# "Study of the Techniques Feasible for Food Synthesis Aboard a Spacecraft"

by

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Semiannual Status Report No. 2
Period: August 1, 1968 to January 31, 1969
Grant NGR 22-017-008

for

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National Aeronautics and Space Administration
Moffett Field, California 94035

March 1, 1969

Abstract

Studies conducted in a continuous stirred tank reactor have for the first time, produced quantitative results on the kinetics of the formose reaction and associated Cannizzaro effects. Of major significance is the fact that the observed inductive and zero order nature of the kinetics of the formose reaction can be explained by deriving rate expressions which have direct analogs in heterogeneously catalyzed systems. Here complexing-decomplexing steps in the formose system directly correlate with adsorption-desorption steps in heterogeneous systems. The controlling nature of product decomplexing in the formose system produces the observed kinetic behavior.

Acknowledgements

The author wishes to acknowledge the efforts of Messrs. William Von Felten and Walter Critz of Santa Clara University in these investigations. The assistance and advice of Mr. Richard Adachi and Dr. Glen Pollack of Ames Research Center, and of Dr. Joseph H. Schneider of St. Francis College is also deeply appreciated.

Most of the experimental work cited in this report was conducted by Mr. Rene LaPierre at NASA's Ames Research Center under the collaborative supervision of Dr. Jacob Shapira and Dr. Alvin H. Weiss. During this period, Dr. Weiss was supported as an ASEE Stanford-Ames Summer Faculty Fellow. Work at the Department of Chemical Engineering of Worcester Polytechnic Institute includes additional contributions by Messrs. Donald Aldrich, Randall Partridge, Ashwin Dalal, David Morris, Joseph Toce, and Dr. David Todd. This work will be used in partial satisfaction of the requirements for the degree of Master of Science in Chemical Engineering for Mr. LaPierre.

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## I. Introduction

The formose reaction, or self-condensation of formaldehyde by alkaline catalysts to a complex carbohydrate mixture was first reported by Butlerow[1] in 1861. Since that time there has been intermittent research on the reaction, primarily to identify and characterize various components of the product mixture. More recently investigations have centered on increasing the selectivity of the reaction to lower molecular weight ($C_2$-$C_4$) compounds and their reduction to polyols. It is to this end and to a more fundamental and quantitative knowledge of the formose reaction that this research has been directed. A study of formose chemistry can be broken down into four major divisions, the initial condensation reaction of formaldehyde with itself, later aldol type condensations, Cannizzaro reaction, and isomerization of the hydroxy-aldehydes and ketones formed.

Glycolaldehyde ($CH_2OHCHO$) has been reported[2] to be the primary condensation product. Katschmann[3] accounts for the autocatalytic nature of the reaction by proposing that the primary condensation to glycolaldehyde is slow compared to later condensation reactions. Franzen and Hauck[4] isolated several metallic salts of formaldehyde and studied the possibility of their being an intermediate in the condensation of formaldehyde to sugars. They suggest a reaction of the type;

$$Ca(OH)_2 + 2\ CH_2(OH)_2 \rightleftharpoons Ca(OCH_2OH)_2 + 2H_2O$$

where methylene glycol, the major form of monomeric formaldehyde in aqueous solution is complexed by $Ca(OH)_2$. In very dilute solutions of formaldehyde they suggest formation of a salt of the type $HOCH_2OCaOH$. It is their conclusion that two salt molecules of this type condense to form complexed glycolaldehyde and $Ca(OH)_2$.

$$2\ HOCH_2OCaOH \rightarrow CH_2OHCHOHOCaOH + Ca(OH)_2$$

They also suggest that further condensations of this type lead to formose sugars. Balezin[5] similarly proposes that complexed $Ca(OH)_2$ plays an essential role in the condensation mechanism.


(1) Butlerow, A.M., Ann., 120, 295 (1861).

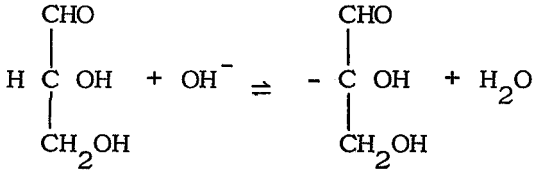
(2) Euler, H.V., and Euler, A., Ber., 39, 50 (1906).

(3) Katschmann, E., Ber., 77B, 579-85 (1944).

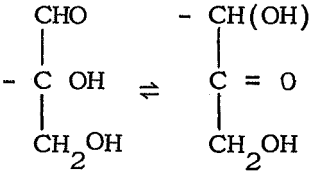
(4) Franzen, H. and Hauck, L., J. Prakt. Chem., 91, 261-84 (1915).

(5) Balezin, S.A., Zhur. Obschei Khim., 17, 2288-91 (1947).

Several authors have studied intermediate aldol type condensations as part of the formose reaction sequence. Pfeil and Ruckert[6], in batch studies, showed that glycolaldehyde reacted with itself to yield hexoses and tetroses, and with formaldehyde to yield $C_3$, $C_4$, $C_5$ and trace $C_6$ products. Glyceraldehyde reacted with itself and dihydroxyacetone reacted with itself to produce hexoses. Glyceraldehyde and glycolaldehyde condensed to give pentoses. Erythrose and formaldehyde also yielded pentoses. Significantly, pentoses and hexoses did not react with formaldehyde at a measurable rate. This nonreactivity is probably due to formation of stable furanose and pyranose ring structures. Berl and Feazel[7] have studied in greater detail the self-condensation of glyceraldehyde in alkaline solutions and the effects of dihydroxyacetone on glyceraldehyde condensation. D-glyceraldehyde condensed with itself to give D-fructose and D-sorbose almost exclusively. Dihydroxyacetone was noted to have a catalytic effect on the glyceraldehyde condensation, while dihydroxyacetone condensed with itself to give a branched chain compound in 45% yield. Frost and Pearson[8] have discussed the mechanism of the glyceraldehyde condensation. Ionization of glyceraldehyde;



is the rate determining step, followed by a proton shift to give the carbanion of dihydroxyacetone. (These proton



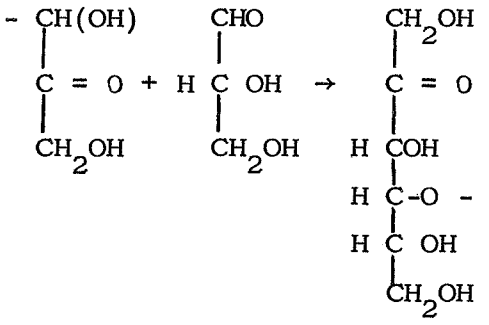
shifts account for the isomerization observed in the formose system.) This carbanion then reacts with glyceraldehyde to give the oxyanion of the

(6) Pfeil, E., and Ruckert, H., Ann., 641, 121-131 (1961).

(7) Berl, W.G., and Feazel, C.E., J. Amer. Chem. Soc., 73, 2054-7, (1951).

(8) Frost, A.A., and Pearson, R.G., "Kinetics and Mechanism", 2nd Ed., 335-350, John Wiley and Sons Inc., N.Y., (1961)

ketohexose



March[9] also considers this mechanism relevant for all types of base catalyzed aldol condensations.

In addition to aldol type condensations, Cannizzaro reaction has been observed to occur in the formose system. The Cannizzaro reaction is the simultaneous oxidation and reduction of two aldehyde groups by $OH^-$. The $Ca(OH)_2$ catalyst for the formose reaction allow Cannizzaro reaction to occur in this system. The Cannizzaro reaction of formaldehyde with $Ca(OH)_2$ has the following stoichiometry

$$4CH_2O + Ca(OH)_2 \rightleftharpoons (CHOO)_2Ca + 2CH_3OH$$

Aldose condensation products of the formose reaction can also undergo Cannizzaro reaction, for example glycolaldehyde,

$$2CH_2(OH)CHO + OH^- \rightarrow CH_2(OH)COO^- + CH_2(OH)CH_2OH$$

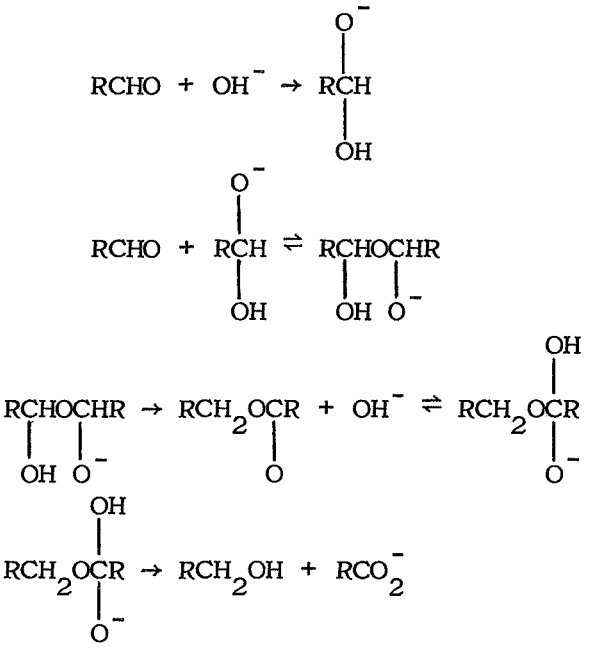
Furthermore cross-Cannizzaro reaction may occur where two dissimilar aldehydes are oxidized and reduced. Cross Cannizzaro reaction may prove useful in reducing aldose condensation products of the formose reaction.

