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MASS SPECTROMETER STUDY OF METAL-CONTAINING FLAMES

TWELFTH QUARTERLY TECHNICAL SUMMARY REPORT  
1 July - 30 September 1964

Contract No. Nonr-3599(00)  
ARPA Order No. 23-63, Amendment No. 38  
Program Code No. 4910

MRI Project No. 2551-P

For

Director  
Advanced Research Projects Agency  
Washington, D. C.

DDC

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MIDWEST RESEARCH INSTITUTE

425 VOLKER BOULEVARD/KANSAS CITY, MISSOURI 64110/AC 818 LO 1-0202

MASS SPECTROMETER STUDY OF METAL-CONTAINING FLAMES

by

Thomas A. Milne  
Frank T. Greene

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## PREFACE

This report was prepared for the Advanced Research Projects Agency under ONR Contract No. Nonr-3599(00), monitored by Mr. Roland Jackel and Dr. Ralph Roberts of the Power Branch, ONR. The report presents data on direct sampling of O, H, and OH radicals from one atmosphere flames, plus a summary of the quantitative sampling results achieved so far.

The research staff consists of Dr. Thomas A. Milne, project leader, and Dr. Frank T. Greene.

Approved:

MIDWEST RESEARCH INSTITUTE



Sheldon L. Levy, Director  
Mathematics and Physics Division

12 November 1964

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### SUMMARY

The free radical OH has been quantitatively sampled from  $H_2-O_2$  and  $CH_4-O_2$  one atmosphere flames at temperatures from 2300 - 3000°K. Oxygen atoms and hydrogen atoms have also been sampled from  $H_2-O_2$  flames. A summary is given of equilibrium constants for various high temperature equilibria studied so far in this program. Agreement is within a factor of two in  $K_{eq}$ . in almost every case.

## I. INTRODUCTION

Work has continued in the past quarter on the verification of the ability to quantitatively extract very reactive species from one atmosphere flames using a properly designed aerodynamic molecular beam sampling system. Described below are studies of O, H, and OH radicals in  $H_2-O_2$  and  $CH_4-O_2$  flames, a summary of quantitative third law checks on known equilibria in flames, and preparations and plans for studies of unknown and condensible species.

## II. HYDROXYL RADICALS SAMPLED FROM $H_2-O_2$ AND $CH_4-O_2$ FLAMES

In attempting to quantitatively sample OH radicals in flames, a problem arose which was similar to that previously encountered with O atoms. It is necessary to distinguish  $17^+$  ions from neutral OH from  $17^+$  ions formed by fragmentation of  $H_2O$ , which is usually present in much larger quantity than OH. This problem is aggravated by a suspected but unknown temperature dependence of fragmentation of species like  $H_2O$  and  $O_2$ . If the room temperature cracking pattern of  $O_2$  and  $H_2O$  is not too much altered at temperatures up to  $3000^\circ K$ , then fragmentation of  $O_2$  and  $H_2O$  poses no problem at a nominal ionizing energy of 20 ev for the flames studied so far. In view of the rather large change in the cracking pattern of  $CO_2$  with temperature, however, it would be desirable to check this unambiguously for  $O_2$  and  $H_2O$ . The problem is much more difficult in this case, however, since we are simultaneously trying to show that the OH and O species can be quantitatively sampled.

A large number of flames, burned on a standard glass blowing torch, have been studied. In most cases, except for the hottest, fastest flames, gases were sampled at 1 mm. from the visible reaction zone. The  $18^+/17^+$  ratios are shown for these flames in Table I at 20 and 50 ev, together with flame composition, theoretical flame temperature and theoretical ratio of  $H_2O/OH$  in the burnt gases. Two things are noticed. First, the  $18^+/17^+$  ratios at 50 ev are scattered but virtually independent of temperature. Second, the 20 ev ratios correlate well with the theoretical  $H_2O/OH$  ratios as indicated in the last column. It seems clear that the  $17^+$  signal observed at 20 ev is mainly due to OH radical. The differences from the theoretical values may be due to differences in cross-section at 20 ev, departure of the flame from equilibrium temperature or composition, some contribution from fragmentation, as well as failure to quench. In general, it once again appears that we are sampling quantitatively to within our previous third law criterion of a factor of two in the equilibrium constant.



