4K
resolution = 0.0075 $cm^{-1}$

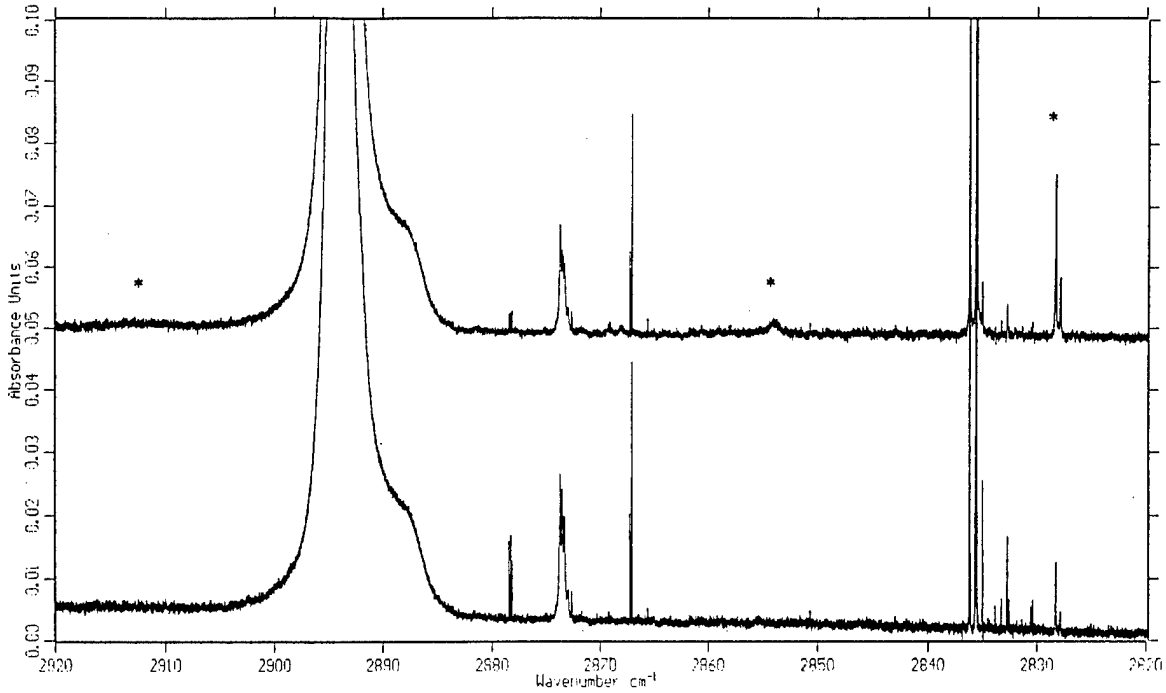
ST27067.6

# 30 ~~PPM~~ ppm $H^{35}Cl/pH_2$ d≈3mm




st27073.17 annealed T=2.4K
st27073.9 as deposited T=2.4K
resolution = 0.005 $cm^{-1}$

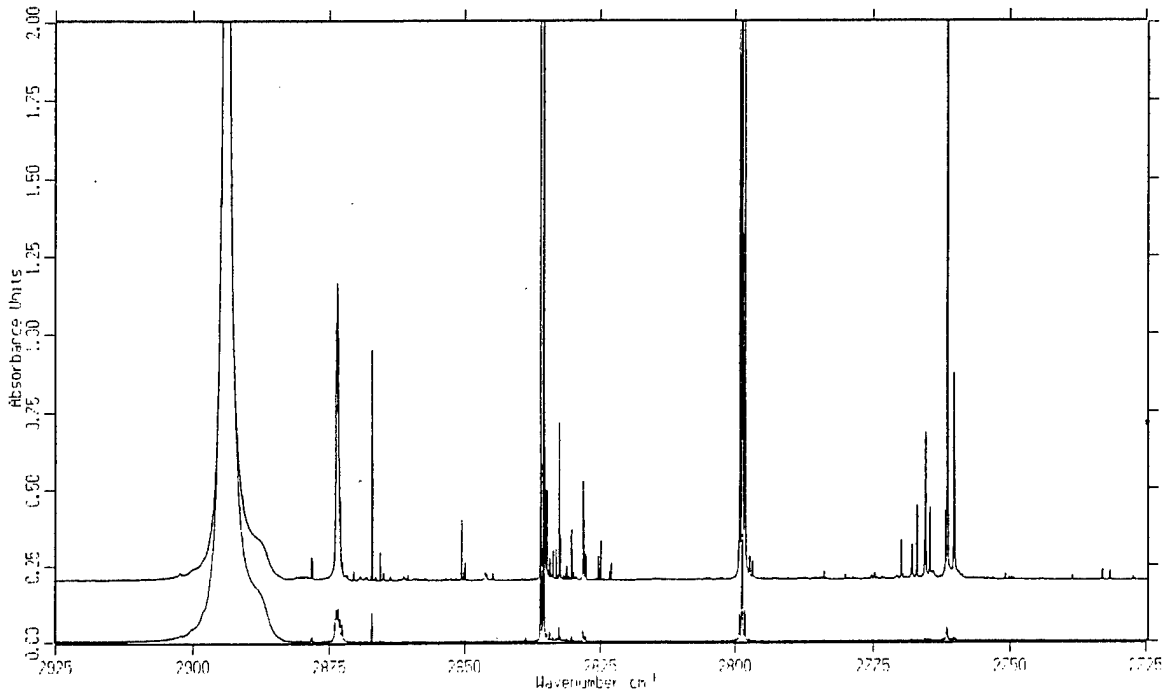
# reversible T dependences




30 PPM $H^{35}Cl$
st27073.11 annealing T=4.8K
st27073.17 annealed T=2.4K

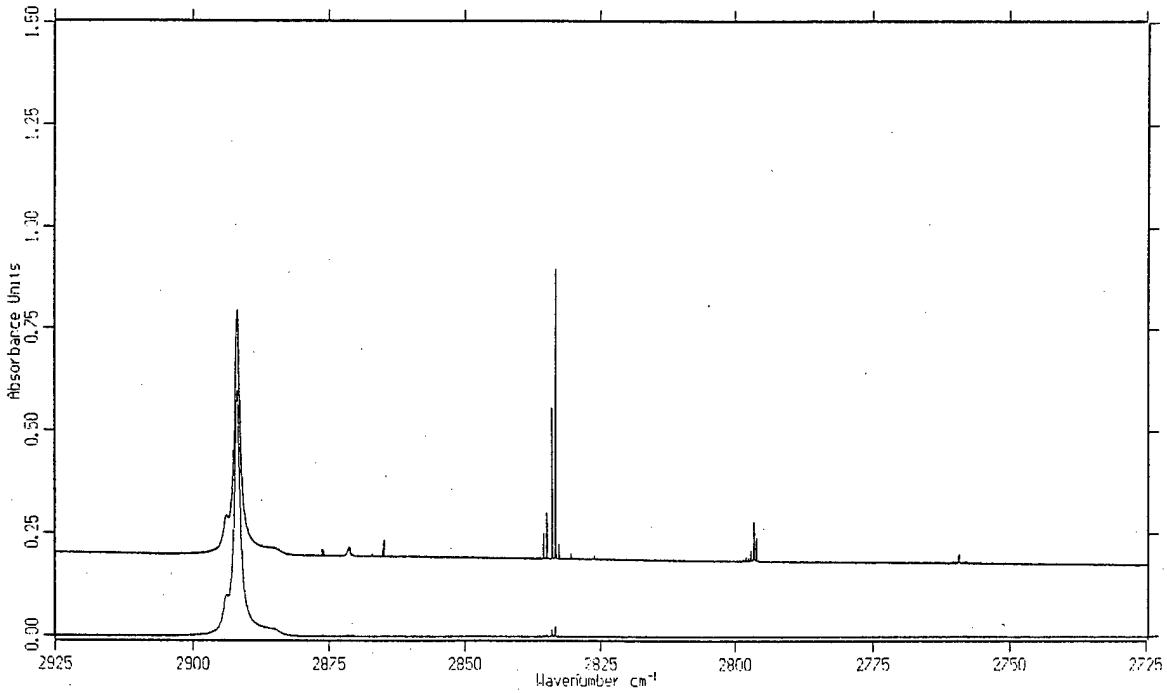
ST27073.11

# 284 ~~PPM~~ ppm $H^{35}Cl/pH_2$ d≈3mm




st27085.9 annealed T=2.4K
st27085.5 as deposited T=2.4K
resolution = 0.005 $cm^{-1}$

# 33 ~~PPM~~ ppm $H^{37}Cl/pH_2$ d≈3mm



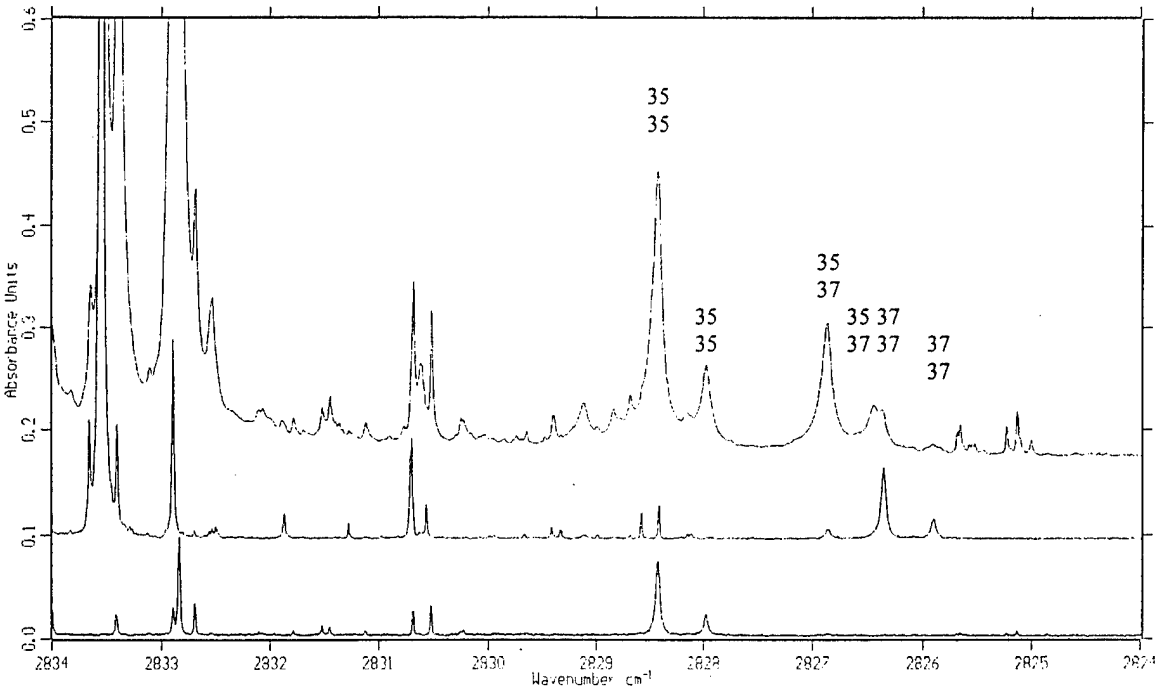

st27097.6 annealed T=2.4K
st27097.2 as deposited T=2.4K
resolution = 0.005 $cm^{-1}$

ST27097.2

# HCl monomer shifts

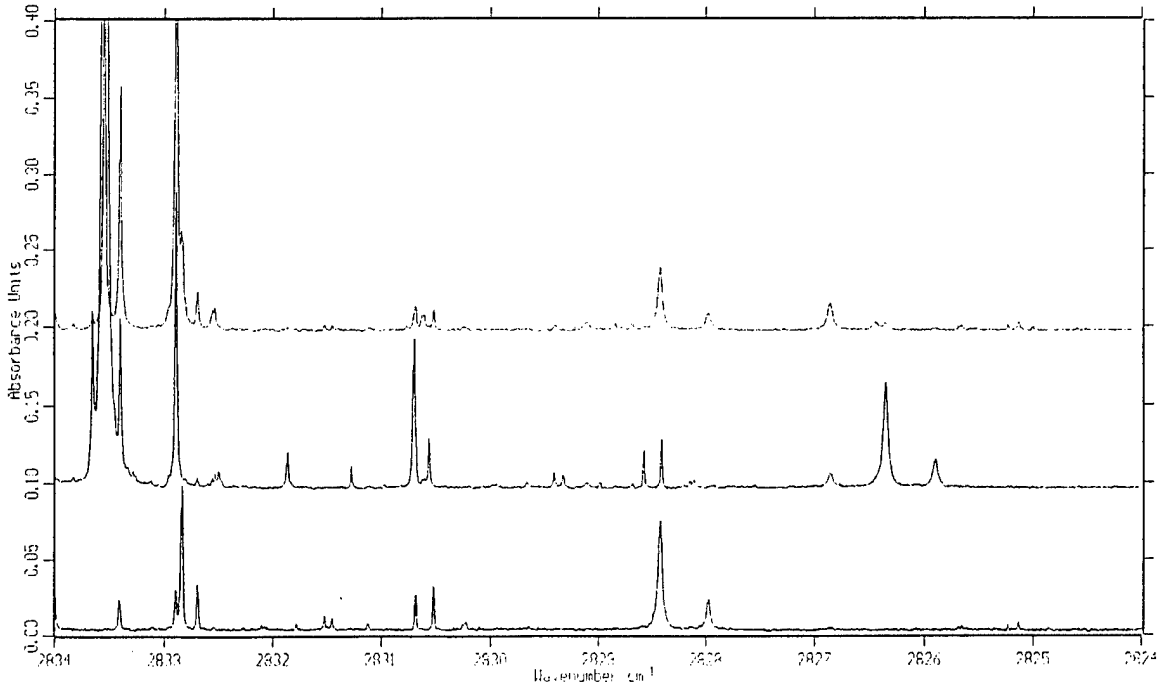
| species | line/band | gas phase ($cm^{-1}$) | solid $pH_2$ | gas-matrix |
|---|---|---|---|---|
| $H^{35}Cl$ | R(1) | 2925.8961 | 2912 | 14 |
| | R(0) | 2906.2464 | 2894.2 | 12.1 |
| | "Q(0)" | 2885.67 | 2873.86 | |
| | | | 2873.67 | 12.0 |
| | | | 2873.46 | |
| | | | 2873.14 | |
| | P(1) | 2865.0977 | 2854.12 | |
| | | | 2853.58 | 11.5 |
| | | | 2852.95 | |
| $H^{37}Cl$ | R(1) | 2923.7315 | 2910.2 | 13.5 |
| | R(0) | 2904.1104 | 2892.1 | 12.0 |
| | "Q(0)" | 2883.57 | 2871.69 | |
| | | | 2871.48 | 12.1 |
| | | | 2871.31 | |
| | | | 2870.97 | |
| | P(1) | 2863.0231 | 2852.07 | |
| | | | 2851.55 | 11.5 |
| | | | 2850.89 | |

# $(HCl)_2$ $\nu_2^-$ region



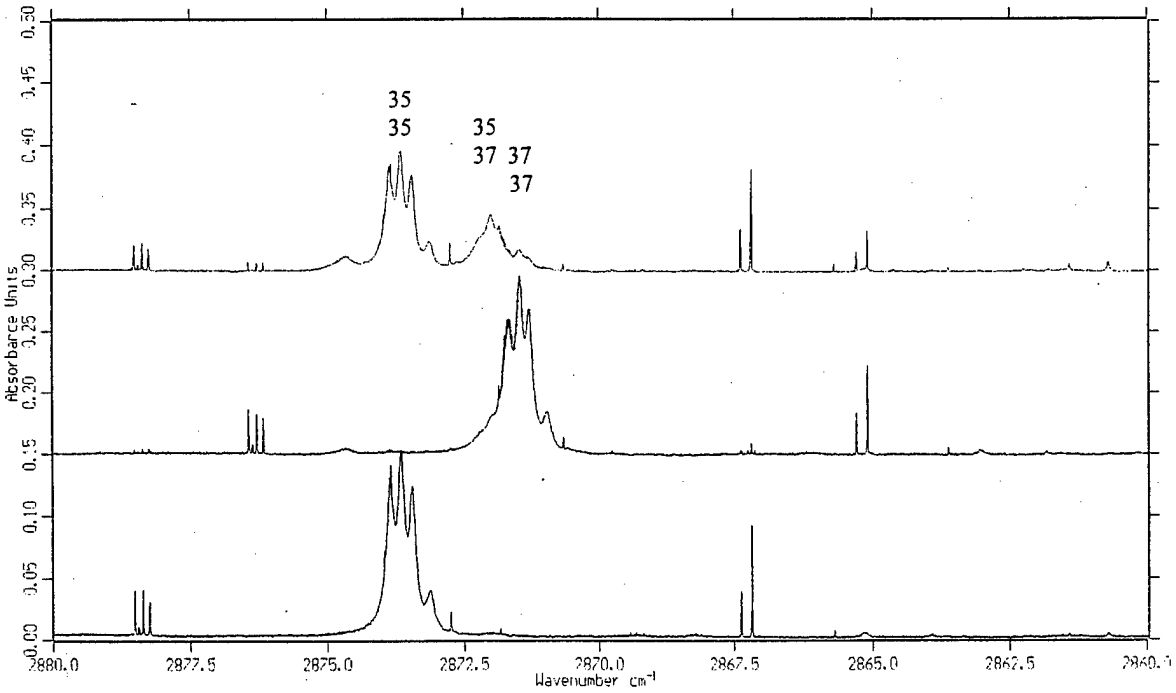

st27067.10 annealed T=2.4K 494 PPM HCl
st27103.6 annealed T=2.4K 94 PPM $H^{37}Cl$
st27079.11 annealed T=2.4K 90 PPM $H^{35}Cl$