Several mechanisms have been proposed for the Cannizzaro reaction. Geissmann[10] in a 1944 review of Cannizzaro literature presents the mechanism of Lock[11].

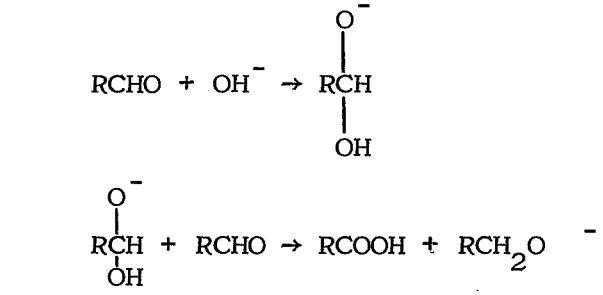
(9) March, J., "Advanced Organic Chemistry", 692-697, McGraw-Hill Book Co., N.Y. (1968).

(10) Geissman, T.A., "Organic Reactions", 2, 94-113 (1944).

(11) Eitel and Lock, Monatsh, 72, 392 (1939).



Geissman concludes, "This mechanism adequately coordinates the well-known variations of base-induced dismutation of aldehydes into a general picture..". March proposes a somewhat similar mechanism,



again involving the singly-charged methylene-glycol anion. Batch experiments conducted by Ackerlof and Mitchell[12] at 60°C show that the kinetics of the cannizzaro reaction of formaldehyde with $Ca(OH)_2$ is first order with respect to $Ca(OH)_2$. These studies also show that glucose is readily converted by Cannizzaro reaction.

In summary, considering the autocatalytic nature of the formose reaction and the overall complexity of the system the experimental approach used is extremely important. The system must be not only thermally stable but also reproducible and analytical data readily attainable on product composition at all conversion levels. Studies have previously been conducted in batch and plug flow reaction systems. The batch system meets neither requirement mentioned while the plug flow system fails in the second criterion. The continuous stirred tank reactor (CSTR) was found to meet both these criteria. A second advantage is the fact that rates are measured

directly, facilitating the description of the kinetics of such a system. Experiments in a CSTR by MacLean and Heinz[13] have shown the feasibility of producing lower molecular weight aldoses and ketoses using lead salts as catalysts.

(12) Ackerlof, G.C., and Mitchell, P.W.D., "A Study of the Feasibility of the Regeneration of Carbohydrates in a Closed Circuit Respiratory System", NASA Contract NASr-88 (1963).

(13) MacLean, A.F., and Heinz, W.E., U.S. Patent 2,760,983 (1956).

II. Equipment and Operating Procedures.

All kinetic studies presented in this report were carried out in a CSTR. A description of the feed system, reactor, and monitoring devices follow.

The $Ca(OH)_2$ slurry and aqueous formaldehyde solution were pumped by Cole Parmer "Masterflex™" tubing pumps through 1/32" and 1/16" tygon tubing respectively. The $Ca(OH)_2$ feed rate could be varied from 0 to 25 cc/min, while formaldehyde rate could be varied from 0 to 125 cc/min. The $Ca(OH)_2$ slurry was fed from a six liter, magnetically stirred, Erlenmeyer flask equipped with a Drierite-Ascarite tube to prevent $CO_2$ contamination. Formaldehyde was fed from a 20 liter glass reagent bottle. The reaction vessel was a 300cc, magnetically stirred, high form pyrex beaker. A combination hotplate stirrer and a 1/8" stainless steel cooling loop provided a simultaneous cooling ballast to the reactor. Two 200 watt quartz immersion heaters on a control circuit maintained temperature stability. The control circuit consisted of the immersion heaters on variacs and a Matheson "Lab Stat" proportional controller which sensed the mercury level in a thermometer with 0.1°C divisions. In this way temperature could be controlled to $\pm$0.2°C. The reactor also contained three cylindrical baffles and two feed lines. Product was continuously withdrawn from the reactor by another tubing pump. The volume of fluid in the reactor could be varied by adjusting the height of the product withdrawal line. For these studies this unit was operated in the following manner.

The feed pumps were started and set to the desired control point. Feed streams were then recycled to the storage reservoirs for thirty minutes to allow the pumping rates to come to steady-state. Feed rates were then individually measured, the reactor filled, and brought to the desired temperature. A small amount of glyceraldehyde was then added to the reactor to speed attaining steady-state. Actually the reaction is self-initiating and no product addition is necessary if sufficient time is available. The reactor was then run from ten to fifteen residence times to ensure steady-state conditions. To confirm that steady-state was attained, if duplicate consecutive HCHO measurement by $Na_2SO_3$ titration in a four residence time period was had, it was presumed that the time allowed to reach steady-state was sufficient.

Samples were taken in the following manner. A known volume of 1.00 molar HCl was pipetted into a 200cc volumetric flask. The amount of acid was always in excess of that required to neutralize the $Ca(OH)_2$ catalyst in the product. The entire product stream was then fed into the flask until full. This sample was also timed to check the flow rate out

of the reactor. A portion of this acidulated sample was back titrated until neutral to thymalpthalein (PH 9.5) by 1.00N NaOH. This back-titration provided the basis for calculation of Cannizzaro effects; and then, this same neutralized sample was used for the sodium sulfite test for formaldehyde. Another portion was adjusted to pH4 with NaOH and freeze dried for gas chromatography. The remaining acidulated sample was refrigerated for later use in the chromatropic acid test for formaldehyde.

The $Ca(OH)_2$ flow rate to the reactor was then changed and measured, the reactor again allowed to come to steady-state, followed by another analysis. In this way several experiments could be performed in a given ten hour period at constant formaldehyde feed rate.

III. Experimental Results

Several series of experiments were carried out to determine the effect of formaldehyde and calcium hydroxide concentrations on reaction rate. In any given series the formaldehyde feed rate was held constant while $Ca(OH)_2$ feed rate was altered. By this means, products were produced over the complete formaldehyde conversion range.

Figure (1) shows the formaldehyde reaction rate as a function of total calcium molarity at 60°C. The data fit a series of parallel straight lines with parameters of formaldehyde feed rate. Of course, at very high conversion, reaction rate approximates feed rate and linearity is lost. It was noted that an increase in formaldehyde feed rate decreased the reaction rate at any given total calcium molarity. This apparent negative order functionality in formaldehyde is due to Cannizzaro reaction of the $Ca(OH)_2$ catalyst. In some cases as much as fifty percent of the $Ca(OH)_2$ was reacted, and so, calcium salts that are not catalysts are included in the total calcium in the reactor.

Figure (2), a plot of formaldehyde reaction rate vs. $Ca(OH)_2$ concentration in the reactor, as determined by acid titration of the product, eliminated the parameters of formaldehyde feed rate at intermediate conversion levels. At these conversion levels formaldehyde reaction rate is first order in $Ca(OH)_2$ and zero order in formaldehyde and product concentrations, or

$$\text{formaldehyde reaction rate} = k\ Ca(OH)_2$$

where $k = 3.5(\text{min}^{-1})$ at 60°C.

In order to eliminate Cannizzaro effects from the formaldehyde reaction rate data, formose reaction rate was defined as (formaldehyde reaction rate - 4 x $Ca(OH)_2$ reaction rate) as determined by the stoichiometry of the Cannizzaro reaction.

$$4\ HCHO + Ca(OH)_2 \rightarrow (CHOO)_2Ca + 2\ CH_3OH$$

Figure (3) records the formose reaction rate as a function of $Ca(OH)_2$ product molarity. One line, independent of HCHO concentration in the reactor, fits intermediate conversion level data. A zero order rate constant can be calculated from this straight line. For the formose reaction at 60°C the rate constant is $3.15(\text{min}^{-1})(\frac{\text{moles HCHO/Liter}}{\text{moles Ca(OH)}_2\text{/Liter}})$. A comparison of Figures 2 and 3 shows that formaldehyde disappears mainly by Cannizzaro reaction at low conversion levels.

These investigations have also confirmed that the formose reaction is autocatalytic. Figure (4) a plot of formose rate divided by $Ca(OH)_2$ concentration vs. formaldehyde molarity in the reactor show that this

normalized rate passes through a maximum as predicted by an autocatalytic rate law. Figure (5) where the normalized rate is plotted against formaldehyde conversion again shows this autocatalytic behavior. Moreover, the plateau in this plot at intermediate conversion levels shows again the zero order nature of the formose reaction by the constancy of rate at wide differences in reactant concentration.