TABLE I

ION INTENSITY RATIOS,  $\text{H}_2\text{O}^+/\text{OH}^+$ , FOR A NUMBER OF  $\text{H}_2\text{-O}_2$  AND  $\text{CH}_4\text{-O}_2$   
FLAMES AT 20 AND 50 EV IONIZING ELECTRON ENERGY

| Flame Composition<br>(Mole Ratios) |               |              |              |             | Adiabatic<br>Flame Temp.<br>(°K) | $\text{H}_2\text{O}^+/\text{OH}^+$ |        | Calc.<br>$\text{H}_2\text{O}/\text{OH}$ | Obs/Calc |
|------------------------------------|---------------|--------------|--------------|-------------|----------------------------------|------------------------------------|--------|-----------------------------------------|----------|
| $\text{H}_2$                       | $\text{CH}_4$ | $\text{O}_2$ | $\text{N}_2$ | $\text{Ar}$ |                                  | 50 ev                              | 20 ev  |                                         |          |
| 3                                  |               | 1            |              |             | 3004                             |                                    | 21.3   | 10.1                                    | 2.1      |
| 2                                  |               | 1            | 1            |             | 2889                             |                                    | 15.8   | 8.5                                     | 1.9      |
|                                    | 1             | 4            |              |             | 2845                             | 2.5                                | 8.3    | 4.0                                     | 2.1      |
| 4                                  |               | 1            |              |             | 2830                             | 2.9                                | 35.8   | 24.9                                    | 1.4      |
| 2                                  |               | 3            |              |             | 2720                             | 2.6                                | 11.9   | 6.5                                     | 1.8      |
| 2                                  |               | 1            | 2            |             | 2709                             | 3.1                                | 19.7   | 14.2                                    | 1.4      |
| 5                                  |               | 1            |              |             | 2627                             | 3.3                                | 52.3   | 66.7                                    | 0.78     |
|                                    | 1             | 1            |              |             | 2611                             | 3.2                                | 37.3   | 64.0                                    | 0.58     |
| 2                                  |               | 4            |              |             | 2570                             |                                    | 11.4   | 8.3                                     | 1.4      |
| 2                                  |               | 1            | 3            |             | 2524                             | 2.8                                | 21.7   | 26.6                                    | 0.82     |
|                                    | 1             | 2            |              | 8           | 2490                             | 2.7                                | 73.6   | 17.0                                    | 4.3      |
|                                    | 1             | 2.4          |              | 8           | 2485                             | 3.0                                | 22.3   | 12.8                                    | 1.7      |
|                                    | 1             | 1.8          |              | 8           | 2442                             | 3.8                                | 52.5   | 28.6                                    | 1.8      |
| 5                                  |               | 1            | 1            |             | 2360                             |                                    | 53.7   | 267.                                    | 0.20     |
| 2                                  |               | 1            | 4            |             | 2334                             | 3.0                                | 32.5   | 56.0                                    | 0.58     |
| 2                                  |               | 5            |              |             | 2330                             | 2.8                                | 14.6   | 15.7                                    | 0.93     |
|                                    | 1             | 8            |              |             | 2330                             | 2.5                                | 9.8    | 13.1                                    | 0.73     |
|                                    | 1             | 1.6          |              | 8           | 2296                             | 3.4                                | > 170. | 117.                                    | > 1.5    |

Several of these flames will be studied more completely on sheathed burners, with line reversal temperature measurements, to establish the detailed behavior to be expected for flames to be used in thermochemical studies.

One of the problems requiring further study is the relative cross-section dependence at low electron energy for, say,  $\text{H}_2\text{O}$  and  $\text{OH}$ . One may be boxed in between increasing fragmentation contributing to  $\text{OH}^+$  at higher energies and the possibility of rapidly changing relative cross section for  $\text{H}_2\text{O}^+$  and parent  $\text{OH}^+$  ions at low energies. There is some indication of a plateau in the ratio of  $\text{H}_2\text{O}^+/\text{OH}^+$  around 20 ev and in the following we simply assume equal cross sections at 20 ev and no fragmentation contribution.