# $(HCl)_2$ $\nu_2^-$ region




st27061.11 annealed T=2.4K 88 PPM HCl
st27103.6 annealed T=2.4K 94 PPM $H^{37}Cl$
st27079.11 annealed T=2.4K 90 PPM $H^{35}Cl$

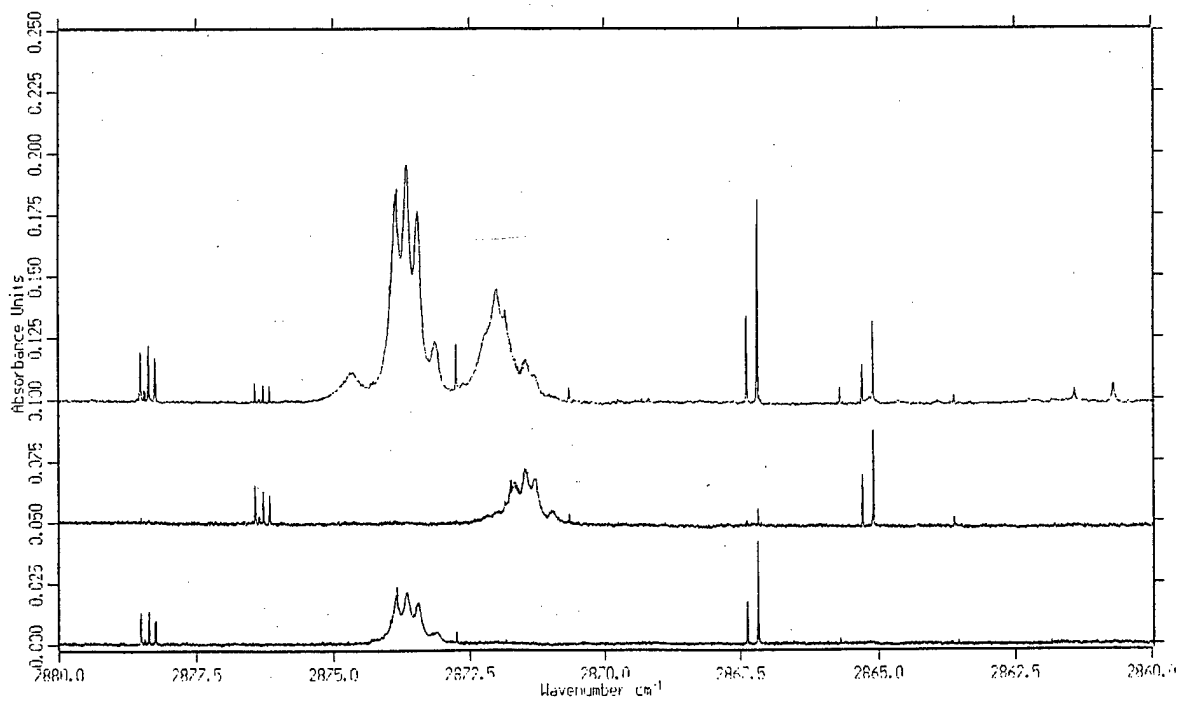
# $(HCl)_2$ $\nu_1^+$ region




st27061.11 annealed T=2.4K 88 PPM HCl
st27103.6 annealed T=2.4K 94 PPM $H^{37}Cl$
st27079.11 annealed T=2.4K 90 PPM $H^{35}Cl$

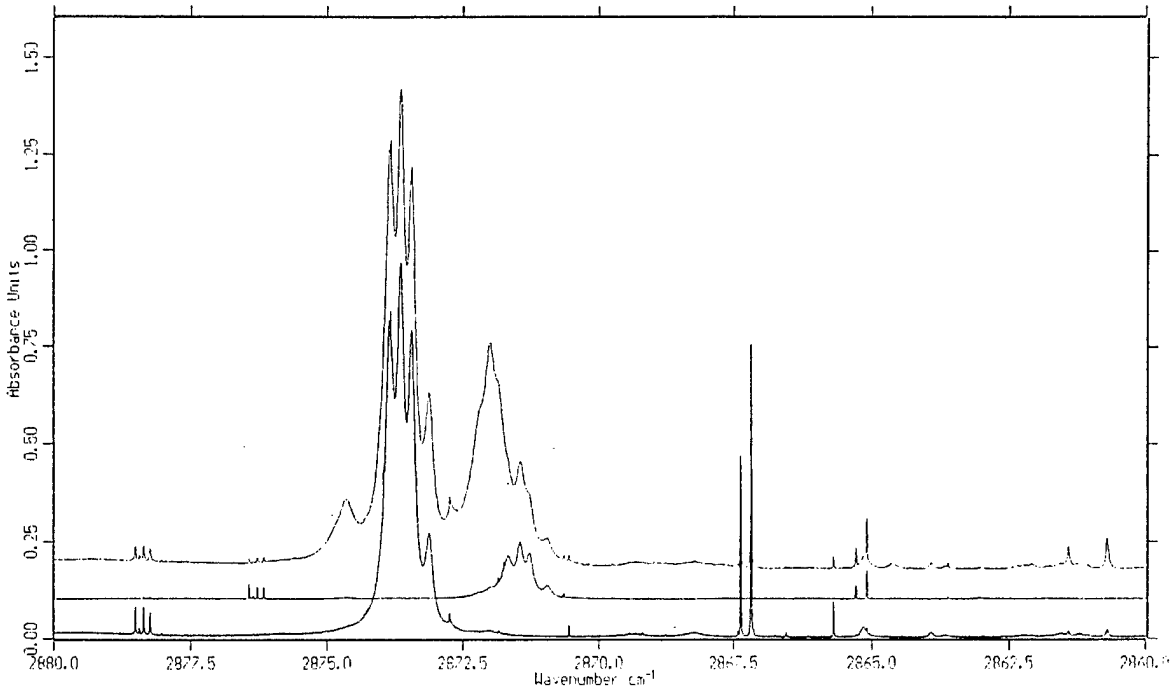
ST27103.6

# $(HCl)_2$ $\nu_1^+$ region



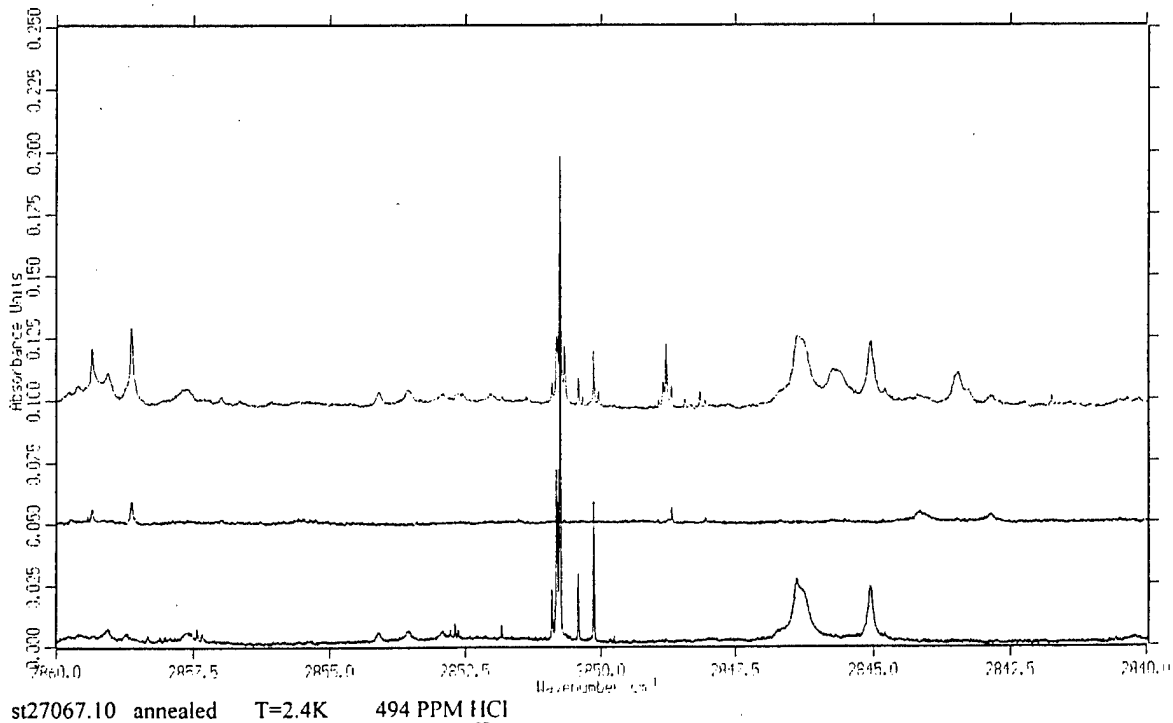

st27061.11 annealed T=2.4K 88 PPM HCl
st27097.6 annealed T=2.4K 33 PPM $H^{37}Cl$
st27073.17 annealed T=2.4K 30 PPM $H^{35}Cl$

# $(HCl)_2$ $\nu_1^+$ region



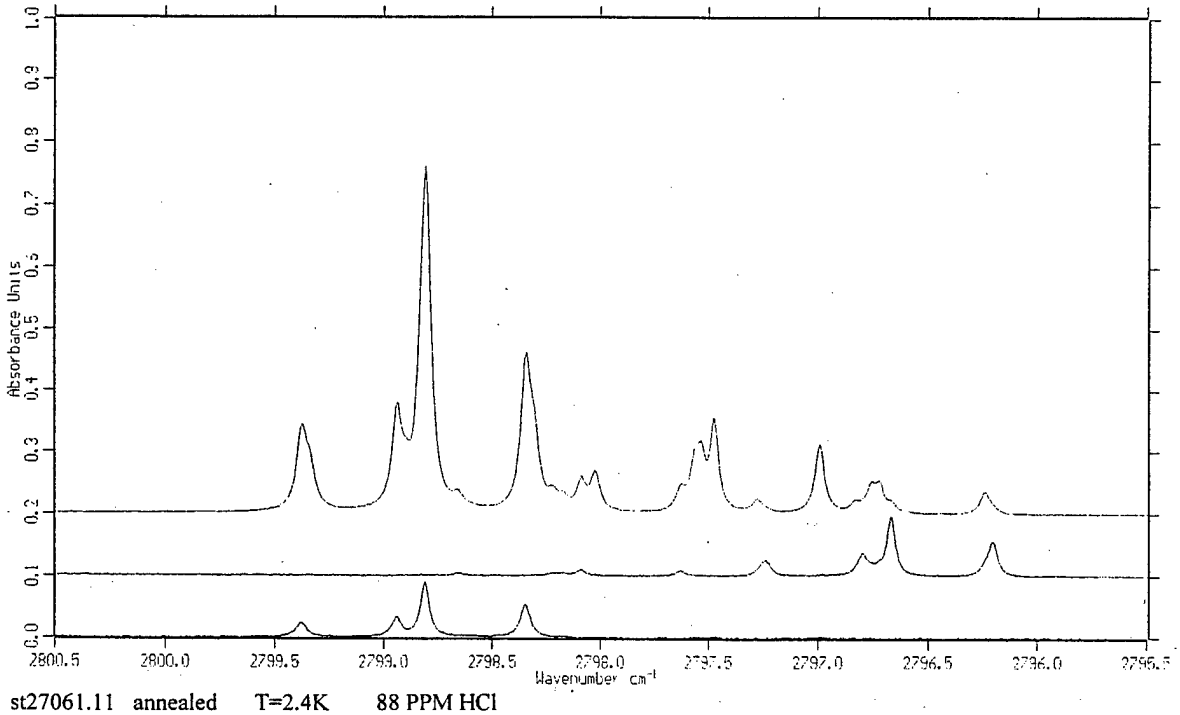

st27067.10 annealed T=2.4K 494 PPM HCl
st27103.6 annealed T=2.4K 94 PPM $H^{37}Cl$
st27085.9 annealed T=2.4K 284 PPM $H^{35}Cl$

# $(HCl)_n$




st27067.10 annealed T=2.4K 494 PPM HCl
st27103.6 annealed T=2.4K 94 PPM $H^{37}Cl$
st27085.9 annealed T=2.4K 284 PPM $H^{35}Cl$

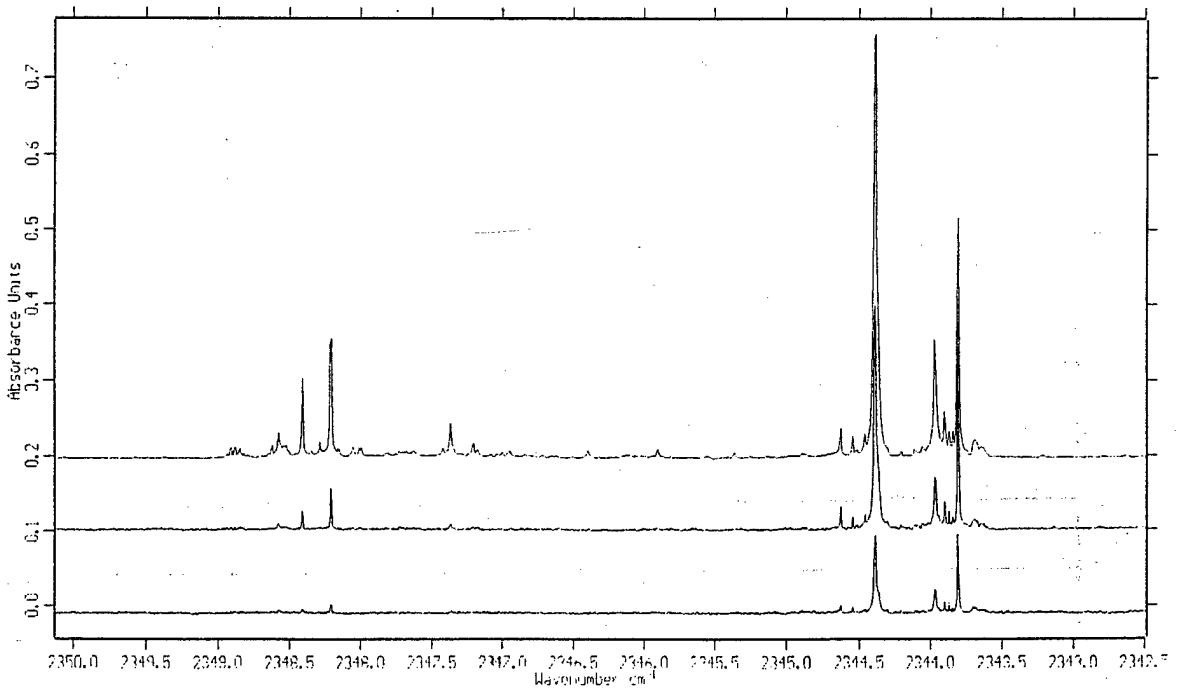
# $(HCl)_3$




st27061.11 annealed T=2.4K 88 PPM HCl
st27097.6 annealed T=2.4K 33 PPM $H^{37}Cl$
st27073.17 annealed T=2.4K 30 PPM $H^{35}Cl$