One series of experiments was carried out, at constant formaldehyde and $Ca(OH)_2$ feed rates while temperature was varied, to determine the activation energy of the formose reaction. This series gave a set of reaction rate data which was lower than expected when compared to the rest of the experimental data. The data do, however, show internal consistency. Figure (6) is an Arrhenius plot of these data which yielded an activation energy of 16 Kcal/mole. The point (x) represents the previously mentioned 60°C zero order rate constant value of 3.15.

A study of the Cannizzaro effects in the formose reaction shows that these effects are dependent on formaldehyde conversion level. Figure (7), a plot of Cannizzaro rate vs. formaldehyde conversion rate with parameters of formaldehyde feed rate, shows that Cannizzaro rate passes through a maximum at intermediate conversion levels, then a minimum at higher levels, and finally increases sharply above 95% conversion. Figure (8) is a plot of $\ell n$ (Cannizzaro rate/$Ca(OH)_2$ concentration) vs. $\ell n$ (formaldehyde concentration) taken from both low conversion data in the CSTR and from Acherlof and Mitchell's batch data at the same 60°C temperature. An approximate first order dependency of the Cannizzaro reaction rate on formaldehyde concentration, as well as agreement with batch data are shown on Figure (8).

A summary of the experimental data may be found in Table (1) while a detailed Table of Operating Conditions and Results is presented in Appendix II.

IV. Discussion

The observed autocatalytic and zero order kinetics of the formose reaction have been explained by the postulation of a series of fast equilibrium reactions which incorporate the observed formation of organic complexes with $Ca(OH)_2$.

Herbo[14] has previously discussed Skrabal's[15] rule of the equality of the resulting rates of partial reactions, where for a series of fast consecutive equilibrium reactions,

$$A \rightleftharpoons B \qquad v_1 = \vec{v}_1 - \overleftarrow{v}_1$$

$$B \rightleftharpoons C \qquad v_2 = \vec{v}_2 - \overleftarrow{v}_2$$

$$C \rightleftharpoons D \qquad v_3 = \vec{v}_3 - \overleftarrow{v}_3$$

the net rate for the $i^{th}$ reaction, $v_i$ is effectively a constant while the absolute forward or reverse rates for any of these reactions may be markedly different. For example, the following three reactions proceed at identical rates:

| reaction i | $v_i$ | $\vec{v}_i$ | $\overleftarrow{v}_i$ |
|---|---|---|---|
| 1 | 24 | 120,024 | 120,000 |
| 2 | 24 | 97 | 73 |
| 3 | 24 | 10,432 | 10,408 |

This fact allows steady-state approximations to be carried out on the reactive intermediates

$$\frac{d(B)}{dt} = \vec{k}_1 A - \overleftarrow{k}_1 B - \vec{k}_2 B + \overleftarrow{k}_2 C = 0$$

$$\frac{d(C)}{dt} = \vec{k}_2 B - \overleftarrow{k}_2 C - \vec{k}_3 C + \overleftarrow{k}_3 D = 0$$

Therefore the system will exhibit overall behavior as if the reaction $A \rightleftharpoons D$ was occuring.

Let us now draw an analogy with the $Ca(OH)_2$ catalyzed condensation of formaldehyde ($A_1$) with condensation product, $A_n$, of carbon number n.

$$A_1 + A_n \overset{Ca(OH)_2}{\rightleftharpoons} A_{n+1}$$

with equilibrium constant $K = \dfrac{A^e_{n+1}}{A^e_1 A^e_n}$

(14) Herbo, C., J. Chim. Phys., 47, 454-73 (1950).

(15) Skrabal, A., Mh. Chem., 64, 289 (1934); 74, 293 (1943).

where superscript "e" denotes the concentration at equilibrium. Consider this overall reaction as resulting from four independent kinetic steps.

| Reaction No. | Molecular Process | Description |
|---|---|---|
| 1 | $A_1 + Ca(OH)_2 \rightleftharpoons A^*_1$ | complexing-decomplexing of formaldehyde |
| 2 | $A_n + Ca(OH)_2 \rightleftharpoons A^*_n$ | complexing-decomplexing of $A_n$ |
| 3 | $A^*_n + A^*_1 \rightleftharpoons A^*_{n+1} + Ca(OH)_2$ | condensation of complexed species |
| 4 | $A^*_{n+1} \rightleftharpoons A_{n+1} + Ca(OH)_2$ | decomplexing-complexing of $A_{n+1}$ |

where $A^*_n$ represents the complexed form of $A_n$ with $Ca(OH)_2$.

Furthermore define s as the total number of active sites where;

$$S = Ca(OH)_2 + \sum_{k=1}^{n+1} A^*_k$$

= uncomplexed $Ca(OH)_2$ + complexed organics

= total $Ca(OH)_2$ as determined by acid titration.

The rate expression and equilibrium constant for each of these steps follow, where $\theta_{A^*_n}$ is the fraction of active sites complexed by $A_n$.

| Reaction No. | Rate Expression | Equilibrium Const. |
|---|---|---|
| 1 | $v_1 = \vec{k}_1 A_1 (1-\theta_{A^*_1}-\theta_{A^*_n}\theta_{A^*_{n+1}})S - \overleftarrow{k}_1 \theta_{A^*_1} S$ | $K_1 = \frac{\vec{k}_1}{\overleftarrow{k}_1}$ |
| 2 | $v_2 = \vec{k}_2 A_n (1-\theta_{A^*_1}-\theta_{A^*_n}-\theta_{A^*_{n+1}})S - \overleftarrow{k}_2 \theta_{A^*_n} S$ | $K_2 = \frac{\vec{k}_2}{\overleftarrow{k}_2}$ |
| 3 | $v_3 = \vec{k}_3 \theta_{A^*_n}\theta_{A^*_1} S^2 - \overleftarrow{k}_3 \theta_{A^*_{n+1}} (1-\theta_{A^*_1}-\theta_{A^*_n}\theta_{A^*_{n+1}})S^2$ | $K = \frac{\vec{k}_3}{\overleftarrow{k}_3}$ |
| 4 | $v_4 = \vec{k}_4 \theta_{A^*_{n+1}} S - \overleftarrow{k}_4 \theta_{A^*_{n+1}} (1-\theta_{A^*_1}-\theta_{A^*_n}-\theta_{A^*_{n+1}})S^2$ | $K_4 = \frac{\vec{k}_4}{\overleftarrow{k}_4}$ |

The overall equilibrium constant for this sequence becomes

$$K = \frac{A^e_{n+1}}{A^e_1 A^e_n} = K_1 K_2 K_3 K_4$$

These are obviously nothing more than a direct analogy to Langmuir-Hinchelwood type rate expressions. Sparing the reader the algebra, an expression for the net rate of the overall reaction may be developed for each of these kinetic steps assuming that particular step is rate limiting.

These expressions are the direct analogy of Langmuir-Hinshelwood relationships on a solid catalyst.

| Rate Limiting Reaction | Rate Expression for Overall Reaction |
|---|---|
| 1 | $v = \dfrac{\vec{k}_1 S \; A_1 \frac{1}{K} \frac{A_{n+1}}{A_n}}{1 + K_2 A_n + K_4 A_{n+1} + \frac{K_4}{K_2 K_3} \frac{A_{n+1}}{A_n}}$ |
| 2 | $v = \dfrac{\vec{k}_2 S \; A_n - \frac{1}{K} \frac{A_{n+1}}{A_1}}{1 + K_1 A_1 + K_4 A_{n+1} + \frac{K_4}{K_1 K_2} \frac{A_{n+1}}{A_1}}$ |
| 3 | $v = \dfrac{\vec{k}_3 K_1 K_2 S \; A_1 A_n - \frac{1}{K} A_{n+1}}{\left[1 + K_1 A_1 + K_2 A_n + K_4 A_{n+1}\right]^2}$ |
| 4 | $v = \dfrac{\overleftarrow{k}_4 K_k K_2 K_3 S \; A_1 A_n - \frac{1}{K} A_{n+1}}{1 + K_1 A_1 + K_2 A_n + K_1 K_2 K_3 A_1 A_n}$ |

Experimentally it has been shown[4,5] that formaldehyde and condensation products such as glycolaldehdye, glyceraldehyde, etc. are readily complexed and there is no indication that steps 1 and 2 are rate limiting. The relatively low activation energy of 16 Kcal/mole might suggest that the condensation reaction itself is not rate limiting. This fact would be analogous with general observations for surface reaction controlled heterogeneously catalyzed systems. More important, there is no means of rationalizing zero order behavior from the third rate expression.