Oxygen atoms have been observed in a number of the flames of Table I.  $\text{H}_2\text{O}$  appears to make a completely negligible contribution to  $\text{O}^+$  at 20 ev and the contribution to  $\text{O}^+$  from  $\text{O}_2$  also appears negligible at 20 ev, based on the  $\text{CO-O}_2$  flame work reported previously.<sup>1/</sup> Table II lists some values for the equilibrium constant for the reaction:



determined in the several flames indicated. The last column gives values calculated from the JANAF tables.<sup>2/</sup> The results are in very good agreement for this equilibrium, which varies only slowly with temperature.

TABLE II

EXPERIMENTAL DETERMINATION OF THE EQUILIBRIUM CONSTANT  
FOR THE REACTION  $\text{H}_2\text{O} + \text{O} \rightleftharpoons 2\text{OH}$  IN SEVERAL  
 $\text{H}_2\text{-O}_2\text{-N}_2$  FLAMES AT ONE ATMOSPHERE<sup>a/</sup>

| Flame Composition<br>(Mole Ratios) |                      |                      | Adiabatic<br>Flame Temp.<br>(°K) | K <sub>eq.</sub> for $\text{H}_2\text{O} + \text{O} \rightleftharpoons 2\text{OH}$ |                   |
|------------------------------------|----------------------|----------------------|----------------------------------|------------------------------------------------------------------------------------|-------------------|
| <u>H<sub>2</sub></u>               | <u>O<sub>2</sub></u> | <u>N<sub>2</sub></u> |                                  | <u>Exptl.</u>                                                                      | <u>Calculated</u> |
| 2                                  | 1                    | 1                    | 2889                             | 0.50                                                                               | 0.52              |
| 2                                  | 3                    |                      | 2720                             | 0.33                                                                               | 0.44              |
| 2                                  | 1                    | 2                    | 2709                             | 0.50                                                                               | 0.43              |
| 2                                  | 4                    |                      | 2570                             | 0.22                                                                               | 0.37              |

<sup>a/</sup> All cross sections assumed equal at 20 ev.

Table III compares the oxygen dissociation equilibrium for the four flames studied.

It is worth noting from Table III that in flames whose  $\text{O}_2$  content varies almost fortyfold, the O atom concentration agrees with theoretical calculations to within a factor of two. The conclusion is that we are quantitatively sampling O and OH simultaneously from  $\text{H}_2\text{-O}_2$  flames.

TABLE III

EXPERIMENTAL DETERMINATION OF THE EQUILIBRIUM  
CONSTANT FOR THE REACTIONS  $1/2 O_2 \rightarrow O$

| Flame Composition<br>(Mole Ratios) |       |       | Adiabatic<br>Flame Temp.<br>(°K) | Partial Pressures in % |      |         | $1/2 O_2 \rightarrow O$ |                      |
|------------------------------------|-------|-------|----------------------------------|------------------------|------|---------|-------------------------|----------------------|
| $H_2$                              | $O_2$ | $N_2$ |                                  | O                      |      | $O_2$   | Keq.                    | Keq.                 |
|                                    |       |       |                                  | Exptl.                 | Lit. | Lit.    | Exptl.                  | Lit.                 |
| 2                                  | 1     | 1     | 2889                             | 1.6                    | 1.3  | 2.7     | $9.8 \times 10^{-2}$    | $7.6 \times 10^{-2}$ |
| 2                                  | 3     |       | 2720                             | 3.3                    | 2.8  | ca 50.0 | $4.7 \times 10^{-2}$    | $3.9 \times 10^{-2}$ |
| 2                                  | 1     | 2     | 2709                             | 0.77                   | 0.46 | 1.54    | $6.2 \times 10^{-2}$    | $3.7 \times 10^{-2}$ |
| 2                                  | 4     |       | 2570                             | 2.4                    | 1.6  | ca 60.0 | $3.1 \times 10^{-2}$    | $2.0 \times 10^{-2}$ |

a/ The data are normalized to the calculated  $O_2$  partial pressure assuming equal cross sections at 20 ev.