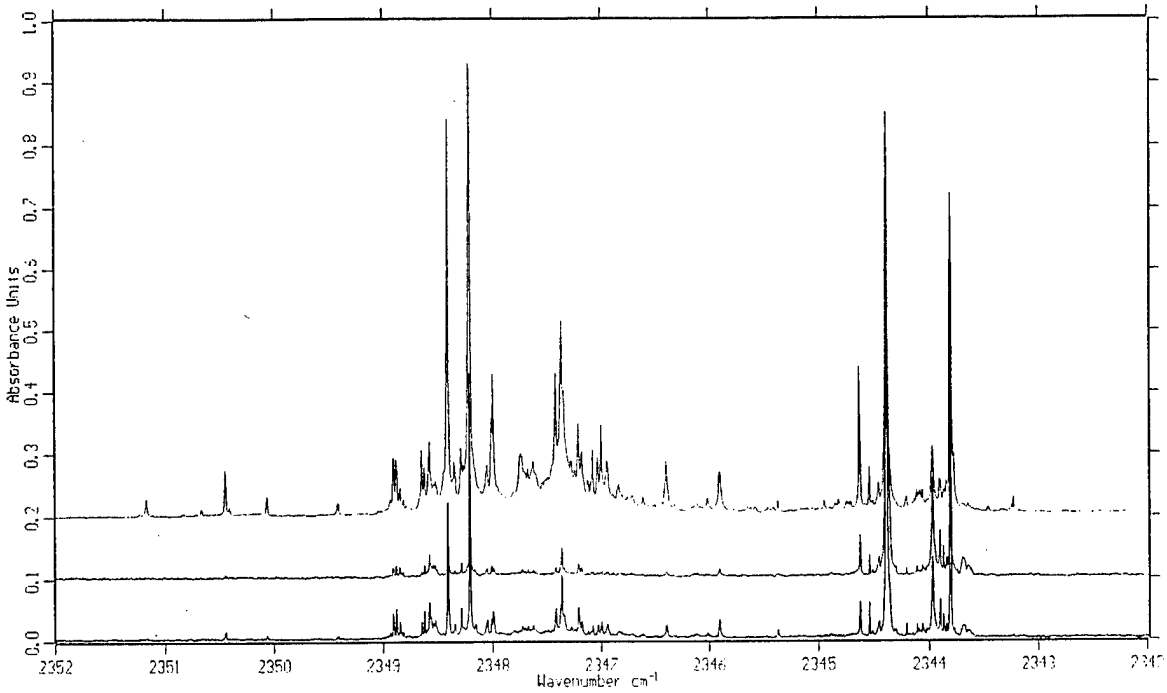
ST27061.11

# $\nu_3$ $CO_2/(HCl)_n$ clusters



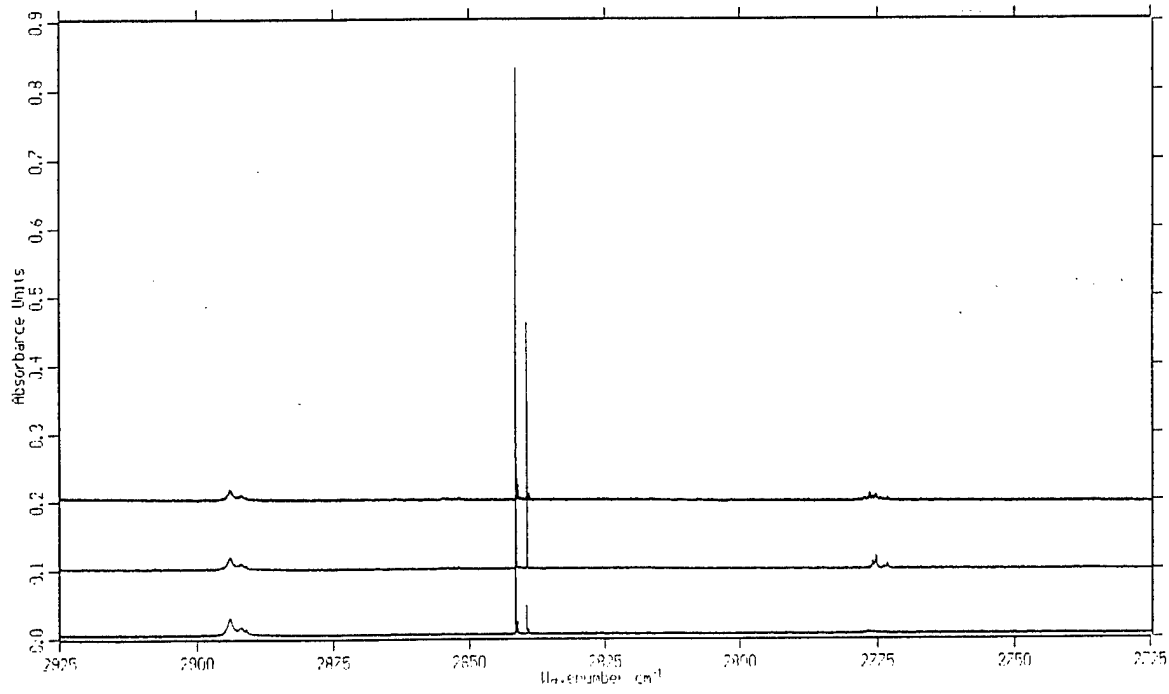

st27061.11 annealed T=2.4K 88 PPM HCl
st27097.6 annealed T=2.4K 33 PPM $H^{37}Cl$
st27073.17 annealed T=2.4K 30 PPM $H^{35}Cl$

# $\nu_3$ $CO_2/(HCl)_n$ clusters



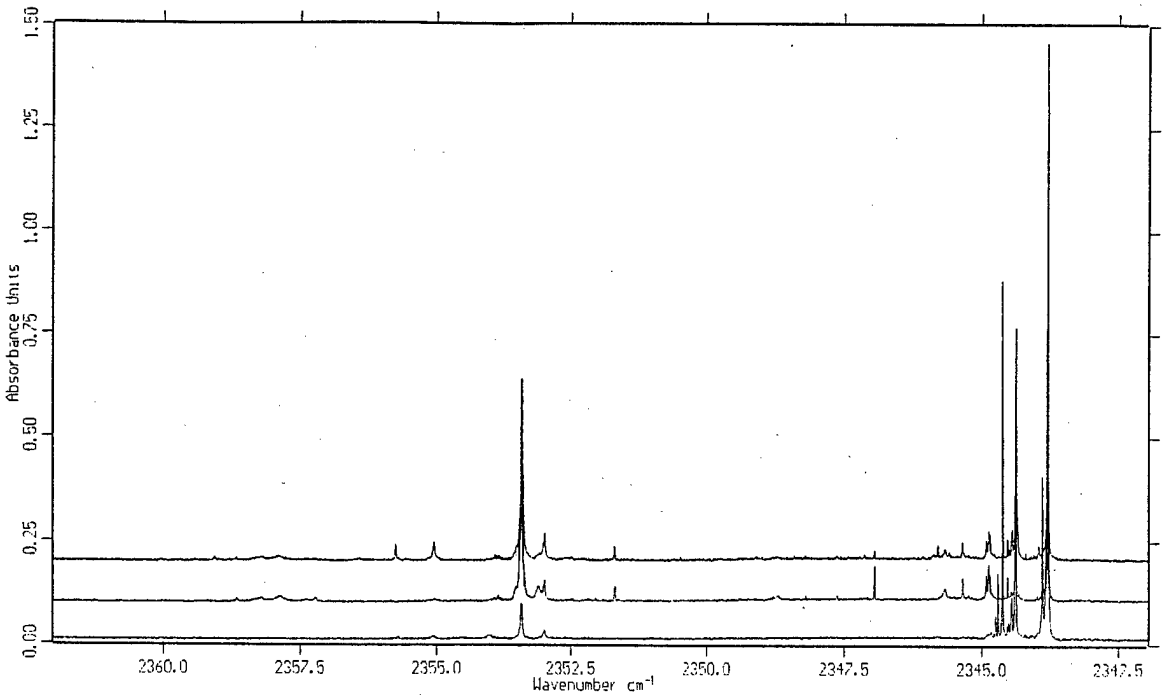

st27067.10 annealed T=2.4K 494 PPM HCl
st27103.6 annealed T=2.4K 94 PPM $H^{37}Cl$
st27085.9 annealed T=2.4K 284 PPM $H^{35}Cl$

# HF-HCl/$pH_2$




st27115.15 annealed T=2.4K
st27115.13 annealing T=4.8K
st27115.9 as deposited T=2.4K 123 PPM HF/$pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

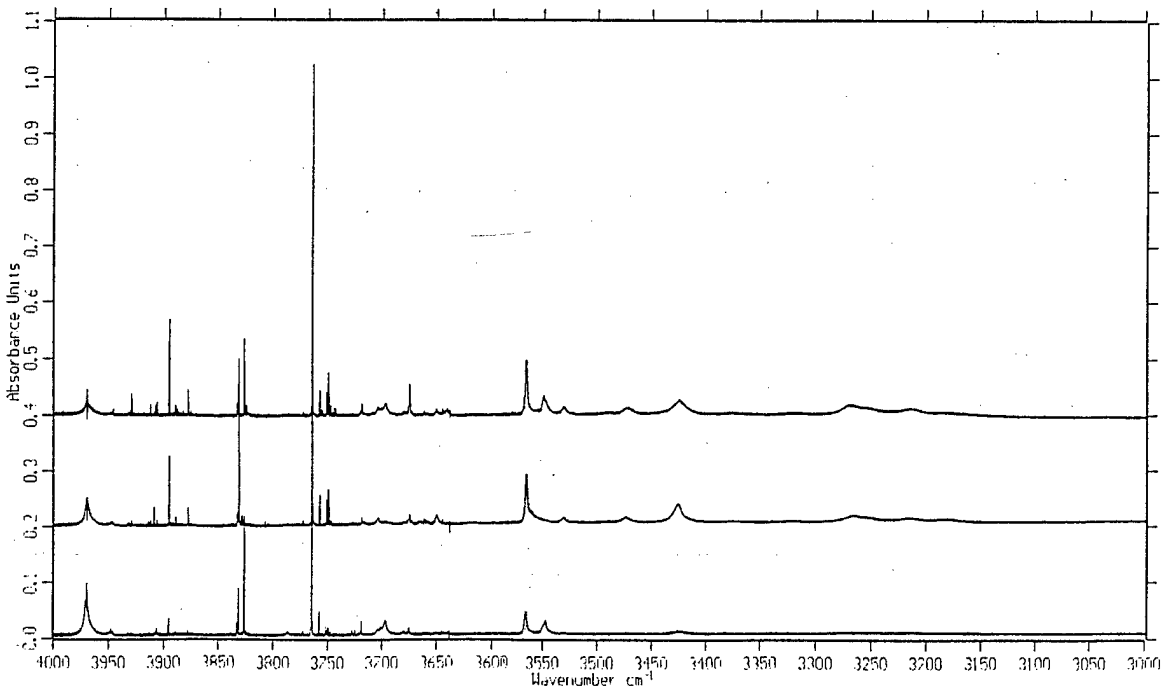
# $CO_2$-HF/$pH_2$




st27115.15 annealed T=2.4K
st27115.13 annealing T=4.8K
st27115.9 as deposited T=2.4K 123 PPM HF/$pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

ST27115.9

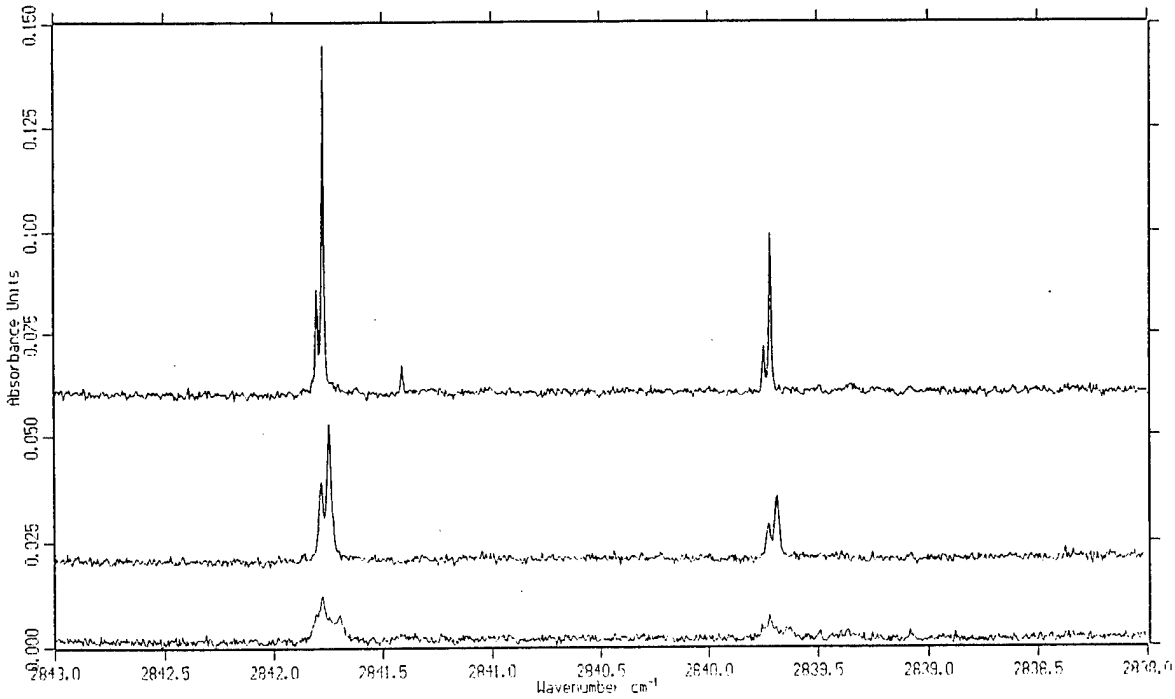
# 27 ~~PPM~~ ppm HF/$pH_2$ d≈3mm




st27121.9 annealed T=2.4K
st27121.7 annealing T=4.8K
st27121.5 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

ST27121.5

# $HF\text{-}HCl/pH_2$



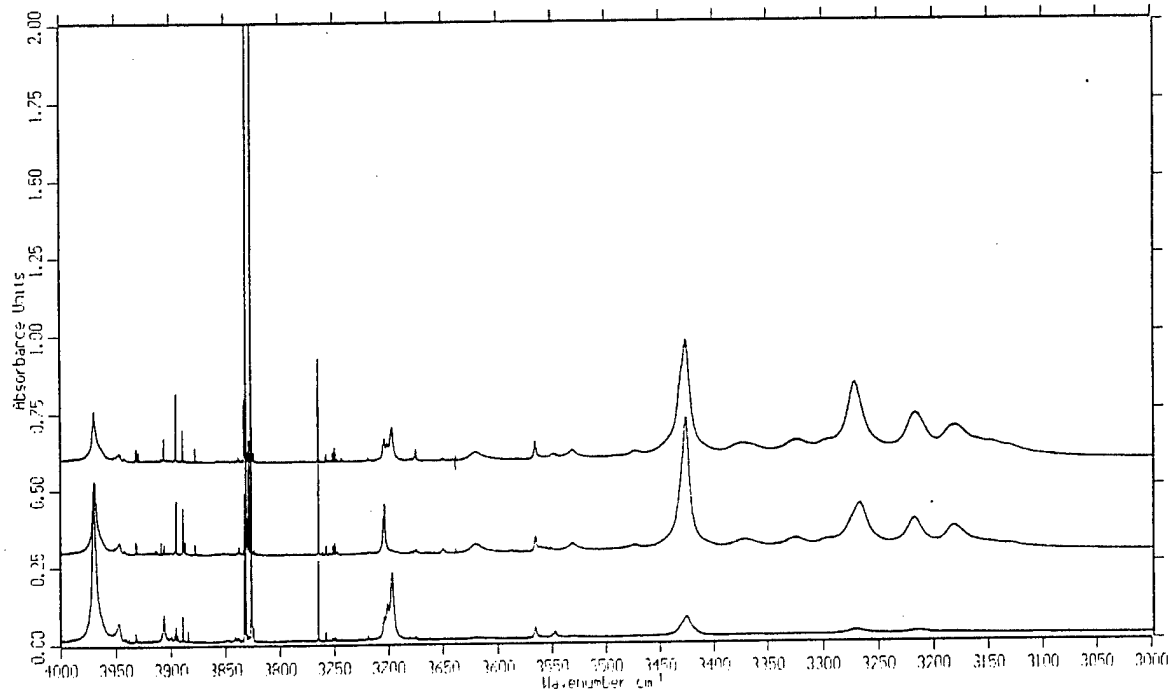

st27121.9 annealed T=2.4K
st27121.7 annealing T=4.8K
st27121.5 as deposited T=2.4K

27 PPM $HF/pH_2$ d≈3mm

resolution = 0.005 $cm^{-1}$

ST27121.5

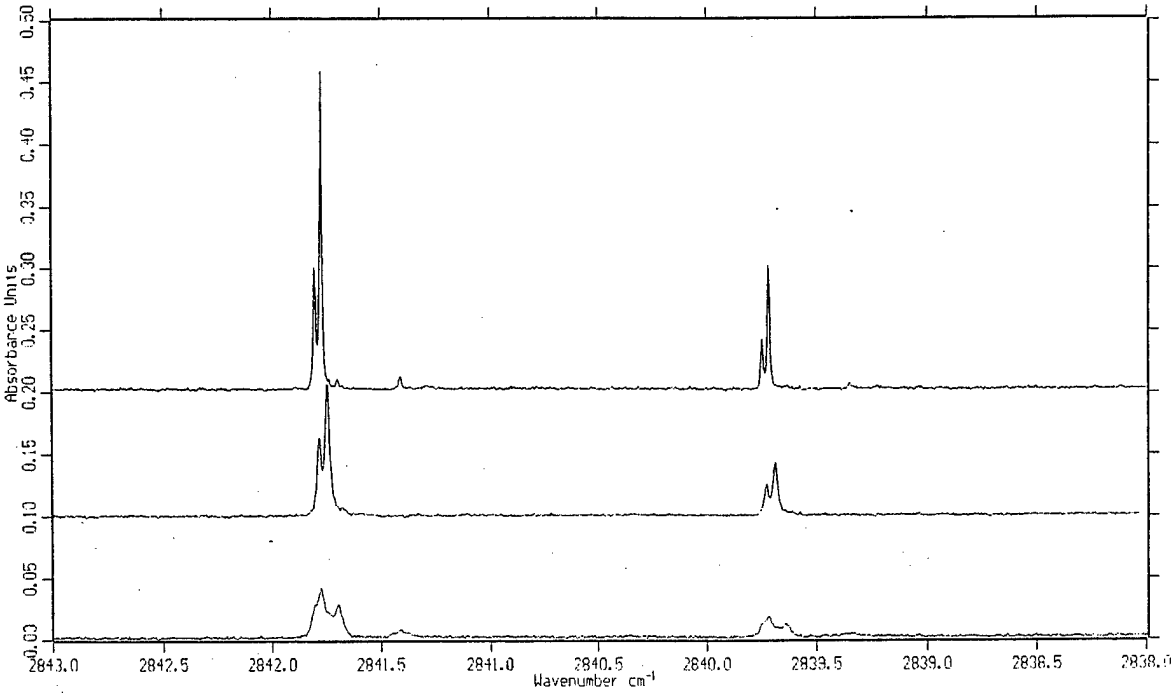
# 91 ~~PPM~~ ppm $HF/pH_2$ d≈3mm




st27127.9 annealed T=2.4K
st27127.7 annealing T=4.8K
st27127.5 as deposited T=2.4K

resolution = 0.005 $cm^{-1}$

# $HF\text{-}HCl/pH_2$



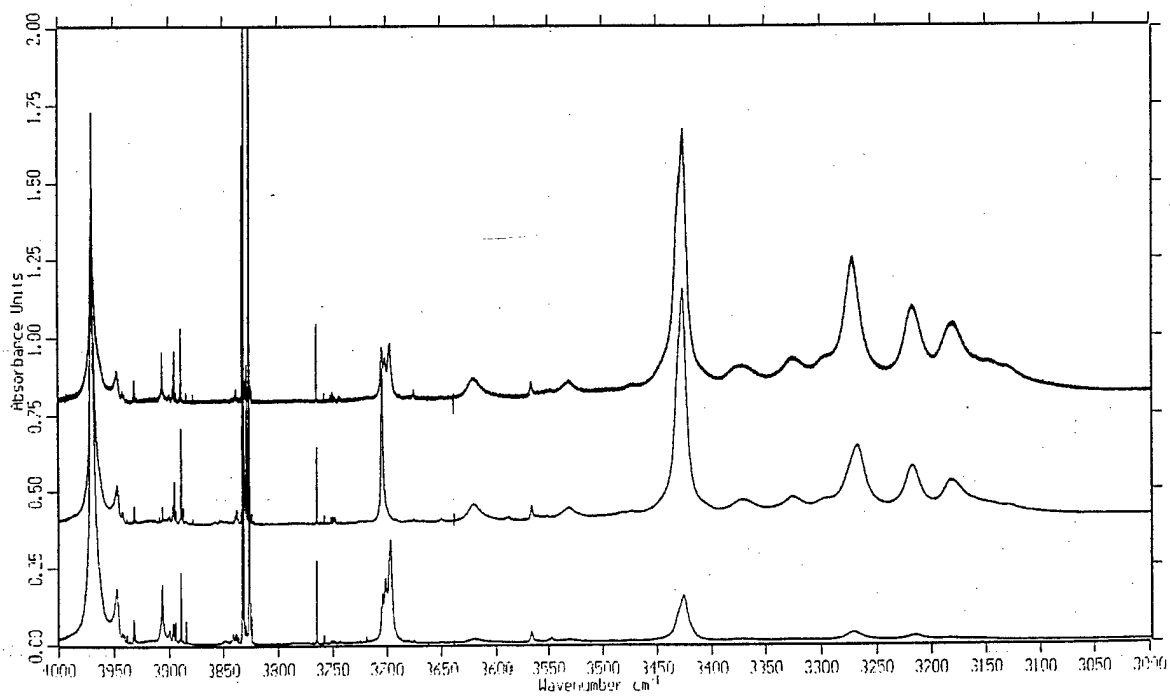

st27127.9 annealed T=2.4K
st27127.7 annealing T=4.8K
st27127.5 as deposited T=2.4K