Assume that step 4, the decomplexing reaction is rate limiting. Since complexing takes place so readily $K_1$ and $K_2 \gg 1$. It has been shown by us and also other investigations[6,7] that the formose reaction is effectively unidirectional

$$A_1 + A_n \rightarrow A_{n+1}$$

and therefore $K_3 \gg 1$.

Neglecting the reverse reaction (which would only be important at extremely high conversion levels) expression 4 reduces to

$$v = \frac{\overleftarrow{k}_4 K_1 K_2 K_3 S A_1 A_n}{K_1 A_1 + K_2 A_n + K_1 K_2 K_3 A_1 A_n}$$

At low conversion levels where $A_1 \gg A_n$,

$$v = \overleftarrow{k}_4 K_2 K_3 S A_n$$

which implies autocatalytic behavior. Furthermore, at intermediate conversion levels since $K_k K_2 K_3 \gg 1$ the $K_1 K_2 K_3 A_1 A_n$ term in the denominator of the rate expression will predominate and the rate expression becomes,

$$v = \overleftarrow{k}_4 S$$

zero order in product and formaldehyde as experimentally observed. At high conversion, a first order relationship can be developed

$$v = \overleftarrow{k}_4 K_1 K_3 S A_1 \text{ - (reverse rate)}.$$

The validity of this has not been tested experimentally. Not only the behavior of the formose reaction, but also the behavior of the Cannizzaro reaction can be accounted for.

At low formaldehyde conversion levels, the first order dependency of the Cannizzaro reaction on formaldehyde and $Ca(OH)_2$ can be explained as follows: Consider March's[9] mechanism for the Cannizzaro reaction

$$RCHO + OH^- \xrightarrow{k_{c1}} RCH(O^-)(OH)$$

$$RCH(O^-)(OH) + RCHO \xrightarrow{k_{c2}} RCOOH + RCH_2O^-$$

which has the following rate expression

$$\frac{d(RCHO)}{dt} = k_{c1}(RCHO)(OH^-) + k_{c2}(RCH(O^-)OH)(RCHO)$$

A steady state approximation on the intermediate anion

$$\frac{d\,RCH(O^-)OH}{dt} = k_{c1}(RCHO)(OH^-) - k_{c2}(RCH(O^-)OH)(RCHO) = 0$$

reduces the Cannizzaro rate expression to

$$\frac{d(RCHO)}{dt} = 2\,k_{c1}(RCHO)(OH^-)$$

The maximum in the Cannizzaro rate at intermediate conversion levels must follow. Consider again the Cannizzaro rate expression for formaldehyde

$$r_c = k_c \, HCHO \;\; Ca(OH)_2 \qquad \text{where } k_c = 2k_{c1}$$

and the rate expression for the formose reaction

$$r_f = \overleftarrow{k}_4 \, Ca(OH)_2 = \frac{A°_1 - A_1}{\tau}$$

where $A°_1$ is the inlet formaldehyde concentration into the reactor and $\tau$ is the residence time. Since generally $r_f > r_c$

$$\frac{A°_1 - A_1}{\tau} = \overleftarrow{k}_4 \, Ca(OH)_2$$

Furthermore define fractional conversion x such that

$$(1-x) = \frac{A_1}{A°_1}$$

$$r_c = k_c \, Ca(OH)_2 A°_1 (1-x)$$

and

$$Ca(OH)_2 = \frac{A°_1 x}{k\tau}$$

substituting and differentiating the rate expression to find the fractional conversion where the differential of the rate equals zero. We find that the maximum will occur at 50% conversion. Admittedly this is an over-simplified approach, for other aldehydes in the system may also undergo Cannizzaro reaction, but it does qualitatively account for the observed behavior of Cannizzaro passing through a mixiumum at intermediate conversion levels.

At extreme conversion levels, e.g. 95%, where conditions are forced, it is not unreasonable that Cannizzaro reaction of products becomes excessive.

V. Analytical Techniques and Observations

The main barrier to the precise determination of the kinetics of the formose reaction is the analysis of the reaction products. Formose is believed to consist of unreacted formaldehyde, glycolaldehyde, $C_3$-$C_8$ aldoses and ketoses and branched chain sugars which are not found in natural carbohydrate mixtures. Due to Cannizzaro effects these compounds may be present in oxidized or reduced forms.

The following techniques are now being employed to reach quantitative and qualitative conclusions concerning the nature of formose reaction products. Detailed analytical procedures are presented in Appendix 1.

Formaldehyde concentrations are determined by two independent methods, the sodium sulfite and chromotropic acid tests.

The sodium sulfite test[16] is based on the reaction;

$$HCHO + Na_2SO_3 + H_2O \rightarrow NaOH + CH_2(NaSO_3)OH$$

and the subsequent neutralization by HCl of the NaOH formed. This technique was used to give a rapid estimate of formaldehyde concentrations in the reaction product. It has been shown, however, that the sodium sulfite test is not specific to formaldehyde due to interference of lower molecular weight aldoses and ketoses, which are reaction products. Table (2) shows the fractional recovery (moles NaOH liberated/mole of aldose or ketose) for some aldoses and ketoses. As a result of this observation the highly specific chromotropic acid test was employed.

Chromotropic acid (4,5-Dihydroxynapthalene-2,7-disulfonic acid) reacts with formaldehyde in the presence of concentrated sulfuric acid at elevated temperatures to give a characteristic violet color which can be monitored colorimetrically at 570mμ. The procedure of Bricker and Johnson[17] was slightly modified by consistantly using a 10 ul aqueous sample whose formaldehyde molarity was between 0.03 to 0.11. Results were reproducible to within 0.5% of full scale colorimeter reading. A comparison of the results obtained by the sodium sulfite and chromotropic acid tests is shown in figure (9). When the conversion level of formaldehyde, as calculated using the results of the two tests, was compared the results were identical to within experimental

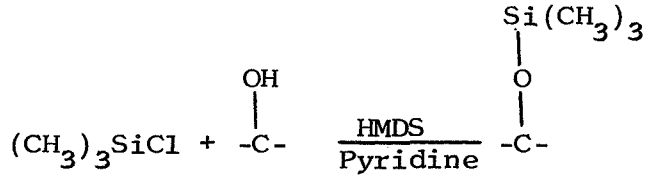
(16) Walker, J.F., "Formaldehyde," Amer. Chem. Soc. Monograph Series, No. 159, p. 486, 3rd Ed., Reinhold Pub. Corp., N.Y. (1964).

(17) Bricker, C.E. and Johnson, H.R., Ind. Eng. Chem., 27, 400-407 (1945).

error up to conversion levels of 95% where some interference with the chromotropic acid test was noted by a rose color instead of the characteristic violet color. Figure (10) shows this comparison with parameters of reaction selectivity to glycolaldehyde. The agreement of the two tests is an indication that selectivity of the formose reaction to lower molecular weight aldoses and ketoses is minimal under the conditions used in this experimental study.

Analysis of the condensation products of the formose reaction does not lend itself to wet chemical tests due to the complex nature of the product mixture. In the past five years, however, literature[18] on the gas chromatography of the trimethylsilyl (TMS) ether derivatives of carbohydrates and their corresponding oxidized and reduced forms has been extensive.

Trimethylchlorosilane (TMCS) reacts quantitatively with a hydroxyl group in the presence of heramethyldisilazane (HMDS) and pyridine to give a TMS ether function



The resulting ether is sufficiently volatile to lend itself to gas chromatography.

A 50 foot Perkin-Elmer Support Coated Open Tubular (SCOT) column with OV-17 methyl phenyl silicone gum liquid phase, as described by Averill[19], was used for separation of the TMS derivatives. The advantages of this column over a conventional packed column are better resolution, sharper peaks, and relatively short analysis time ($\approx$45 minutes). The procedure of formation of the TMS derivatives is basically that of Sweeley[20], where a two to one volumetric mixture of HMDS and TMCS is reacted with a sample dissolved either in pyridine or acetonitrile. The following experiments were conducted in order to confirm Sweeley's results and adopt the procedure to our specific needs.

Experiments were conducted at Worcester Polytechnic Institute on a Perkin-Elmer Model 900 gas chromatograph equipped with dual flame ionization detectors, capillary inlet system and the OV-17 column previously described. Typical operating conditions are injector and detector temperature 220°C, column, linear temperature program from 100° to 220°C at 4°C/min, $N_2$ carrier at 4 cc/min STP.

(18) "A Bibliography of Silylation" Pierce Chem. Co. 1967.

(19) Averill, W., Perkin-Elmer Instrument News, 18, No. 2, p. 10.

(20) Sweeley, C.C., Bentley, R., Makita, M., and Wells, W.W., J. Amer. Chem. Soc., 85, 2497-2507 (1963).