Note: If the ion intensity data are normalized to the theoretical  $H_2O$  composition data, instead of  $O_2$ , then both O and  $O_2$  are about a factor of two below theoretical and equilibrium constants are correspondingly smaller.

Some measurements of H atoms were made at 20 ev in four rich-to-stoichiometric flames. The  $H^+$  results, due to the low sensitivity caused by the mass separation effect, are less reliable than the O and OH results. Still, in three out of four of the flames, the equilibrium constant for  $1/2 H_2 \rightarrow H$  agreed with literature values to within a factor of two.

In one very hot flame, we attempted to measure every species of even minor importance. Table IV shows the raw ion intensities observed at 20 ev, the values being corrected for mass separation and normalized to make the  $H_2O$  agree with the theoretical values at the adiabatic flame temperature. With no attempted correction for relative cross sections or for true temperature of the burnt gases, the results reflect the expected compositions.

TABLE IV

RELATIVE ION INTENSITIES OBSERVED IN A  $H_2-O_2-N_2$ , 2-1-1 FLAME  
(T-2889°K) AT 20 EV IONIZING ENERGY<sup>a/</sup>

|          | Percent       |              |
|----------|---------------|--------------|
|          | <u>Exptl.</u> | <u>Calc.</u> |
| $H^+$    | 0.75          | 3.2          |
| $H_2^+$  | 2.25          | 8.8          |
| $O^+$    | 0.42          | 1.3          |
| $OH^+$   | 3.2           | 5.6          |
| $H_2O^+$ | (47.5)        | 47.5         |
| $N_2^+$  | 14.7          | 29.9         |
| $NO^+$   | 0.12          | 1.0          |
| $O_2^+$  | 0.70          | 2.7          |

a/ Intensities have been corrected for mass separation by the first power of the molecular weight and normalized to the calculated  $H_2O$  composition. No corrections for sensitivity have been made.

### III. SUMMARY OF EQUILIBRIUM CONSTANTS DETERMINED SO FAR IN ONE ATMOSPHERE FLAMES

In Table V, we summarize the type of equilibria studied so far and compare the observed and JANAF calculated values of the appropriate equilibrium constants. The chlorine dissociation data differ from that reported in the Tenth Quarterly Technical Summary Report.<sup>3/</sup> Since that time, we have repeated the runs, made corrections to the experimental temperatures, and recomputed the literature equilibrium constant from JANAF tables. These results support the idea that quenching of highly reactive species is being accomplished in our sampling system. It is quite possible that the variations and departures from literature values are due to essentially analytical difficulties, such as uncertainties in relative cross sections, fragmentation contributions, departures from equilibrium in the flame, temperature errors, etc., and are essentially unconnected with quenching ability.