91 PPM $HF/pH_2$ d≈3mm

resolution = 0.005 $cm^{-1}$

ST27127.5

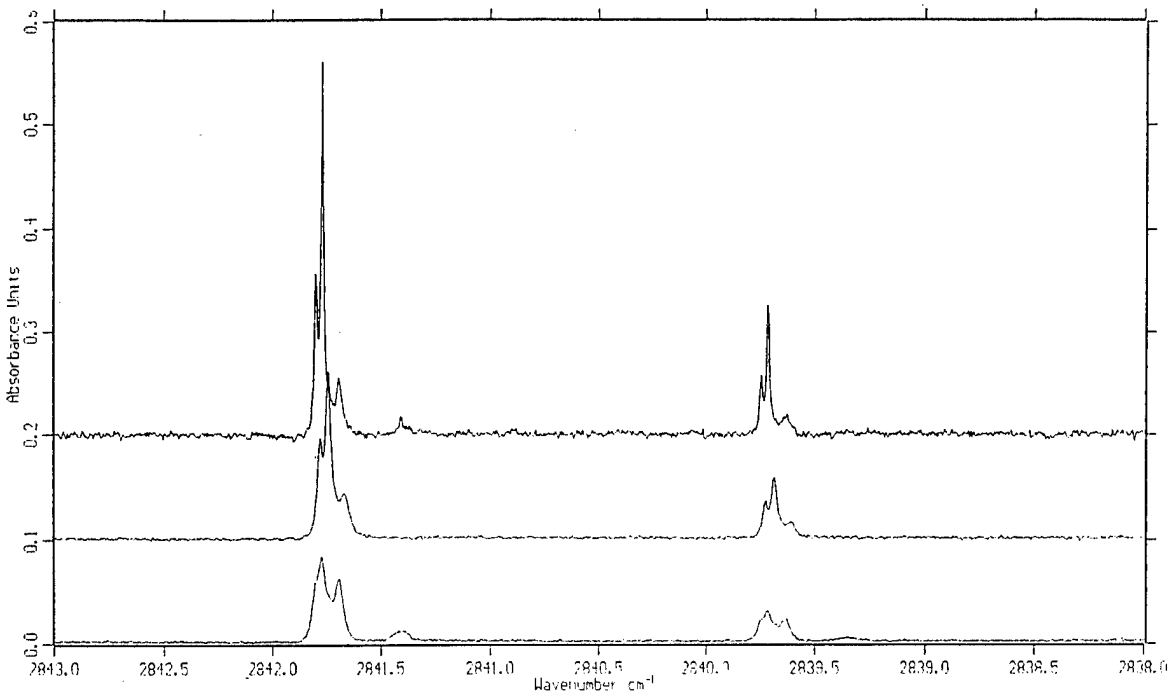
# 268 ~~PPM~~ ppm $HF/pH_2$ d≈3mm




st27133.9 annealed T=2.4K
st27133.7 annealing T=4.8K
st27133.5 as deposited T=2.4K

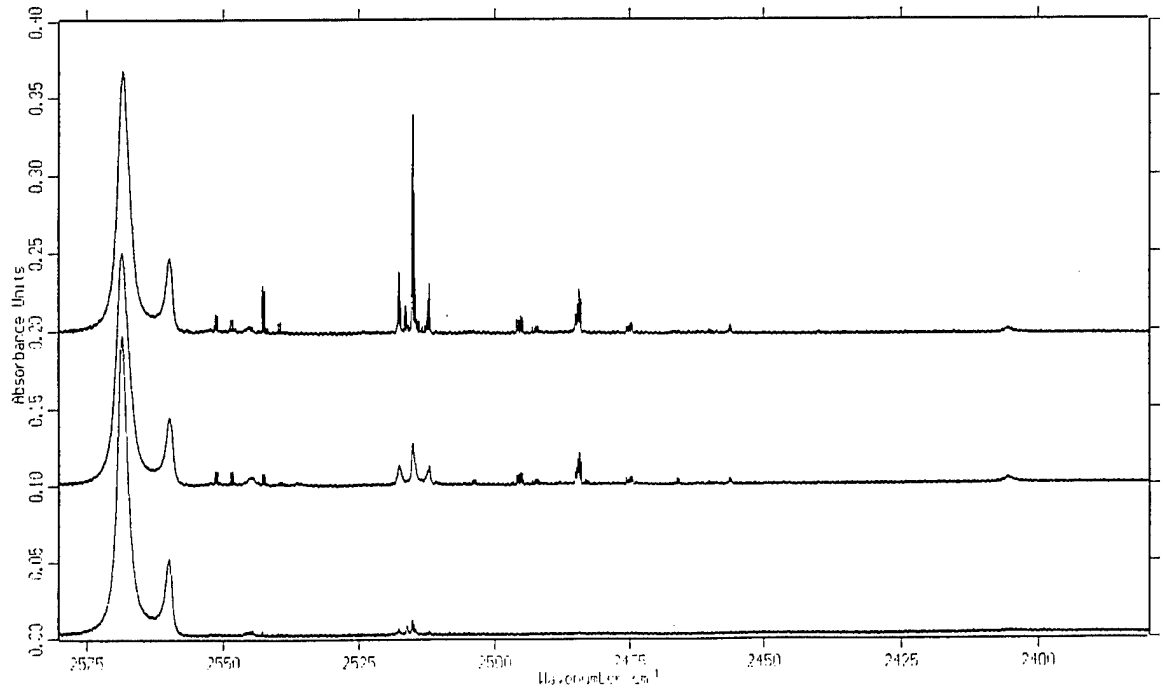
resolution = 0.005 $cm^{-1}$

# HF-HCl/$pH_2$



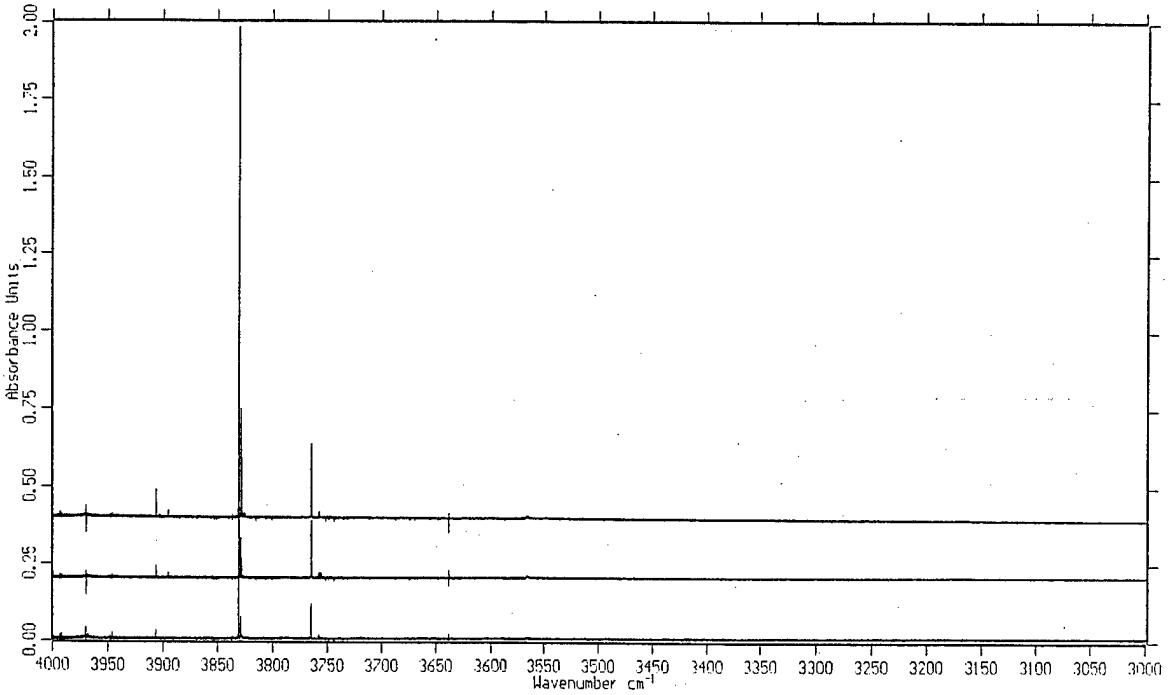

st27133.9 annealed T=2.4K
st27133.7 annealing T=4.8K
st27133.5 as deposited T=2.4K 268 PPM HF/$pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

# 80 ~~PPM~~ ppm HBr/$pH_2$ d≈3mm



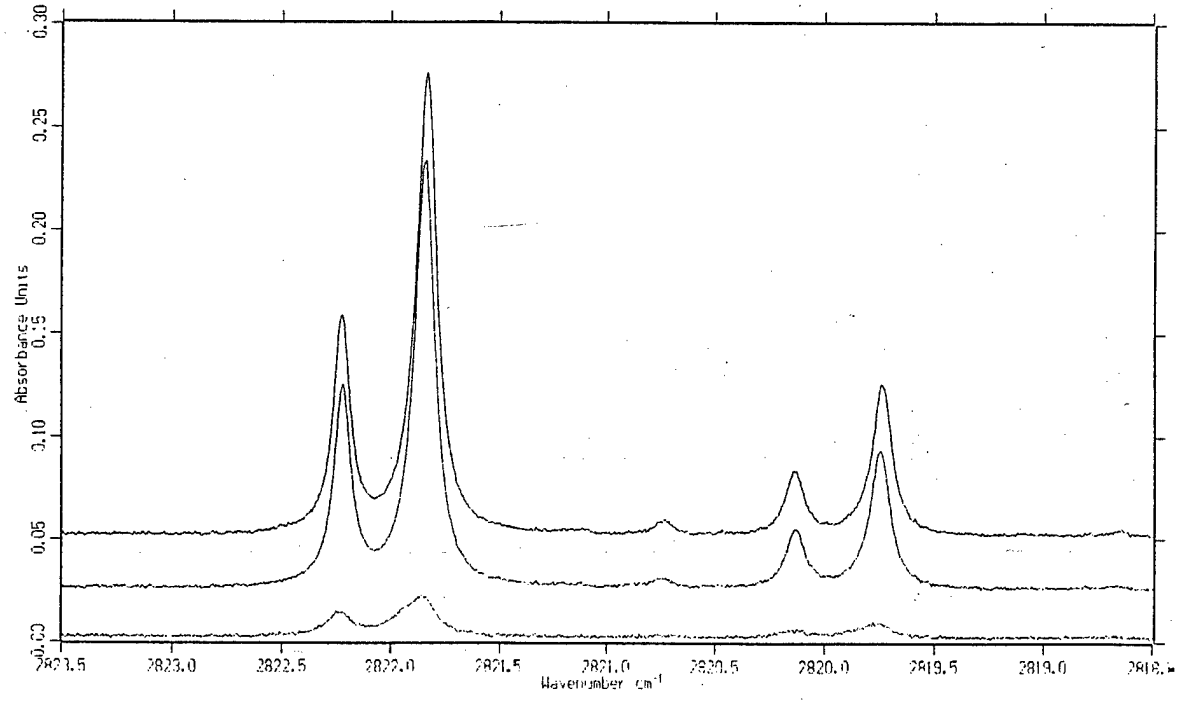

st27140.9 annealed T=2.4K
st27140.7 annealing T=4.8K
st27140.5 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

# HF-(HF, HCl, HBr)/$pH_2$



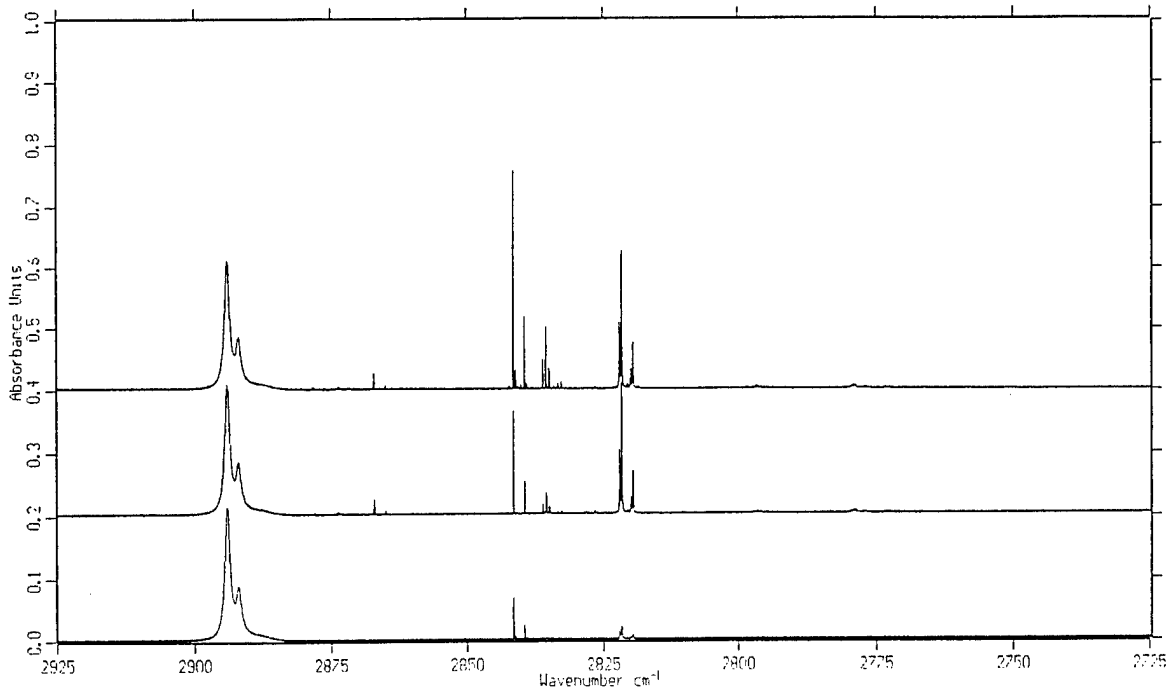

st27140.9 annealed T=2.4K
st27140.7 annealing T=4.8K
st27140.5 as deposited T=2.4K **80** PPM HBr/$pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

# HCl-HBr/$pH_2$




st27140.9 annealed T=2.4K
st27140.7 annealing T=4.8K
st27140.5 as deposited T=2.4K **80** PPM HBr/$pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