Ethylene glycol, in quantities ranging from 0.05 to 0.50 ml. was silylated in 2.0 ml acetonitule by 1.0 ml HMDS and 0.5 ml TMCS to determine the practical silylating capacities of these reagents. Maximum sample quantity is 0.10 ml, as shown by Figure (11), a plot of relative detector response vs. ml. ethylene glycol. Below the 1.0 ml. sample level, detector response is linear with sample size. This is shown in Figure (12) which records the results of experiments made using from 0.02 to 0.10 ml. of a 50/50 weight % mixture of ethylene glycol and glycerol with 2.0 ml. pyridine, 1.0 ml. HMDS and 0.5 ml. TMCS.

It was found that water does not interfere with the linear response of the detector. Figure (13) shows results obtained of the 50/50 ethylene glycol-glycerol mixture diluted with as much as four times the quantity of water. However great care must be taken to avoid flashing during silylation, since the reaction of TMCS with water is rapid and exothermic.

Experiments where a mixture of ethylene glycol, glycerol, erythritol, arobitol, and mannitol were dissolved in pyridine and silylated show that the flame ionization detector gave a constant response (peak area/gm) for all these compounds to within $\pm$ 10%.

Further experimentation was conducted at Ames Research Center using a similarly equipped Perkin-Elmer Model 800 gas chromatograph, the OV-17 column, and the same operating conditions as previously described.

Carbohydrate reference standards most of which were "A" grade from Cal. Biochem. were individually dissolved in pyridine and silylated. The OV-17 column separated anomers of erythrose, arabinose, lyxore, xylore, ribose, galactose, mannose, fructose, and glucose. Sweeley has observed similar behavior on a SE-52 silicone gum packed column. These studies also confirmed the observation that dihydroxyacetone and glyceraldehyde are present mainly as dimers. Table (3) is a comparison of relative retention time data obtained in this study using the OV-17 column and a 100°-240°C linear temperature program at 4°C/min, Sweeley's results on the SE-52 column at 140°C, and Averill's results on the OV-17 column linear temperature program 150°-200°C at 2.5°C/min. Relative retention time data presented in this study were obtained in the following manner.

Due to the fact that the absolute value of the retention time could vary as much as $\pm$0.5 minutes, even after the carrier gas flow rate and the time the column was allowed to soak at the initial temperature had been rigorously controlled, relative retention times were calculated by using a mixture of known compounds. Several mixtures of compounds whose retention times fell into a range of less than 7 minutes were built up one compound

at a time which allowed positive identification of the components of the mixture. A maximum deviation of $\pm$0.05 minutes in the retention time difference between 2 peaks in any given mixture could be attained. The values of relative retention times presented in this report are for a mixture where the retention time of β-glucose was 29.6 minutes. The reference standard for glyceraldehyde showed a distribution of several peaks whose retention times were between 24 and 26 minutes, the major of which was at 25.7 minutes. A mixture of glyceraldehyde and dihydroxyacetone intensified the first peak of the glyceraldehyde series. An experiment where glyceraldehyde was recrystallized from ethanol in an effort to eliminate impurities shifted the major peak to the first in the series indicating an isomerization to dihydroxyacetone while other impurities were not eliminated.

Another series of experiments were conducted with ribose to determine the effect of the pyridine solvent on the distribution of anomers and isomerization to other five carbon aldoses. One sample was silylated immediately after it had dissolved in room temperature pyridine while 3 others were heated in 70°C pyridine for 30, 120, and 450 minutes before silylation. A typical chromatogram of ribose has 3 peaks.

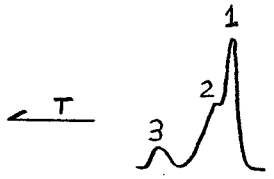



Table (4) shows the relative peak areas for the three peaks after the treatment in pyridine. Some anomerization but no isomerization to other aldoses was observed.

## VI Conclusions

In summary, the following conclusions are apparent.

I. The C.S.T.R. has proved to be an excellent means of studying the kinetics of the formose reaction.

II. The observed autocatalytic and zero order nature of the formose reaction appears to be the result of complexing-decomplexing reactions.

III. The use of Langmuir-Hinshelwood type kinetics should prove to be a valuable tool in the description of the kinetics of homogeneously catalyzed systems.

IV. Considerable progress has been made in developing gas-chromatographic techniques for the analysis of formose reaction products.

# APPENDIX I

## Sodium Sulfite Test for Formaldehyde

(1) Transfer 50 ml. of a 1 molar sodium sulfite solution to a 250 ml Erlenmeyer flask.

(2) Add 5 drops of thymolphthalein indicolor solution (0.1% in ethanol)

(3) Neutralize sodium sulfite solution with 1 molar HCl until blue color disappears (one or two drops will suffice)

(4) Add volumetrically a neutral sample of the solution to be analyzed. This sample should not contain more than 0.025 moles of formaldehyde

(5) Stir magnetically and titrate slowly with analytical standard NaOH until blue color disappears. The endpoint is not extremely sharp, therefore keep a reference blank for comparison.

(6) The molarity of HCHO in the sample is calculated as follows:

$$\text{HCHO molarity} = \frac{(\text{molarity of NaOH})(\text{ml NaOH})}{(\text{ml sample})}$$

# Chromotropic Acid Test for Formaldehyde

(1) Turn on spectrophotometer (Bausch and Lomb Model 20) and check to see that wavelength is set to 570mμ. Allow at least 30 minutes for the instrument to warm up.

(2) Dilute samples to be analyzed to a formaldehyde concentration between (0.03 - 0.11) molar using pipettes and volumetric flasks. Always use distilled water.

(3) Make up Chromotropic acid sol. (o.10 gm of the disodium salt (Aldrich Chem Co.)/ml. distilled $H_2O$. This sol. will be useful for 48 hours. After this time period the acid will turn dark and affect the results of the test.

(4) Inject 0.5 ml of the chromotropic acid sol. using a 1.0 ml tuberculin syringe into a graduated 10 ml glass stoppered test tube.

(5) Inject 10.0 μl of the sol. to be analyzed into the test tube containing the chromotropic acid. A standard 10 μl syringe from Hamilton is recommended.

(6) Pipette 5.0 ml concentrated $H_2SO_4$ directly down the center of the test tube containing the chromotropic acid and sample. This will eliminate mixing problems later on.

(7) Rotate the test tube on an angle such that the solution wets the walls up to the 10 ml line.

(8) Stopper the test tube and place in boiling water for 30 min.

(9) While the solution is in the boiling water bath adjust the left hand knob of the spectrophotometer to 0% transmittance with no cuvette in the holder and the door closed. Fill the cuvette to be used with distilled water, make sure that the outside of the cuvette is dry. Insert the cuvette into the holder, close the cover and adjust the right hand knob until the instrument reads 100% transmittance. The instrument is now ready for use.

(10) When the samples have been heated for 30 minutes remove them from the bath and quench in an ice bath.

(11) Transfer the entire contents of the test tube through a 35 mm funnel into a 50cc volumetric flask. This can be done by rinsing the lip and inside of the test tube several times and transferring the rinse water to the volumetric flask. Fill the volumetric flask to the mark and let the contents come to room temperature. Check level again and add water if necessary. Stopper the flask and mix contents well.

(12) Rinse the cuvette with the diluted sample 3 times, wipe outside dry, insert into instrument, close cover and read % transmittance.

(13) Calibration curve will give a straight line when log (% transmittance) is plotted against formaldehdye concentration.

(14) What ever you do be consistent!

## Preparation of TMS Derivatives of Formose Reaction Products

(1) Adjust the Ph of the acidulated formose reaction products to 3-4.

(2) Freeze dry the above sample.

(3) In a 5 ml plastic stoppered vial dissolve 50 mg of the freeze dried sample in 1.0 ml pyridine. (heating is required in some cases).

(4) Add 1.0 ml HMDS followed by dropwise addition of 0.5 ml TMCS. Stopper vial, agitate for 30 seconds, and allow to stand 24 hours before analysis.

## Carbohydrate Reduction Procedure

(1) In a 5 ml vial dissolve 50 mg of freeze dried sample in 0.5 ml $H_2O$

(2) Add 25 mg $NaBH_4$.

(3) Let stand for several hours.

(4) Destroy excess $NaBH_4$ by adding HCl until solution is Ph 3. Transfer to 100 ml round bottom blask.

(5) Add 50 ml methanol and dry on a rotary evaporator.

(6) Dissolve reduced solid in 2 ml boiling pyridine and silylate by same procedure used for formose reaction products.