TABLE V

SUMMARY OF EXPERIMENTAL EQUILIBRIUM CONSTANTS  
DETERMINED IN ONE ATMOSPHERE FLAMES

| Flame                 |                      |                      |           | Exptl.<br>Temp.<br>(K°) | K <sub>eq.</sub>                               |              |                                                           |              |
|-----------------------|----------------------|----------------------|-----------|-------------------------|------------------------------------------------|--------------|-----------------------------------------------------------|--------------|
| <u>CH<sub>4</sub></u> | <u>CO</u>            | <u>O<sub>2</sub></u> | <u>Ar</u> |                         | <u>Exptl.</u>                                  | <u>Calc.</u> | <u>Exptl.</u>                                             | <u>Calc.</u> |
|                       |                      |                      |           |                         | <u>CO + 1/2 O<sub>2</sub> → CO<sub>2</sub></u> |              | <u>H<sub>2</sub> + 1/2 O<sub>2</sub> → H<sub>2</sub>O</u> |              |
| 1                     |                      | 2                    | 8         | 2454                    | 36.4                                           | 36.0         | 234                                                       | 210          |
| 1                     |                      | 2.4                  | 8         | 2457                    | 28.9                                           | 36.0         | 151                                                       | 210          |
|                       |                      |                      |           |                         | <u>CO + 1/2 O<sub>2</sub> → CO<sub>2</sub></u> |              | <u>O → 1/2 O<sub>2</sub></u>                              |              |
|                       | 1                    | 1                    |           | 2769                    | 4.9                                            | 7.6          | 24.5                                                      | 20.4         |
|                       | 4                    | 3                    |           | 2824                    | 4.5                                            | 6.0          | 22.0                                                      | 15.9         |
|                       | 2                    | 1                    |           | 2834                    | 4.8                                            | 5.7          | 22.5                                                      | 15.1         |
|                       | 3                    | 1                    |           | 2807                    | 4.4                                            | 6.4          | 20.9                                                      | 17.0         |
|                       |                      |                      |           |                         | <u>1/2 Cl<sub>2</sub> → Cl</u>                 |              |                                                           |              |
|                       | 2                    | 1                    | 2.7       | 2219                    | 1.42                                           | 1.58         |                                                           |              |
|                       | 2                    | 1                    | 3.8       | 2077                    | 1.43                                           | 0.85         |                                                           |              |
|                       | 2                    | 1                    | 5.0       | 1832                    | 0.89                                           | 0.37         |                                                           |              |
|                       |                      |                      |           | Calc.<br>Temp.<br>(°K)  |                                                |              |                                                           |              |
| <u>H<sub>2</sub></u>  | <u>O<sub>2</sub></u> | <u>N<sub>2</sub></u> |           |                         | <u>H<sub>2</sub>O + O → 2OH</u>                |              | <u>O → 1/2 O<sub>2</sub></u>                              |              |
| 2                     | 1                    | 1                    |           | 2889                    | 0.50                                           | 0.52         | 10.1                                                      | 13.2         |
| 2                     | 3                    |                      |           | 2720                    | 0.33                                           | 0.44         | 21.3                                                      | 25.6         |
| 2                     | 1                    | 2                    |           | 2709                    | 0.50                                           | 0.43         | 16.1                                                      | 27.0         |
| 2                     | 4                    |                      |           | 2570                    | 0.22                                           | 0.37         | 32.3                                                      | 50.0         |
|                       |                      |                      |           |                         | <u>1/2 H<sub>2</sub> → H</u>                   |              |                                                           |              |
| 3                     | 1                    |                      |           | 3004                    | 0.068                                          | 0.155        |                                                           |              |
| 2                     | 1                    | 1                    |           | 2889                    | 0.10                                           | 0.112        |                                                           |              |
| 4                     | 1                    |                      |           | 2835                    | 0.018                                          | 0.100        |                                                           |              |
| 5                     | 1                    |                      |           | 2627                    | 0.025                                          | 0.043        |                                                           |              |

#### IV. DISCUSSION AND FUTURE PLANS

More detailed study of any of the equilibria mentioned above will probably be done only in conjunction with our studies of unknown or poorly known species. The big remaining question to be quantitatively answered is that of sampling condensible metal-containing species. So far we have only looked at  $\text{HBO}_2$  in a  $\text{H}_2\text{-O}_2$  flame. Work is under way on means of getting metal salts into flames at up to 0.1 per cent by sprays, transpiration, diffusion or a volatile metal compound. Alkemade<sup>4/</sup> and co-workers at Utrecht have been unsuccessful in detecting condensible metal-containing species in a sampling system for one atmosphere flames not unlike ours. Both this group and a group under Dr. Gg. Wagner<sup>5/</sup> at Göttingen are actively working on the direct sampling of reactive species from flames.

During the next quarter we will continue to study ways of adding metals to the flame and the resulting plugging problems at the first orifice. We plan to try the Studier continuous mode of operation of the Bendix, which has been reported to give a maximum gain in sensitivity of greater than 100. This full gain may not be achieved with the aerodynamic beam and at low electron energies. We will also increase the modulation rate of our beam for better operation and discrimination. Species in the B-O system will be studied as will SH, FeO and alkali metal oxides and hydroxides.

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