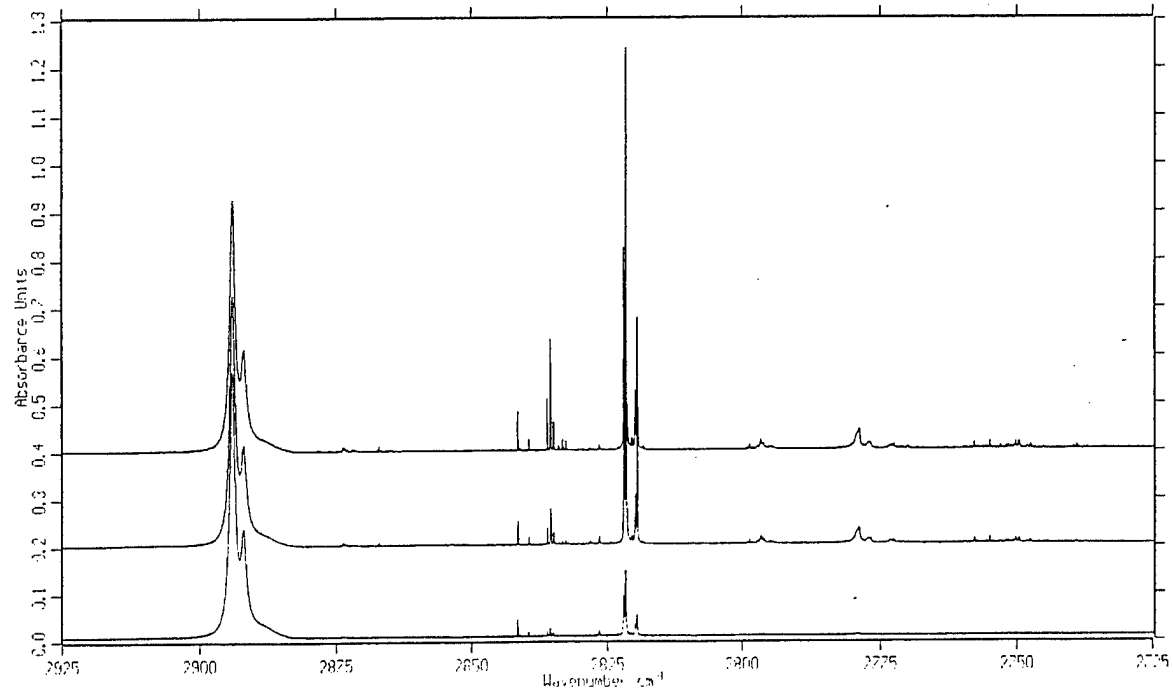
# $HCl-(HF, HCl, HBr)/pH_2$




st27140.9 annealed T=2.4K
st27140.7 annealing T=4.8K
st27140.5 as deposited T=2.4K 80 PPM $HBr/pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

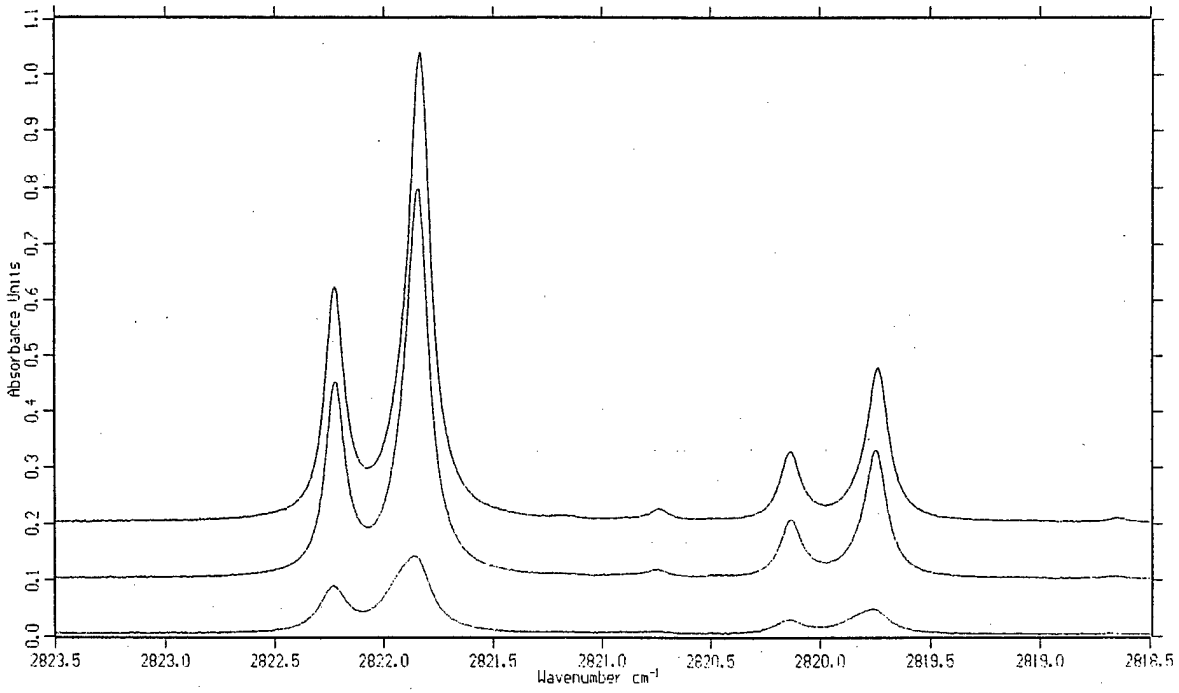
ST27140.5

# $HCl-(HF, HCl, HBr)/pH_2$




st27145.9 annealed T=2.4K
st27145.7 annealing T=4.8K
st27145.5 as deposited T=2.4K 260 PPM $HBr/pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

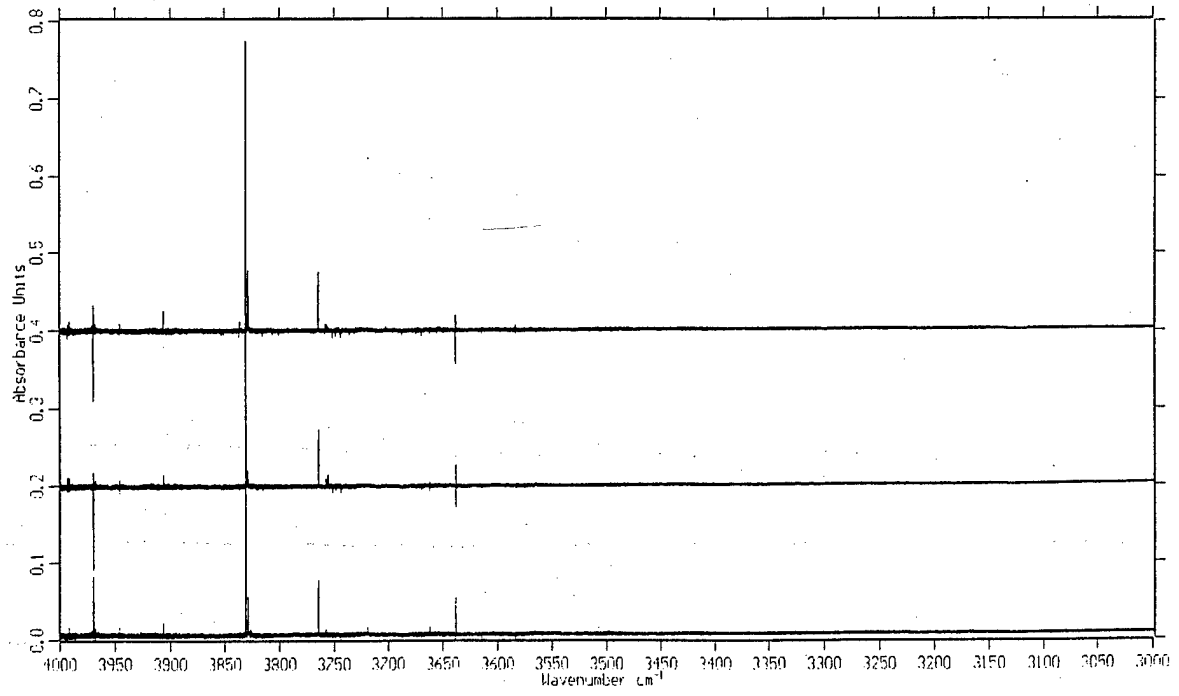
# HCl-HBr/$pH_2$




st27145.9 annealed T=2.4K
st27145.7 annealing T=4.8K
st27145.5 as deposited T=2.4K 250 PPM HBr/$pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

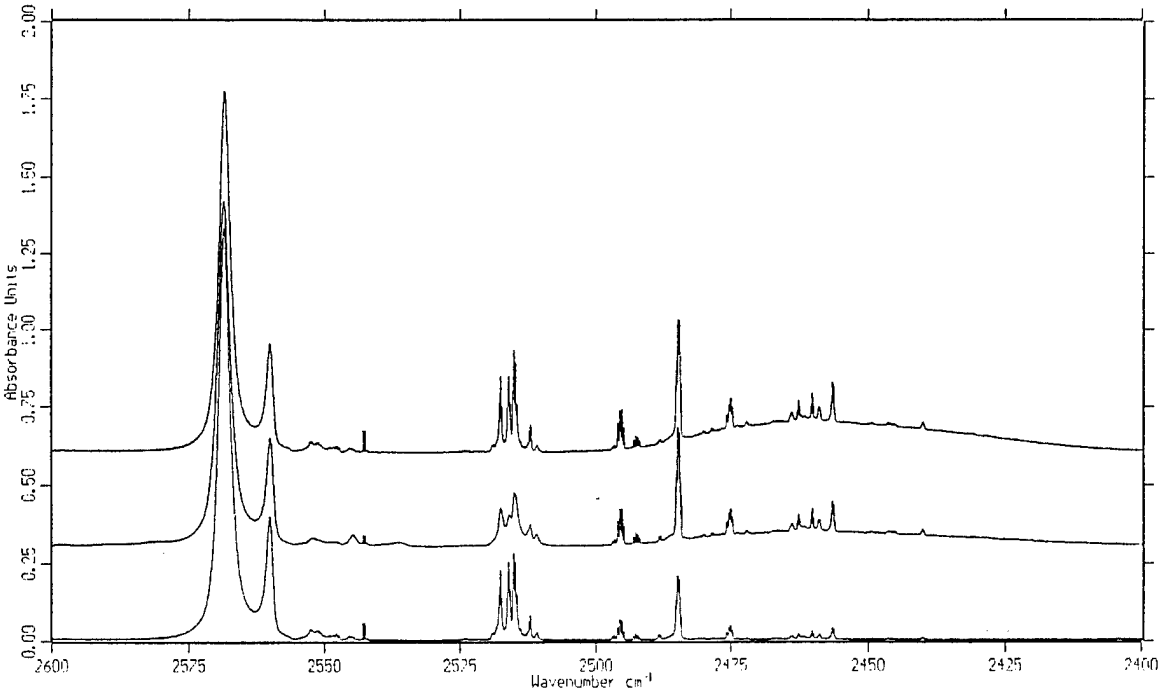
ST27145.5

# HF-(HF, HCl, HBr)/$pH_2$




st27145.9 annealed T=2.4K
st27145.7 annealing T=4.8K
st27145.5 as deposited T=2.4K 260 PPM HBr/$pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

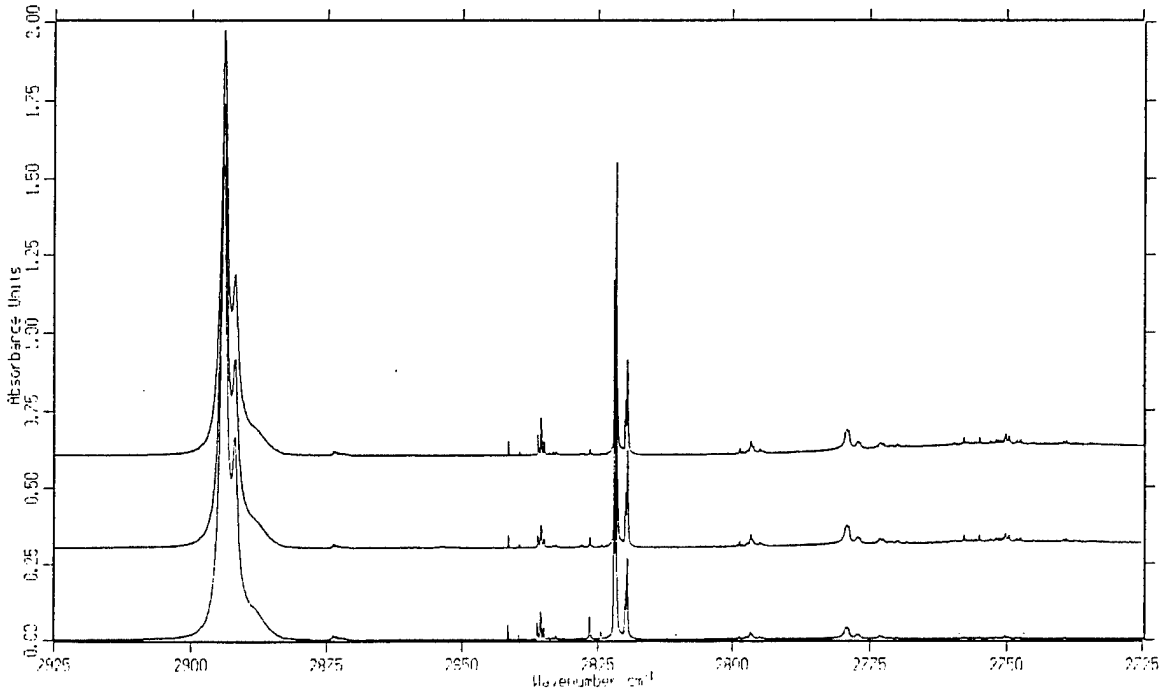
# 645 $HBr/pH_2$ d≈3mm




st28003.9 annealed T=2.4K
st28003.7 annealing T=4.8K
st28003.5 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

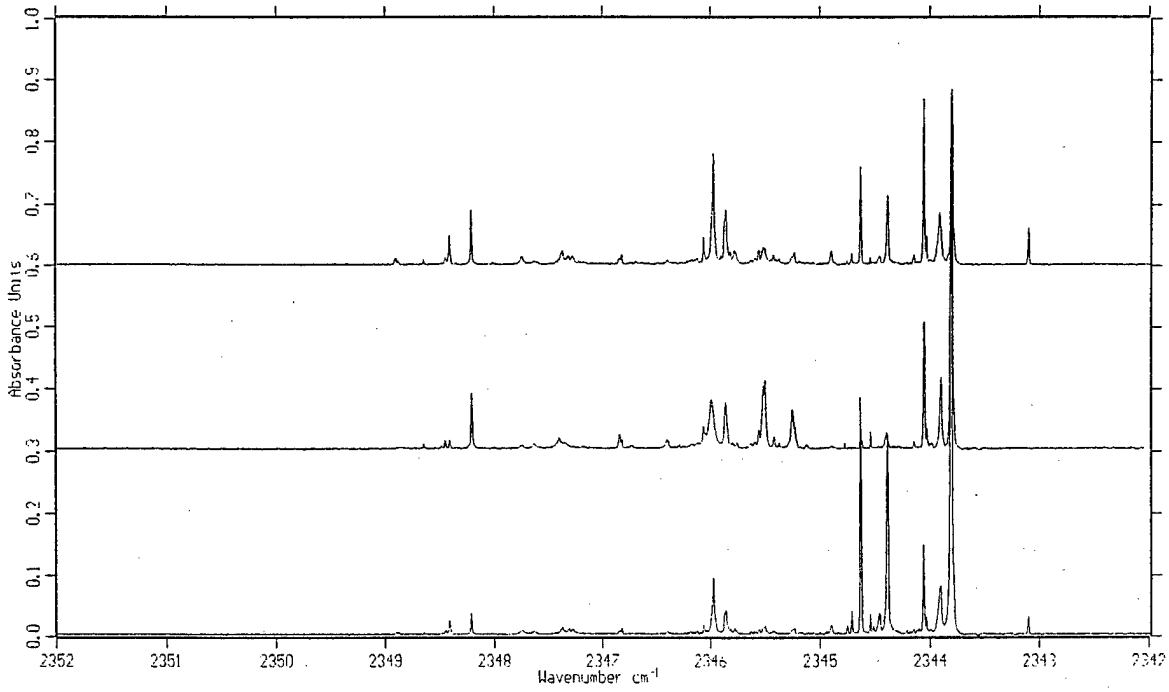
ST28003.5

# $HCl(HBr)_n/pH_2$




st28003.9 annealed T=2.4K
st28003.7 annealing T=4.8K
st28003.5 as deposited T=2.4K 645 $HBr/pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

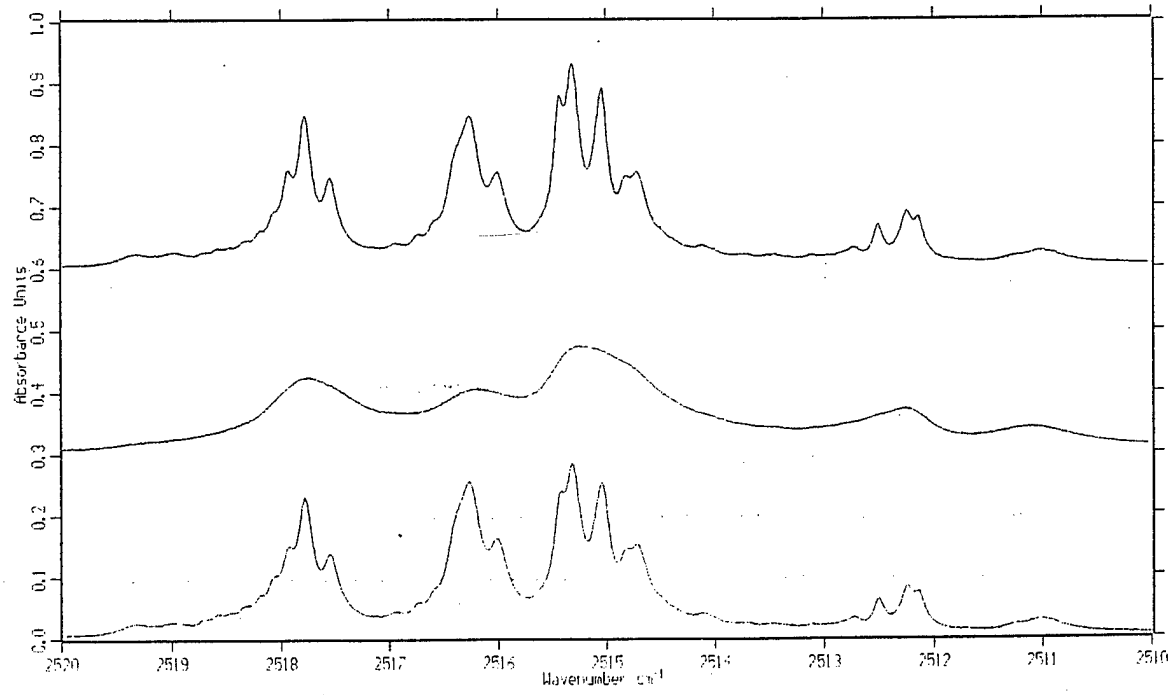
# $CO_2(HBr)_n/pH_2$




st28003.9 annealed T=2.4K
st28003.7 annealing T=4.8K
st28003.5 as deposited T=2.4K 645 $HBr/pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