# APPENDIX II

## Formose Experimental Data

| Run No. | 730-1 | 730-2 | 730-3 | 731-1 | 731-2 | 731-3 | 805-3 | 805-5 |
|---|---|---|---|---|---|---|---|---|
| Temperature °C | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 |
| Residence Time (minutes) | 4.71 | 4.94 | 5.37 | 4.60 | 5.33 | 4.39 | 4.92 | 5.32 |
| Formaldehyde Concentration in Combined Feed (moles/liter) | 3.73 | 3.87 | 4.22 | 3.56 | 4.15 | 3.36 | 4.20 | 4.55 |
| $Ca(OH)_2$ Concentration in combined Feed (moles/liter) | 0.221 | 0.176 | 0.070 | 0.269 | 0.098 | 0.329 | 0.254 | 0.163 |
| Formaldehyde Concentration in Reactor by $Na_2SO_3$ (moles/liter) | 0.83 | 1.65 | 3.99 | 0.30 | 3.14 | 0.08 | 0.95 | 2.39 |
| Formaldehyde Concentration by Chromotropic acid (moles/liter) | 0.65 | 1.70 | 4.13 | 0.32 | 3.23 | 0.18 | 0.96 | 2.47 |
| $Ca(OH)_2$ Concentration in Reactor (moles/liter) | 0.198 | 0.133 | 0.047 | 0.252 | 0.063 | 0.315 | 0.187 | 0.117 |
| Formaldehyde Conversion by $Na_2SO_3$ (%) | 77.9 | 57.3 | 5.5 | 91.5 | 24.3 | 97.7 | 77.7 | 48.6 |
| Formaldehyde Conversion by Chromotropic acid (%) | 82.6 | 56.1 | 2.1 | 91.5 | 22.2 | 94.6 | 77.1 | 45.7 |
| $Ca(OH)_2$ Conversion (%) | 10.3 | 24.8 | 33.5 | 6.5 | 35.7 | 4.1 | 26.4 | 28.2 |
| Formaldehyde Reaction rate by $Na_2SO_3$ (moles/liter/min) | 0.618 | 0.449 | 0.044 | 0.709 | 0.189 | 0.747 | 0.663 | 0.416 |
| Formaldehyde Reaction Rate by Chromotropic acid (moles/liter/min) | 0.654 | 0.439 | 0.017 | 0.704 | 0.173 | 0.724 | 0.659 | 0.391 |
| $Ca(OH)_2$ Reaction rate (moles/liter/min x $10^2$ | .485 | .886 | .438 | .379 | .660 | .310 | 1.36 | .864 |

| 805-6 | 806-2 | 806-3 | 806-4 | 807-1 | 807-2 | 807-4 | 807-5 | 807-6 | 808-2 | 808-3 |
|---|---|---|---|---|---|---|---|---|---|---|
| 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 |
| 5.57 | 4.75 | 4.97 | 5.36 | 4.24 | 4.57 | 4.76 | 4.92 | 5.42 | 4.56 | 4.44 |
| 4.83 | 1.67 | 1.76 | 1.92 | 1.48 | 1.57 | 1.78 | 1.84 | 2.03 | 0.65 | 0.65 |
| 0.077 | 0.340 | 0.258 | 0.103 | 0.155 | 0.093 | 0.077 | 0.066 | 0.030 | 0.052 | 0.051 |
| 4.70 | | | 0.32 | 0.09 | 0.22 | 0.76 | 1.06 | 2.01 | 0.06 | 0.03 |
| 4.73 | 0.04 | 0.04 | 0.32 | 0.09 | 0.16 | 0.77 | 1.12 | 2.05 | 0.08 | 0.04 |
| 0.047 | 0.300 | 0.230 | 0.089 | 0.113 | 0.087 | 0.054 | 0.047 | 0.021 | 0.040 | 0.040 |
| 2.7 | 100.0 | 100.0 | 82.1 | 94.2 | 85.7 | 57.4 | 42.2 | 1.0 | 89.4 | 95.6 |
| 2.1 | 97.6 | 97.7 | 83.3 | 93.9 | 89.8 | 56.7 | 39.1 | --- | 87.7 | 93.8 |
| 39.1 | 11.8 | 10.1 | 13.7 | 1.1 | 7.2 | 29.5 | 28.8 | 29.5 | 22.3 | 20.6 |
| 0.024 | 0.352 | 0.354 | 0.297 | 0.329 | 0.293 | 0.215 | 0.158 | 0.004 | 0.127 | 0.140 |
| 0.018 | 0.343 | 0.346 | 0.297 | 0.328 | 0.308 | 0.212 | 0.146 | 0.000 | 0.125 | 0.137 |
| .538 | .845 | .521 | .263 | .031 | .147 | .475 | .385 | .164 | .254 | .273 |

| 813-1 | 813-3 | 813-4 | 813-5 | 814-1 | 814-2 | 816-1 | 816-2 | 816-3 | 816-4 |
|---|---|---|---|---|---|---|---|---|---|
| 70.0 | 65.0 | 60.0 | 55.0 | 55.0 | 50.0 | 60.0 | 60.0 | 60.0 | 60.0 |
| 5.84 | 5.93 | 5.91 | 5.91 | 5.74 | 5.74 | 5.24 | 5.43 | 5.90 | 4.74 |
| 3.05 | 3.05 | 3.05 | 3.05 | 3.00 | 3.00 | 4.92 | 5.11 | 5.60 | 4.41 |
| 0.168 | 0.171 | 0.170 | 0.170 | 0.167 | 0.167 | 0.290 | 0.243 | 0.122 | 0.413 |
| 0.04 | 0.54 | 1.13 | 1.75 | 1.78 | ---- | 1.47 | 2.22 | 5.34 | 0.15 |
| 0.09 | ---- | 1.18 | 1.83 | 1.93 | ---- | 1.46 | 2.22 | 5.60 | 0.13 |
| 0.106 | 0.128 | 0.125 | 0.130 | 0.127 | ---- | 0.193 | 0.155 | 0.058 | 0.360 |
| 98.6 | 82.4 | 63.0 | 42.5 | 40.5 | ---- | 70.1 | 56.6 | 4.75 | 96.64 |
| 97.0 | ---- | 61.3 | 40.0 | 35.7 | ---- | 70.3 | 56.6 | ---- | 97.1 |
| 36.9 | 25.0 | 26.6 | 23.6 | 23.9 | ---- | 33.3 | 36.1 | 52.5 | 12.9 |
| 0.516 | 0.424 | 0.325 | 0.219 | 0.211 | ---- | 0.657 | 0.533 | 0.045 | 0.899 |
| .507 | ---- | 0.311 | 0.206 | .186 | ---- | 0.660 | 0.532 | ---- | 0.903 |
| 1.062 | .721 | .765 | .679 | .695 | ---- | 1.843 | 1.616 | .086 | 1.124 |

# APPENDIX III

Excerpt from Submission

to

Northeast Section, Institute of Food Technologists

for

Annual Undergraduate Scholarship Award

by

Mr. Randall Partridge

Chemical Engineering Freshman

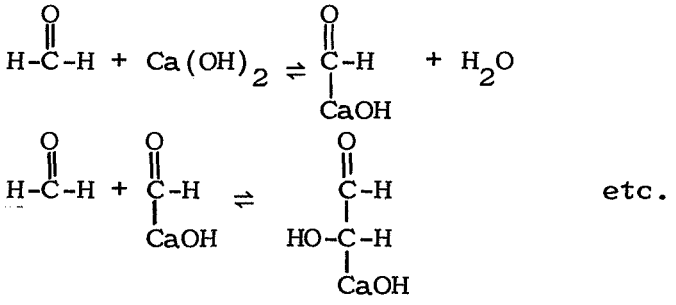
Worcester Polytechnic Institute

Experience in Food Technology

When in high school, I became interested in the separation technique of gas chromatography. As I became more experienced in the field, I began to study the use of gas chromatography for the separation and analysis of complex biochemical mixtures (e.g. protein hydrolyzates). Gas chromatography offers advantages over such techniques as electrophoresis and thin-layer chromatography by producing better separations and more reproducible quantitative data in less time.

Here at W.P.I. Dr. Alvin Weiss has been studying the kinetics and mechanism of the formose reaction under a grant from N.A.S.A. This reaction is of interest to N.A.S.A. because it may be used as the basis of a closed system to produce food for astronauts in sustained spaceflight and also because it offers an explanation of the primordial origin of monosaccharides. Through the Freshman Honors Lab program I have been most fortunate to become involved in this study.

The formose reaction is simply the condensation of formaldehyde in the presence of an alkaline catalyst such as $Ca(OH)_2$. This




reaction is of particular interest because it produces all the possible isomers and stereoisomers of five and six carbon number aldoses and ketoses. Unfortunately, it has previously been shown that these products are toxic to weanling rats when fed at more than fifteen percent of their total diet.

The problem then is to study the reaction and determine which products will be applicable for human consumption or to determine at which point to stop the reaction in order to maximize C-3, which can easily be reduced to glycerol, which is metabolized to D(+)-Glucose by humans. This necessitates an analysis of the formose produced at different time intervals of the reaction. Previous work using gas chromatography has been hampered by the inability of the methods used to supply quantitative data for the lower carbon number species. I have been assigned to develop a rapid, simple and quantitative method for analyzing the carbohydrate content of the formose solution.