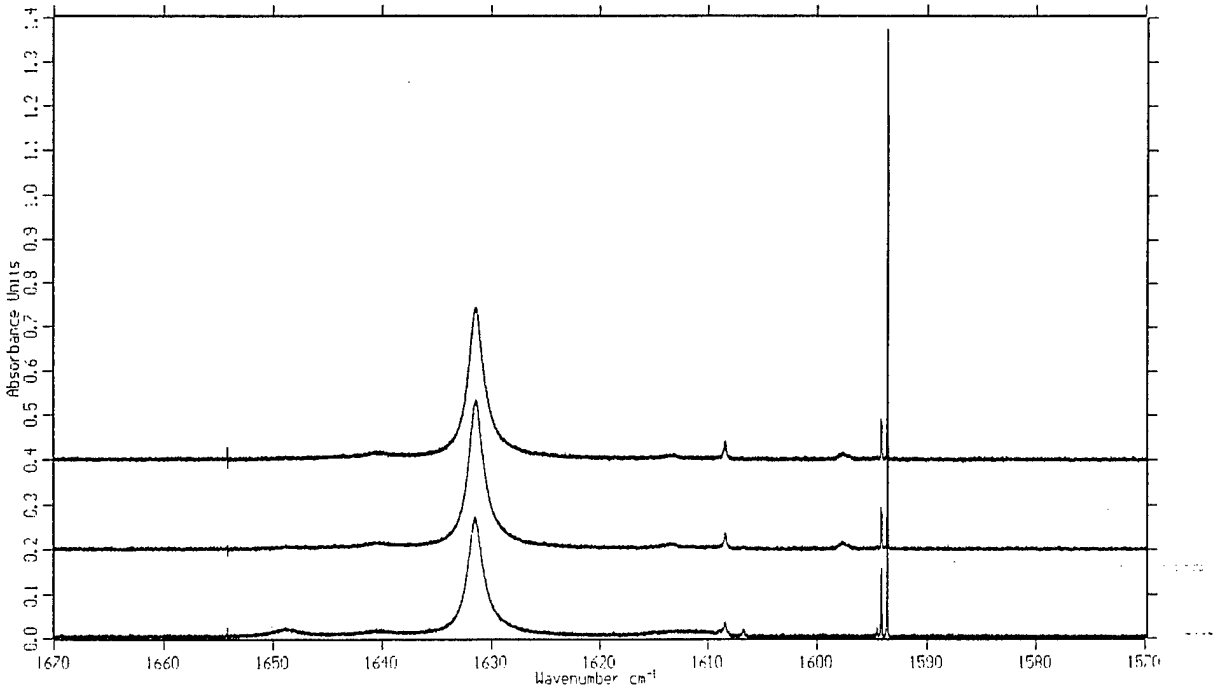
ST28003.5

# $(HBr)_2/pH_2$




st28003.9 annealed T=2.4K
st28003.7 annealing T=4.8K
st28003.5 as deposited T=2.4K 645 $HBr/pH_2$ d≈3mm resolution = 0.005 $cm^{-1}$

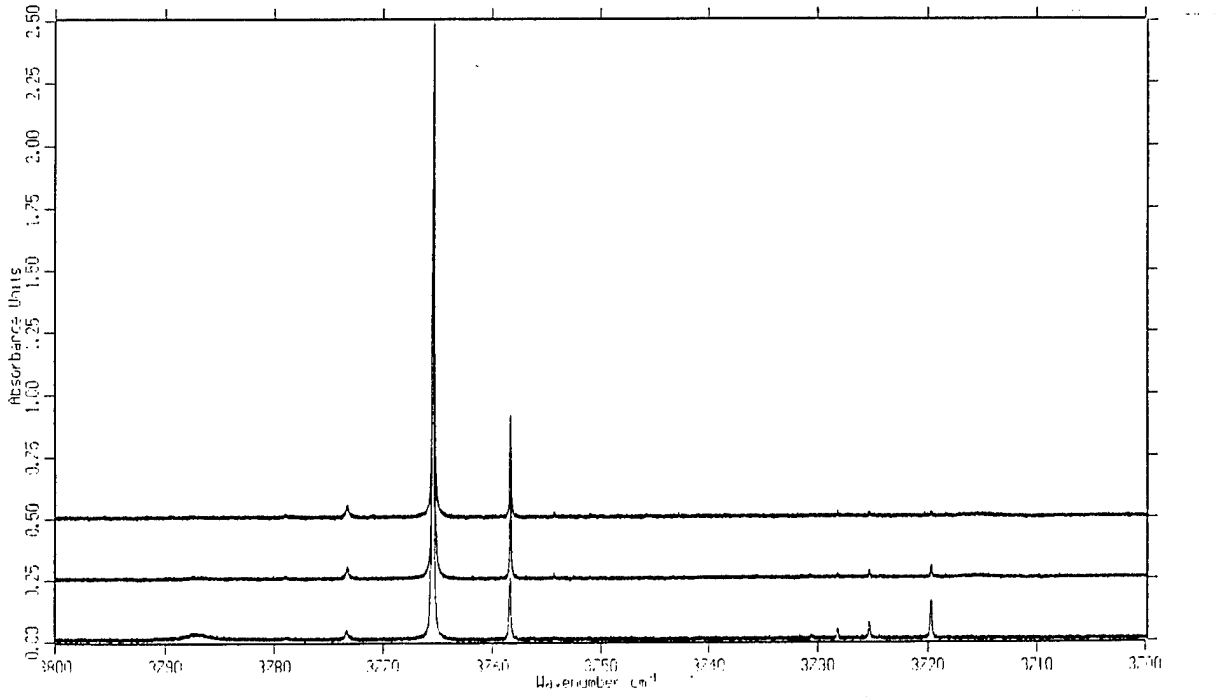
# 15 ~~PPM~~ ppm $H_2O/pH_2$ d≈3mm




st28010.6 annealed T=2.4K
st28010.4 annealing T=4.8K
st28010.2 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

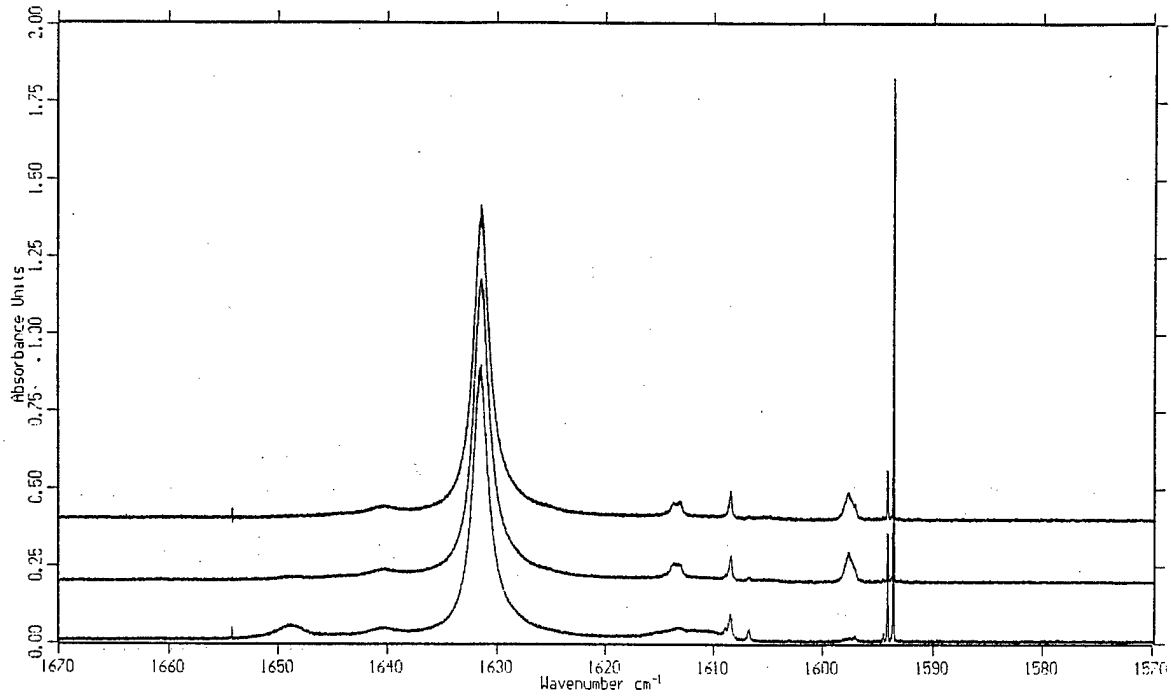
ST28010.2

# 15 ~~PPM~~ ppm $H_2O/pH_2$ d≈3mm




st28010.6 annealed T=2.4K
st28010.4 annealing T=4.8K
st28010.2 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

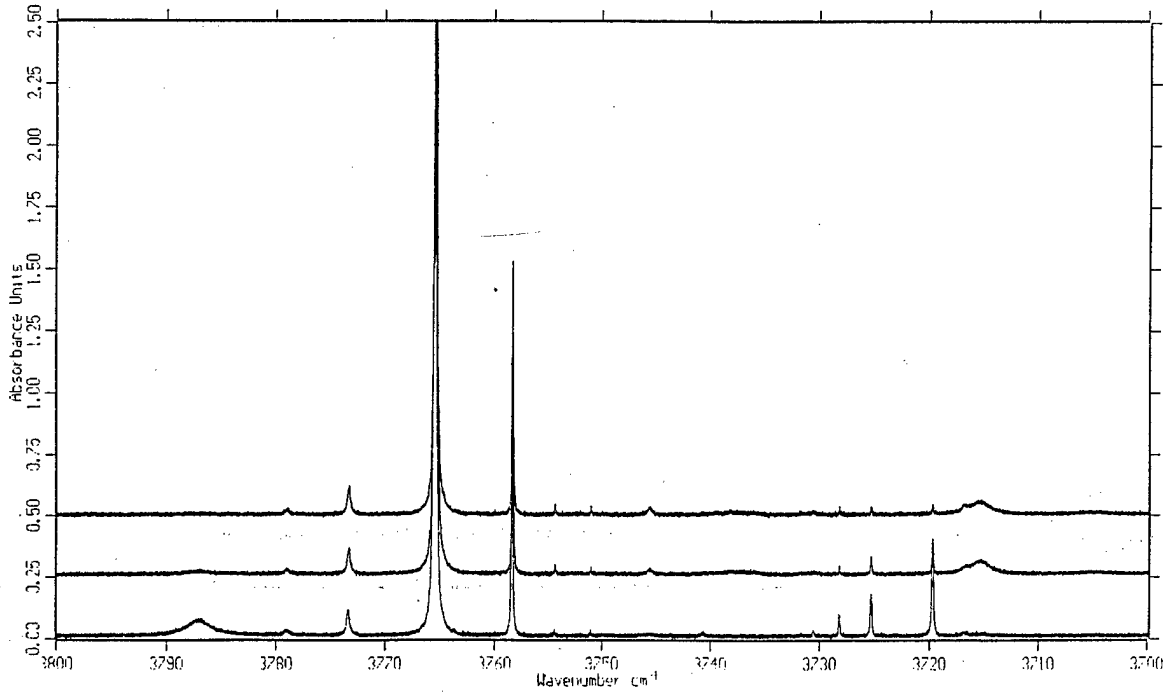
# 45 ~~PPM~~ ppm $H_2O/pH_2$ d≈3mm




st28014.6 annealed T=2.4K
st28014.4 annealing T=4.8K
st28014.2 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

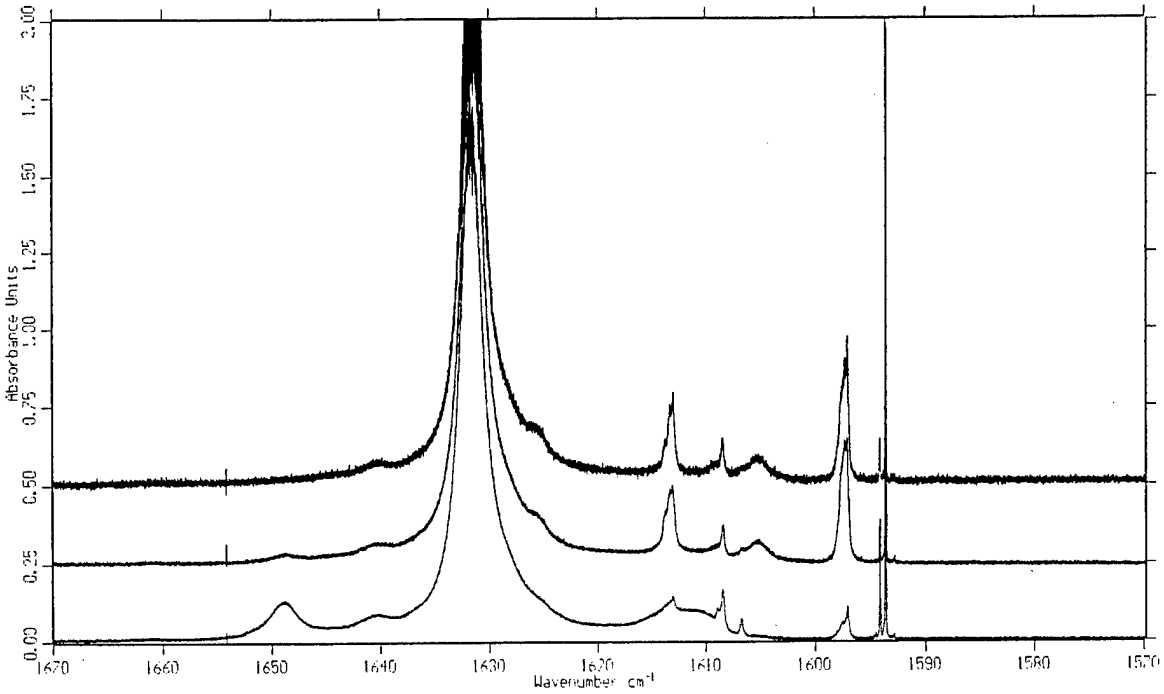
ST28014.2

# 45 ~~PPM~~ ppm $H_2O/pH_2$ d≈3mm




st28014.6 annealed T=2.4K
st28014.4 annealing T=4.8K
st28014.2 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

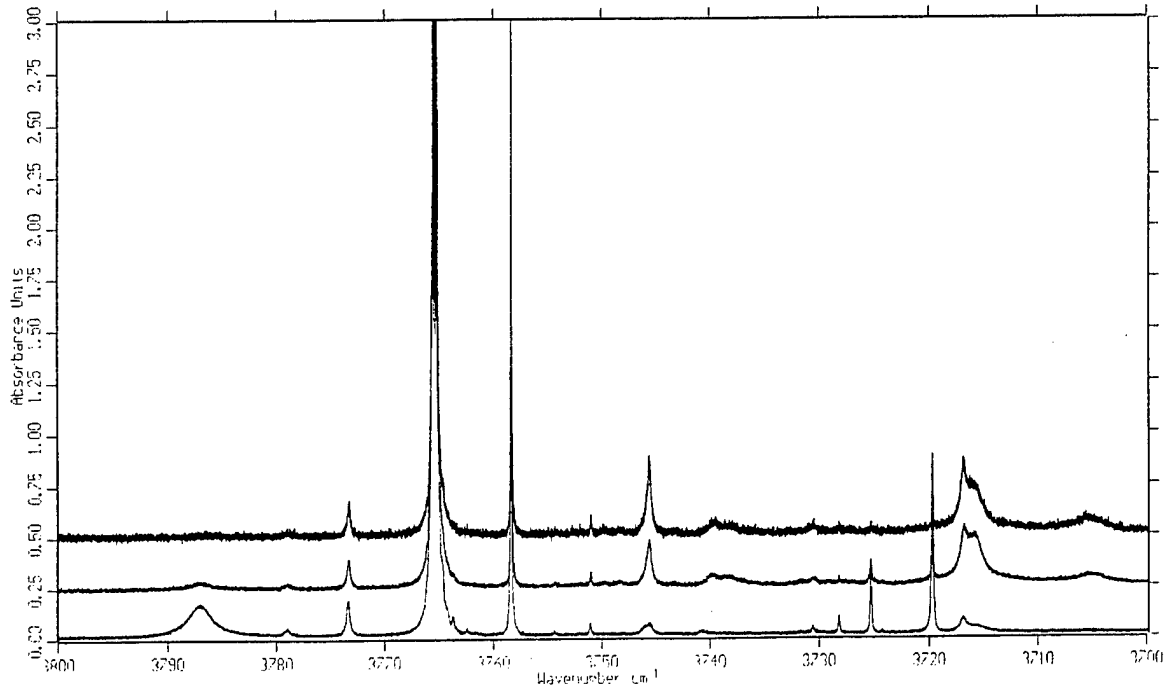
# 138 ~~PPM~~ ppm $H_2O/pH_2$ d≈3mm




st28018.6 annealed T=2.4K
st28018.4 annealing T=4.8K
st28018.2 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