Gas chromatography of the trimethylsilyl ether (TMS) derivatives of the hydroxy compounds prepared by a method similar to that of Sweeley [1] was used to analyse the formose solutions initially. The hydroxy compounds were dissolved in pyridine and then reacted overnight with hexamethyldisilizane (HMDS) and trimethylchlorosiline (TMCS). A sample of this reaction mixture was injected directly into the chromatograph.

A 50 foot Perkin Elmer OV-17 SCOT column was used to effect separation of the carbohydrate derivatives. This column has been shown to be quite effective for carbohydrate analysis[2]. A Perkin Elmer Model 900 Gas Chromatograph with capillary inlet system and operated with a temperature program of 100° to 220°C was used for all the analysis. The OV-17 column had negligible baseline drift, even at relatively high sensitivities with this program.

The chromatograms obtained by injecting the TMS reaction mixture directly showed excessive tailing of the pyridine peak. This obscured a number of the low carbon number species to a large extent. The tail of the pyridine peak also resulted in a mound towards the center of the chromatogram when temperature programming which made quantitation difficult.

I overcame the "pyridine problem" by devising an extraction procedure which would remove only the TMS derivatives from the reaction mixture. This was accomplished by converting the pyridine to pyridine hydrochloride with 3 F. HCl, which also served to destroy the excess TMS reagents, and extracting the solution three times with 1:1 ether-hexane after cooling in ice water. The extracts were combined and evaporated to dryness <u>in vacuo</u> at 30°C on a rotary evaporator. The residue was then dissolved in chloroform and was stored at 0°C with no noticeable decomposition for up to three weeks.

Chromatograms of standard carbohydrates and polyols have shown essentially quantitative transfer of the TMS derivatives and have been excellent with respect to the baseline. Figure 1 illustrates the chromatograms obtained using the two procedures. I have also begun to study the separation of the D and L optical isomers by gas chromatography on optically active and specific liquid phases. This separation may be of considerable value, since only the sugars such as D(+)-Glucose are metabolized by human beings.

The need for the rapid and accurate analysis of complex reactions cannot be overlooked when eventual human consumption is likely. Gas chromatography should prove to be the most rapid and accurate technique for the monitoring

of reactions with the complexity of the formose reaction. With the possibility of producing toxic substances, there is no room for analytical error.

References:

1 Sweeley, C.C., Bentley, R., Makita, M., and Wells, W.W., J. Am. Chem. Soc., 85, 2497-2507 (1963).

2 Averill, W., Perkin Elmer Instrument News, 18, No. 2, p. 10 (1967).

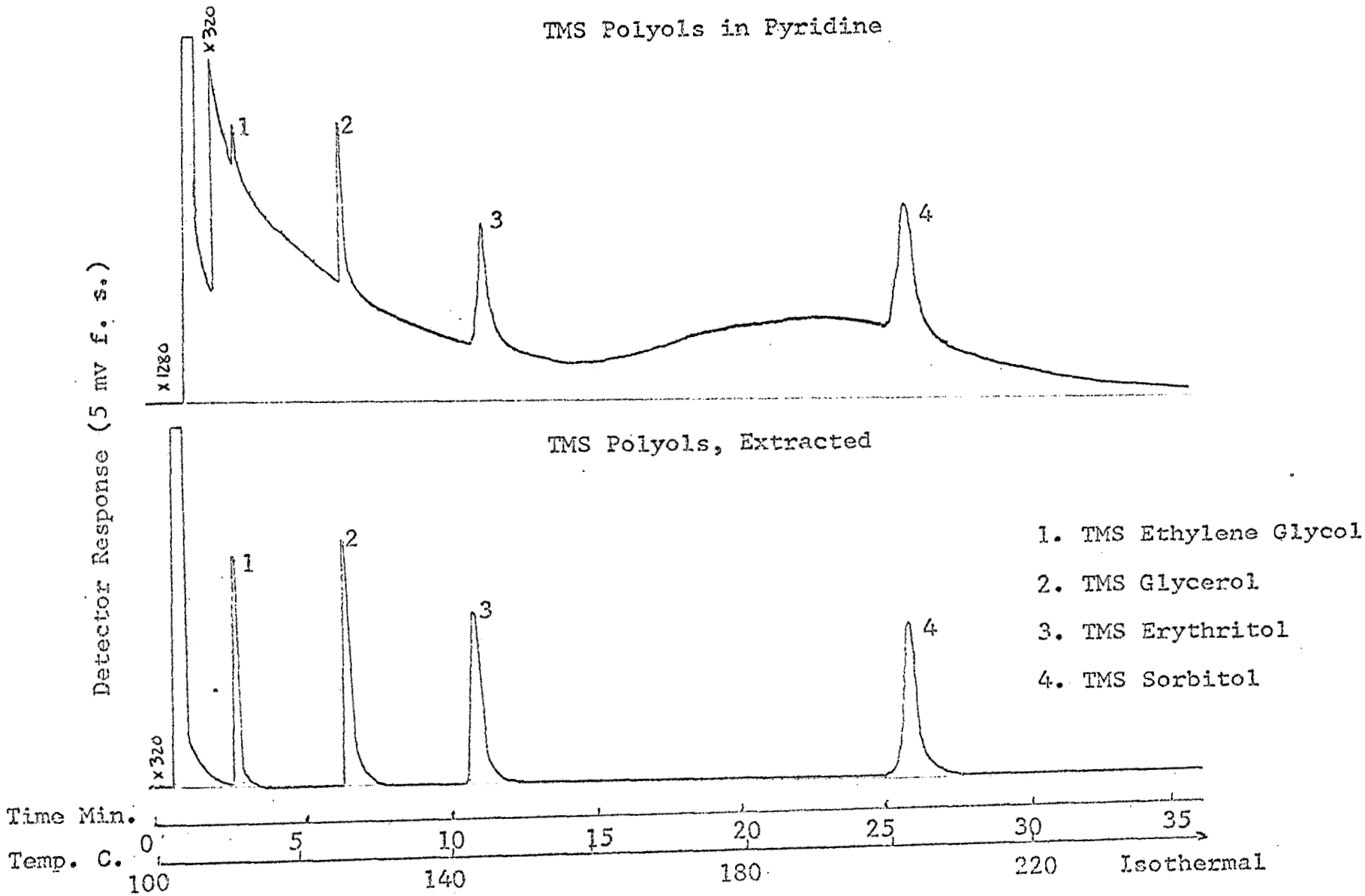



FIGURE 1. COMPARISON OF GC TECHNIQUES

Table 1

Experimental Data

| Run No. | Temp (°C) | HCHO Feed Rate (mol/l/min) | $Ca(OH)_2$ Feed Rate (mol/l/min) | Residence Time (min) | Concentrations in Reactor (moles/liter) $Ca(OH)_2$ by acid titration | HCHO by $Na_2SO_3$ | HCHO by chromotropic acid |
|---|---|---|---|---|---|---|---|
| 808-2 | 60.0 | 0.15 | 0.0113 | 4.56 | 0.040 | 0.06 | 0.08 |
| 808-3 | | 0.15 | 0.0113 | 4.44 | 0.040 | 0.03 | 0.04 |
| 807-6 | | | 0.0055 | 5.42 | 0.021 | 2.01 | 2.05 |
| 807-5 | | 0.37 | 0.0134 | 4.92 | 0.047 | 1.06 | 1.12 |
| 807-4 | | | 0.0162 | 4.76 | 0.054 | 0.76 | 0.77 |
| 807-2 | | | 0.0204 | 4.57 | 0.087 | 0.22 | 0.16 |
| 806-4 | 60.0 | | 0.192 | 5.36 | 0.089 | 0.32 | 0.32 |
| 807-1 | | 0.35 | 0.0272 | 4.24 | 0.113 | 0.09 | 0.09 |
| 806-3 | | | 0.0520 | 4.97 | 0.230 | Nil | 0.04 |
| 806-2 | | | 0.0715 | 4.75 | 0.300 | Nil | 0.04 |
| 730-3 | | | 0.0130 | 5.37 | 0.047 | 3.99 | 4.13 |
| 731-2 | | | 0.0184 | 5.33 | 0.063 | 3.14 | 3.23 |
| 730-2 | 60.0 | 0.78* | 0.0356 | 4.94 | 0.133 | 1.65 | 1.70 |
| 730-1 | | | 0.0469 | 4.71 | 0.198 | 0.83 | 0.65 |
| 731-1 | | | 0.0585 | 4.60 | 0.252 | 0.30 | 0.32 |
| 731-3 | | | 0.0750 | 4.39 | 0.315 | 0.08 | 0.18 |
| 805-6 | | | 0.0138 | 5.57 | 0.047 | 4.70 | 4.73 |
| 805-5 | 60.0 | 0.86 | 0.0306 | 4.55 | 0.117 | 2.39 | 2.47 |
| 805-3 | | | 0.0516 | 4.20 | 0.187 | 0.95 | 0.96 |
| 816-3 | | | 0.0206 | 5.90 | 0.058 | 5.34 | 5.60 |
| 816-2 | 60.0 | 0.94 | 0.0448 | 5.43 | 0.155 | 2.22 | 2.22 |
| 816-1 | | | 0.0555 | 5.24 | 0.193 | 1.47 | 1.46 |
| 816-4 | | | 0.0872 | 4.74 | 0.360 | 0.15 | 0.13 |
| 814-1 | 55.0 | | | 5.74 | 0.127 | 1.78 | 1.93 |
| 813-5 | 55.0 | | | 5.91 | 0.130 | 1.75 | 1.83 |
| 813-4 | 60.0 | 0.52 | 0.0288 | 5.91 | 0.125 | 1.13 | 1.18 |
| 813-3 | 65.0 | | | 5.93 | 0.128 | 0.54 | ---- |
| 813-1 | 70.0 | | | 5.84 | 0.106 | 0.04 | 0.09 |