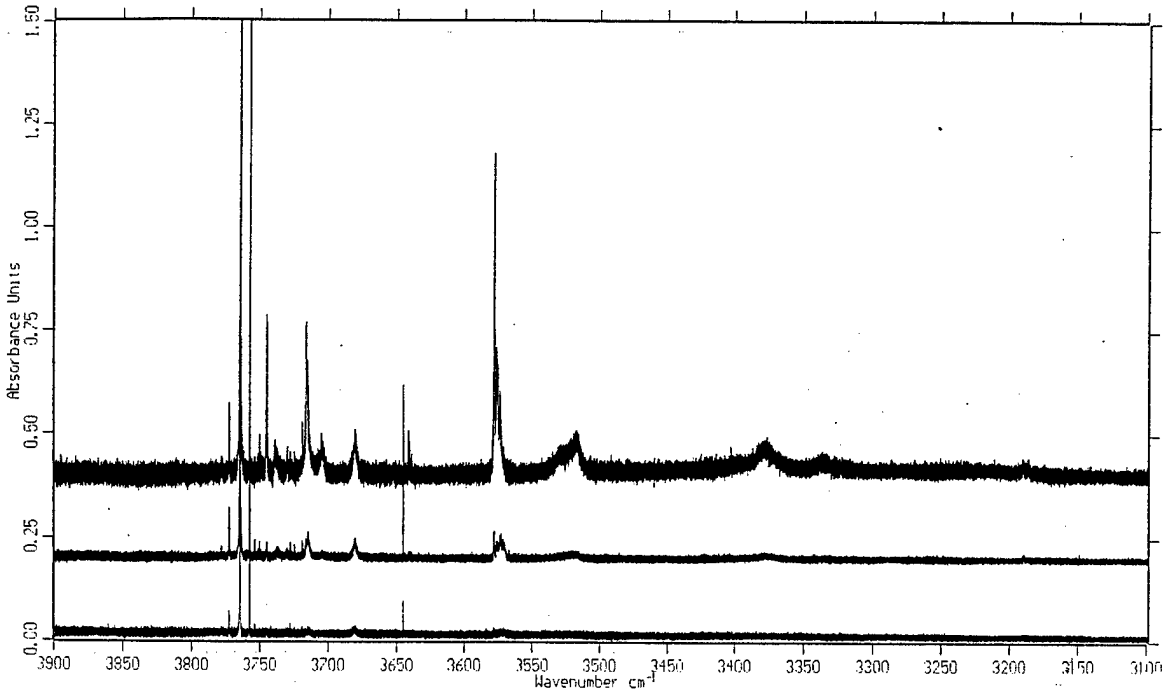
ST28018.3

# 138 ~~PPM~~ ppm $H_2O/pH_2$ d≈3mm




st28018.6 annealed T=2.4K
st28018.4 annealing T=4.8K
st28018.2 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

# $H_2O$ clusters in $pH_2$

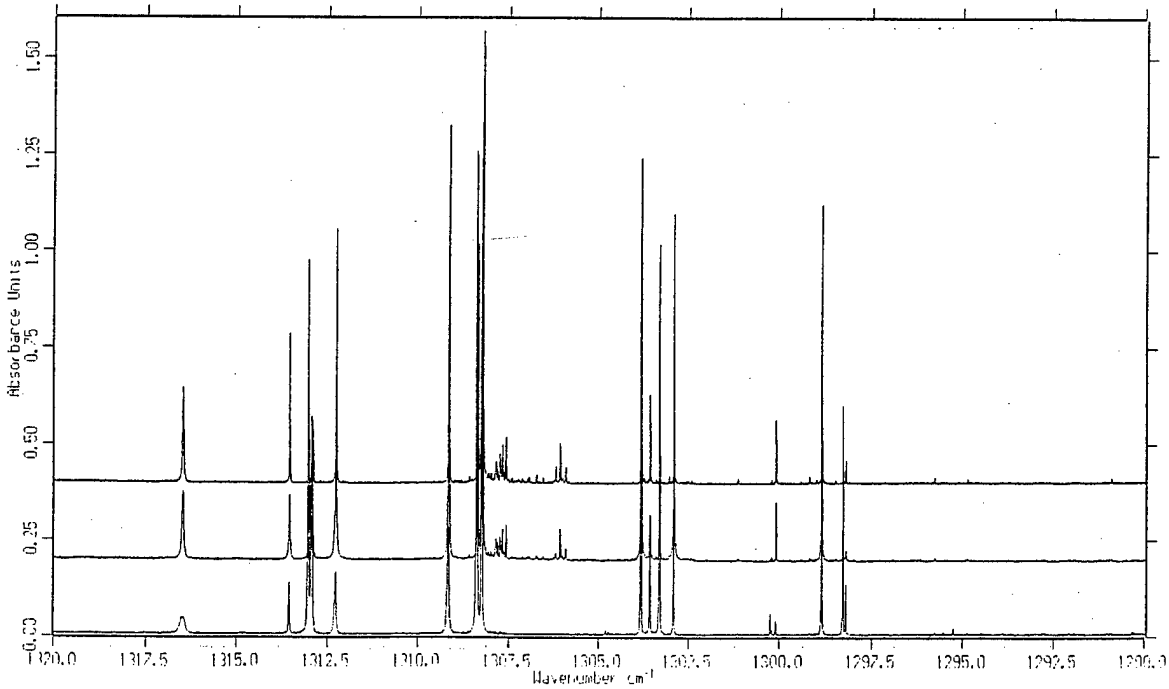



| | | | |
|---|---|---|---|
| st28018.6 | annealed | T=2.4K | 138 PPM $H_2O/pH_2$ |
| st28014.6 | annealed | T=2.4K | 45 PPM $H_2O/pH_2$ |
| st28010.6 | annealed | T=2.4K | 15 PPM $H_2O/pH_2$ |

resolution = 0.005 $cm^{-1}$

ST28010.6

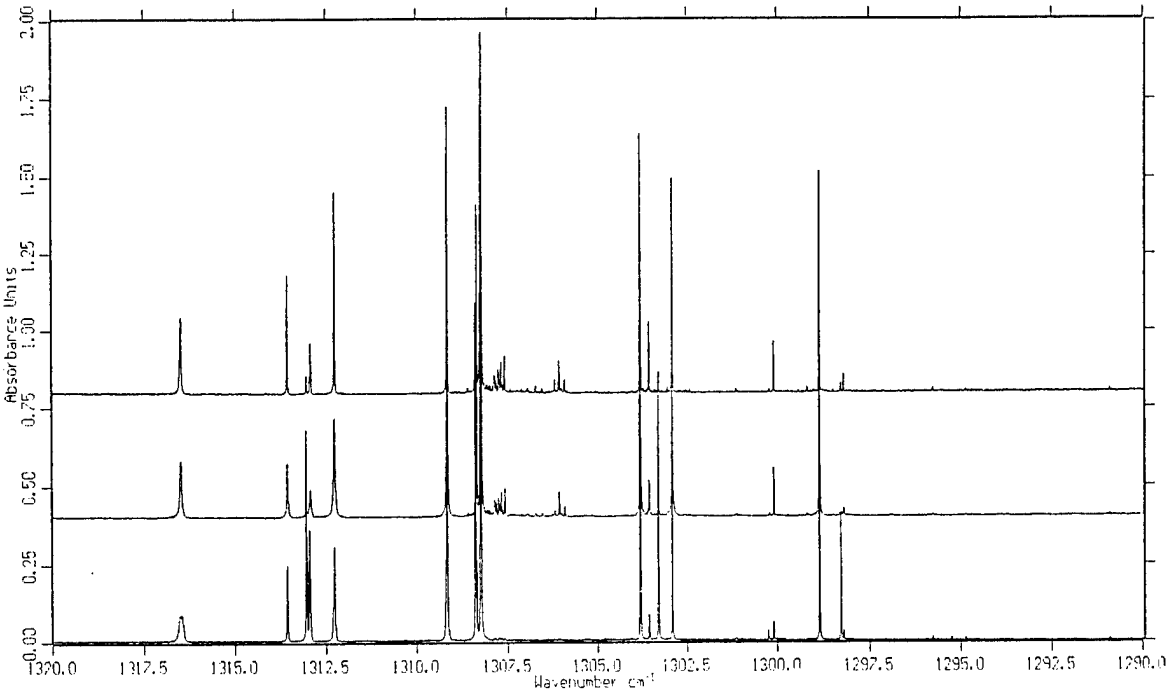
# 56 ~~PPM~~ ppm $CH_4/pH_2$ d≈0.7mm




| | | |
|---|---|---|
| st28022.20 | annealed | T=2.4K |
| st28022.19 | annealing | T=4.8K |
| st28022.18 | as deposited | T=2.4K |

resolution = 0.005 $cm^{-1}$

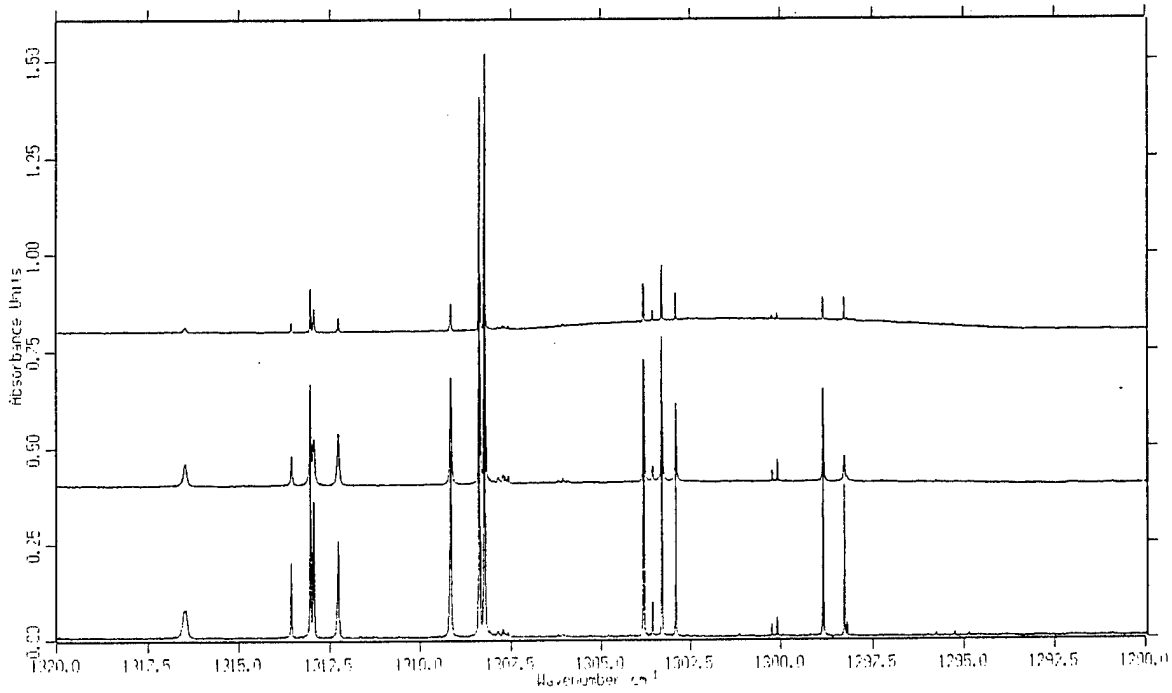
# 200 ~~PPM~~ ppm $CH_4/pH_2$ d≈0.2mm




st28026.21 annealed T=2.4K
st28026.20 annealing T=4.8K
st28026.19 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

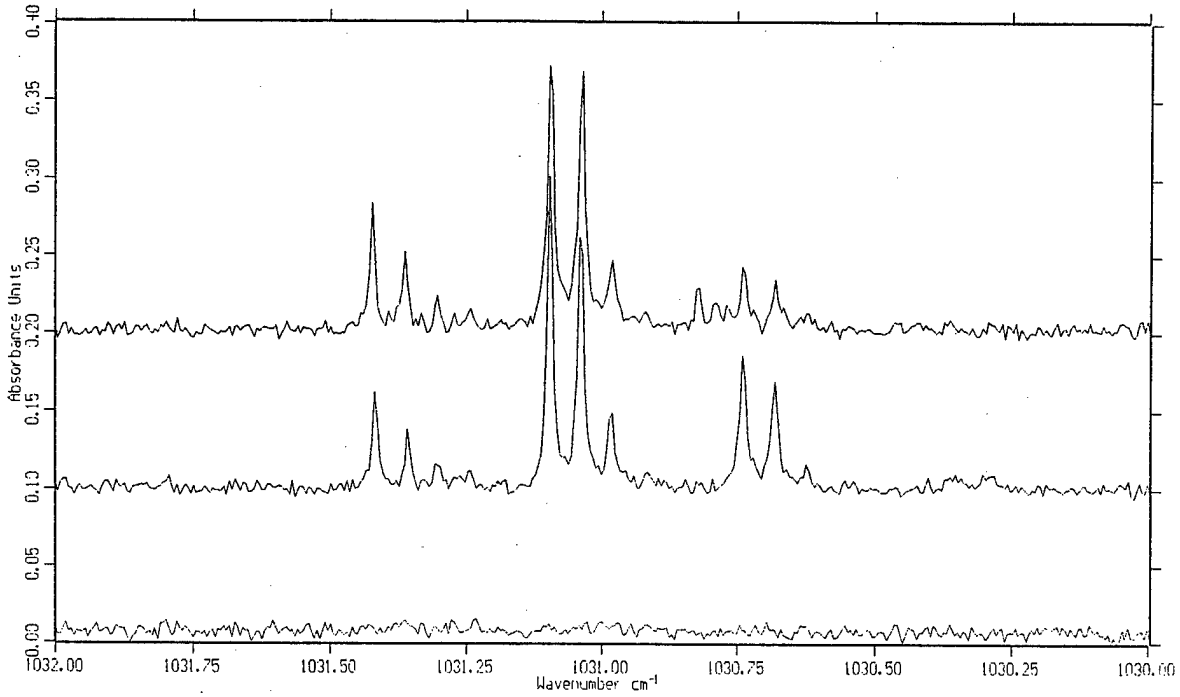
ST28026.19

# 550 ~~PPM~~ ppm $CH_4/pH_2$ d≈0.05mm




st28030.14 annealed T=2.4K
st28030.13 annealing T=4.8K
st28030.12 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

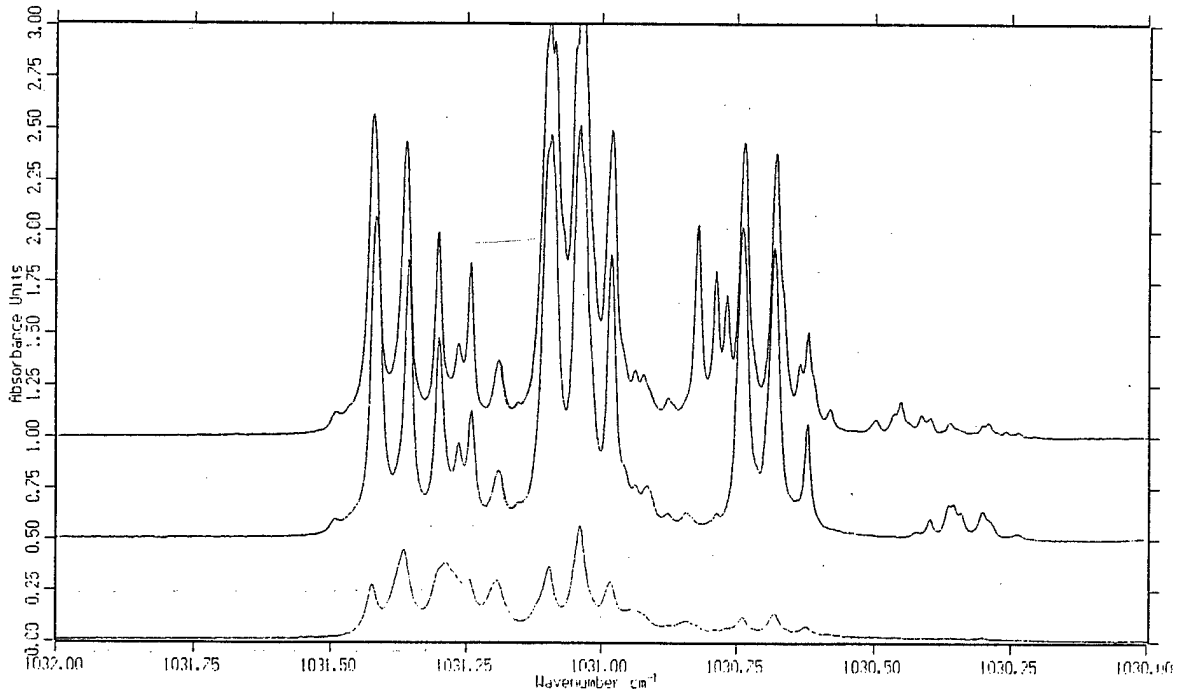
# $(CH_3F)_2/pH_2$




st28039.11 annealed T=2.4K
st28039.9 annealing T=4.8K
st28039.5 as deposited T=2.4K 10 PPM $CH_3F/pH_2$ resolution = 0.005 $cm^{-1}$

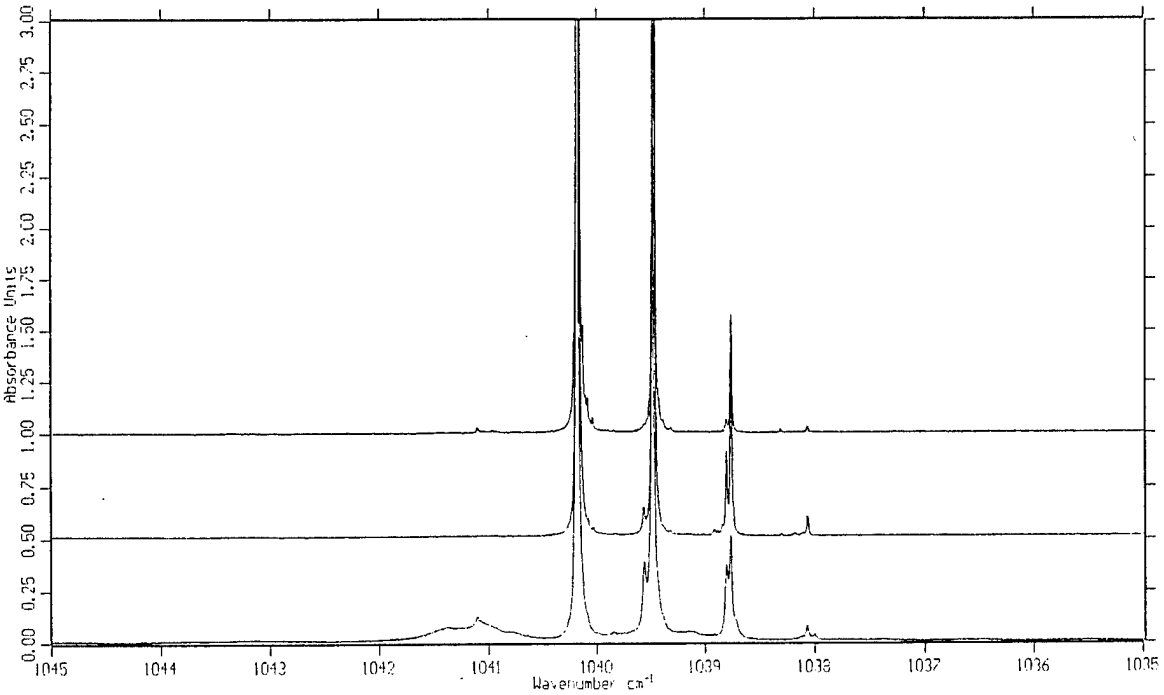
ST28039.5

# $(CH_3F)_2/pH_2$




st28048.11 annealed T=2.4K
st28048.7 annealing T=4.8K
st28048.3 as deposited T=2.4K 91 PPM $CH_3F/pH_2$ resolution = 0.005 $cm^{-1}$

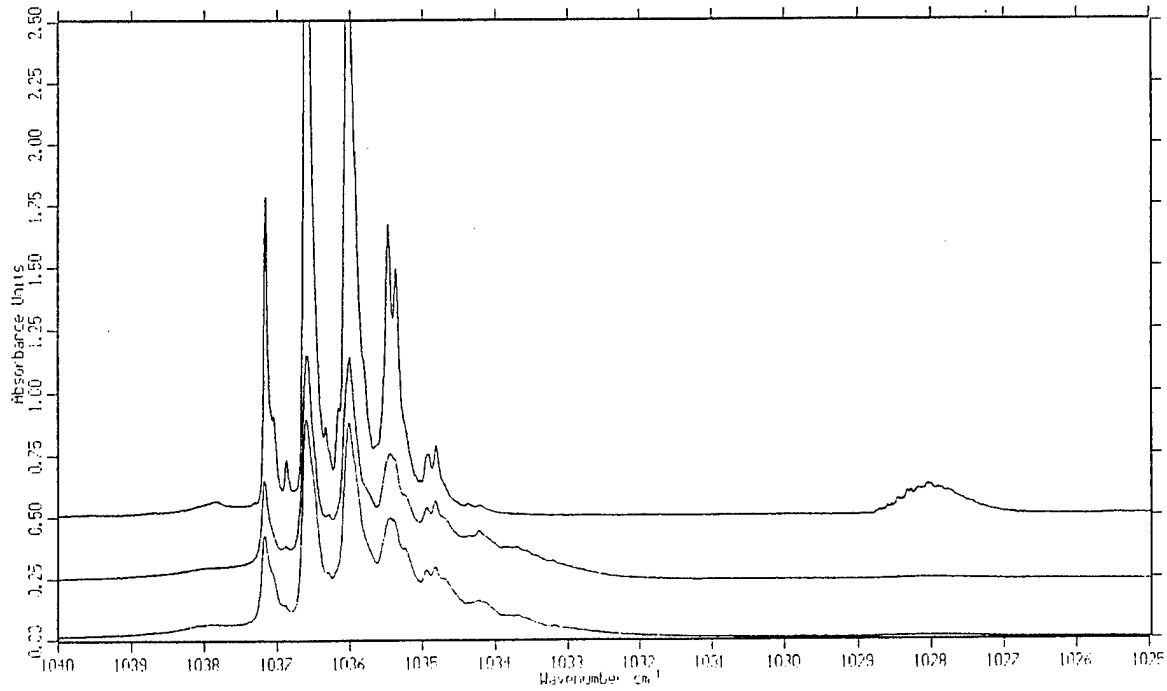
# 6 ~~PPM~~ ppm $CH_3F/pH_2$ d≈3mm




st28052.10 annealed T=2.4K
st28052.6 annealing T=4.8K
st28052.2 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

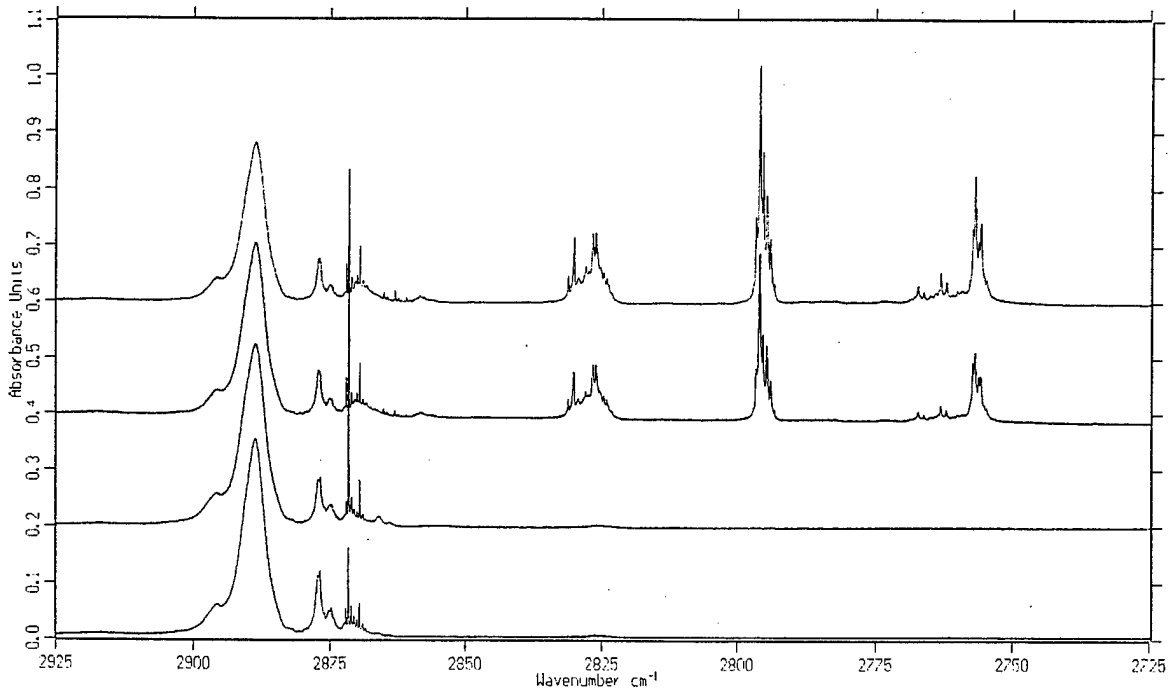
ST28052.2

# 33 ~~PPM~~ ppm $CH_3F/oD_2$ d≈2mm




st28073.11 flash annealed to 10K T=2.4K
st28073.7 annealing T=4.8K
st28073.3 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

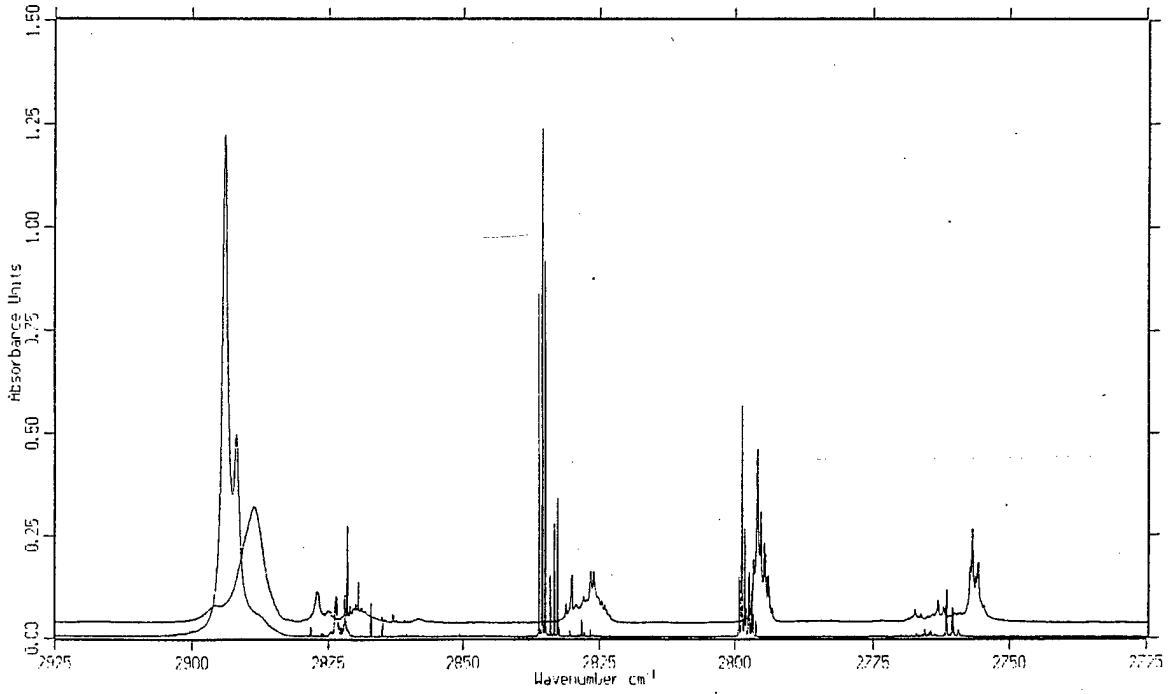
# 93 ~~PPM~~ ppm $HCl/oD_2$ d≈2mm




st28079.7 2nd flash annealing T=2.4K st28079.3 annealing T=4.8K
st28079.5 flash annealed to 10K T=2.4K st28079.1 as deposited T=2.4K resolution = 0.005 $cm^{-1}$

ST28079.1

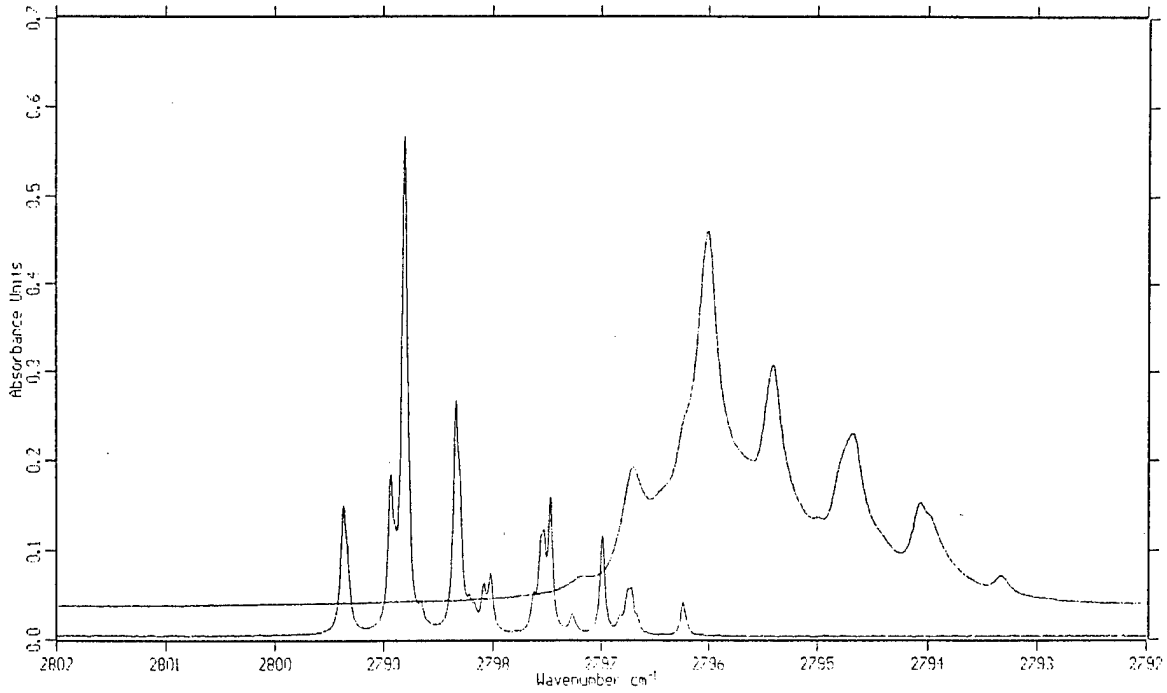
# $HCl/pH_2$ vs. $HCl/oD_2$




st28079.7 annealed T=2.4K 93 PPM $HCl/oD_2$ (≈98%)
st27061.11 annealed T=2.4K 88 PPM HCl/pH2 (99.99+%)

ST27061.11

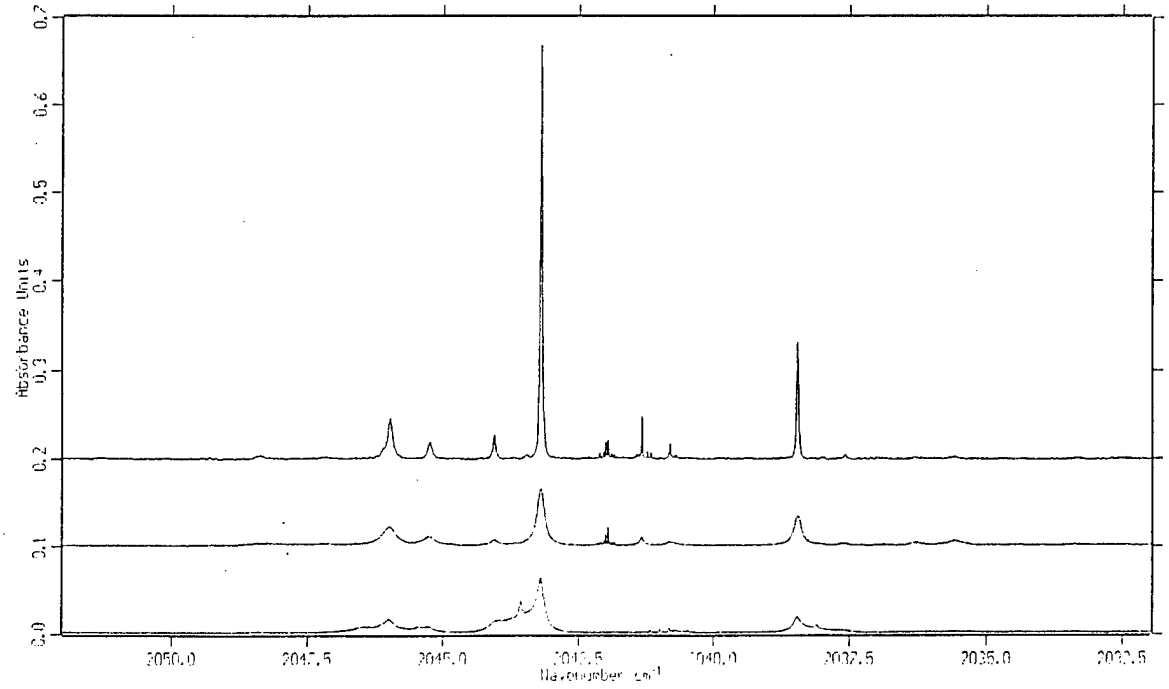
# $(HCl)_3/pH_2$ & $(HCl)_3/oD_2$




st28079.7 annealed T=2.4K 93 PPM $HCl/oD_2$ (≈98%)
st27061.11 annealed T=2.4K 88 PPM HCl/pH2 (99.99+%)

ST27061.11

# $^{13}C^{18}O/pH_2$ d≈3mm




st28082.6 annealed T=2.4K
st28082.4 annealing T=4.8K
st28082.2 as deposited T=2.4K 11 PPM $^{13}CO/pH_2$ resolution = 0.005 $cm^{-1}$