*$CH_3OH$ Stabilized

Table 2

Sensivity of $Na_2SO_3$ Test to Some Carbohydrates

| Compound | Sample Size (grams) | Fractional Recovery |
|---|---|---|
| Glycolaldehyde | 1.17 | 0.95 |
| Glyceraldehyde | 1.52 | 0.94 |
| | 0.43 | 0.86 |
| Dihydroxyacetone | 1.18 | 0.34 |
| D-Arabinose | 3.06 | 0.217 |
| Fructose | 3.17 | 0.014 |
| Dextrose monohydrate | 3.32 | 0.032 |

Table 3

Relative Retention Times for TMS Derivatives

| Parent Compound | Relative Retention Time OV-17 100°-240°C at 4°C/min | OV-17 150-200 at 2.5°c/min | SE-52 140°C |
|---|---|---|---|
| Ethylene Glycol | 0.118 | ---- | ---- |
| Glycerol | 0.297 | ---- | ---- |
| Glycolaldehyde | 0.355(s) | ---- | 0.039*(s) |
| " " | 0.370 | ---- | 0.044 |
| " " | 0.388(s) | ---- | ** |
| Erthrose | 0.477 | ---- | 0.10 |
| " | 0.490 | ---- | 0.12 |
| " | ** | ---- | 0.14 |
| Erythritol | 0.510 | ---- | 0.16 |
| Dihydroxyacetone | 0.574 | ---- | ** |
| Arabinose | 0.666 | 0.43 | 0.28 |
| Lyxose | 0.666 | ---- | 0.26 |
| Ribose | 0.689 | 0.47 | 0.27(s) |
| " | 0.697(s) | 0.48 | 0.32 |
| Arabinose | 0.708 | ** | 0.33 |
| Lyxose | 0.708 | ---- | 0.33 |
| ribose | 0.715(s) | 0.50(s) | 0.35 |
| Arabitol | 0.737 | ---- | 0.46 |
| Xylotol | 0.737 | ---- | 0.42 |
| ribotol | 0.737 | ---- | 0.46 |
| Xylose | 0.765 | 0.58 | 0.43 |
| Xylose | 0.813 | ** | 0.54 |
| Dihydroxyacetone(2) | 0.813 | ---- | 0.57 |
| β Fructose | 0.823 | 0.67 | 0.69 |
| Mannose | 0.836 | 0.70 | 0.70 |
| Fructose | 0.836 | ---- | ** |
| Galactose | 0.864(s) | ** | 0.076(s) |
| Glyceraldehyde(2) | 0.868 | ---- | 0.48 |
| Sorbose | 0.894 | 0.80 | 0.85 |
| Galactose | 0.894 | 0.80 | 0.88 |
| Mannitol | 0.909 | ---- | 1.21 |
| Mannose | 0.914 | 0.84(s) | 1.08(s) |
| Dulcitol | 0.922 | ---- | 1.28 |
| Sorbitol | 0.922 | ---- | 1.24 |
| Galactose | 0.928 | ** | 1.08 |
| α Glucose | 0.928 | 0.86 | 1.00 |
| β Glucose | 1.000 | 1.000 | 1.57 |

* Sweeley claims this peak is glyceraldehyde monometer

** No peak observed

(s) minor component

Table 4

Effect of Pyridine on Distribution of Ribose Anomers

| Pyridine Treatment before Silylation | Relative Peak Area 1 | 2 | 3 |
|---|---|---|---|
| 15 min at 20°C | 85.8 | 7.0 | 7.2 |
| 30 min at 70°C | 81.3 | 4.5 | 14.2 |
| 120 min at 70°C | 79.7 | 3.4 | 16.9 |
| 450 min at 70°C | 78.0 | 8.4 | 13.6 |

Figure 1

# FORMALDEHYDE CONVERSION RATE AT 60°C

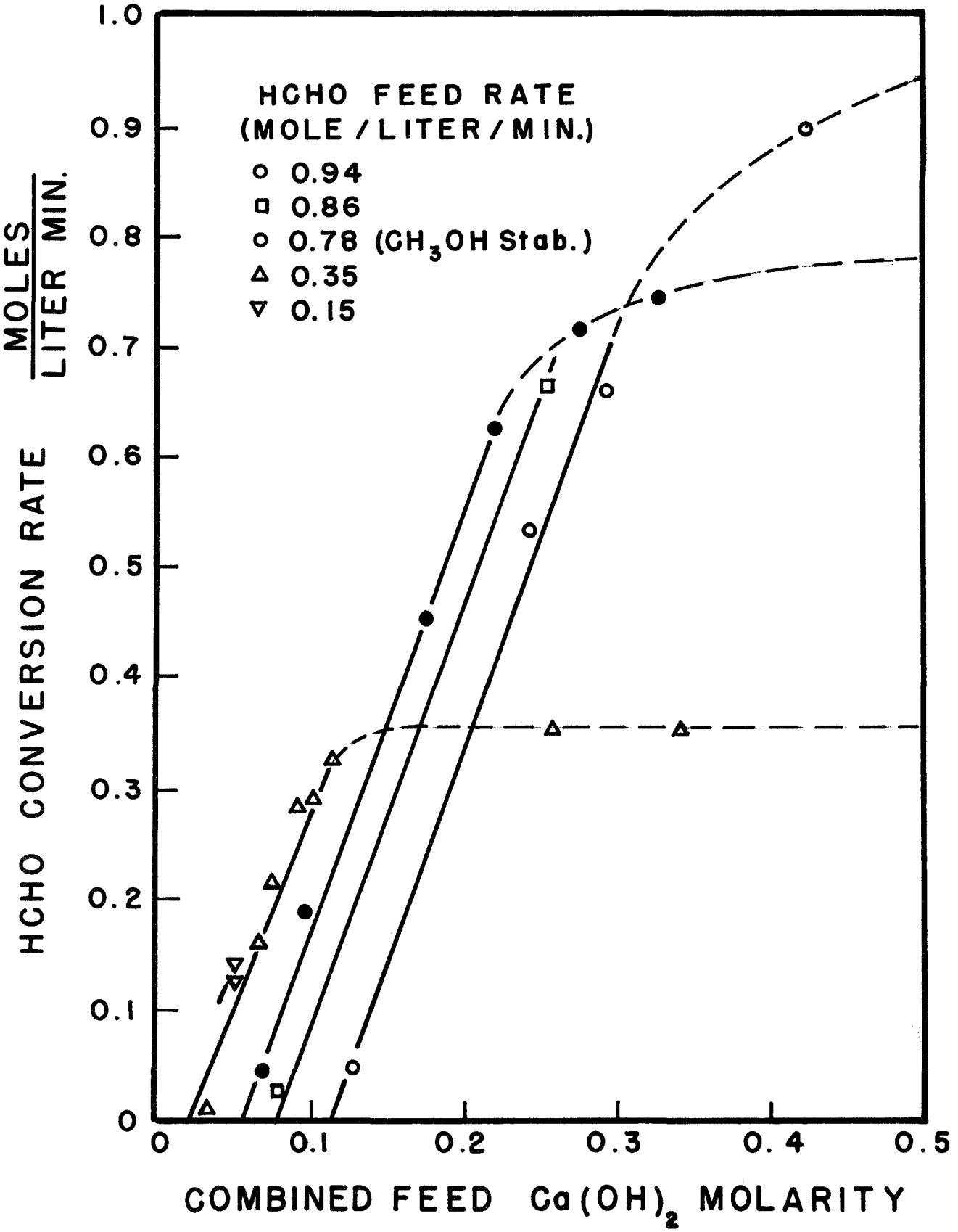


Figure 2

# FORMALDEHYDE CONVERSION RATE AT 60°C DEPENDENCE ON $Ca(OH)_2$ CONCENTRATION

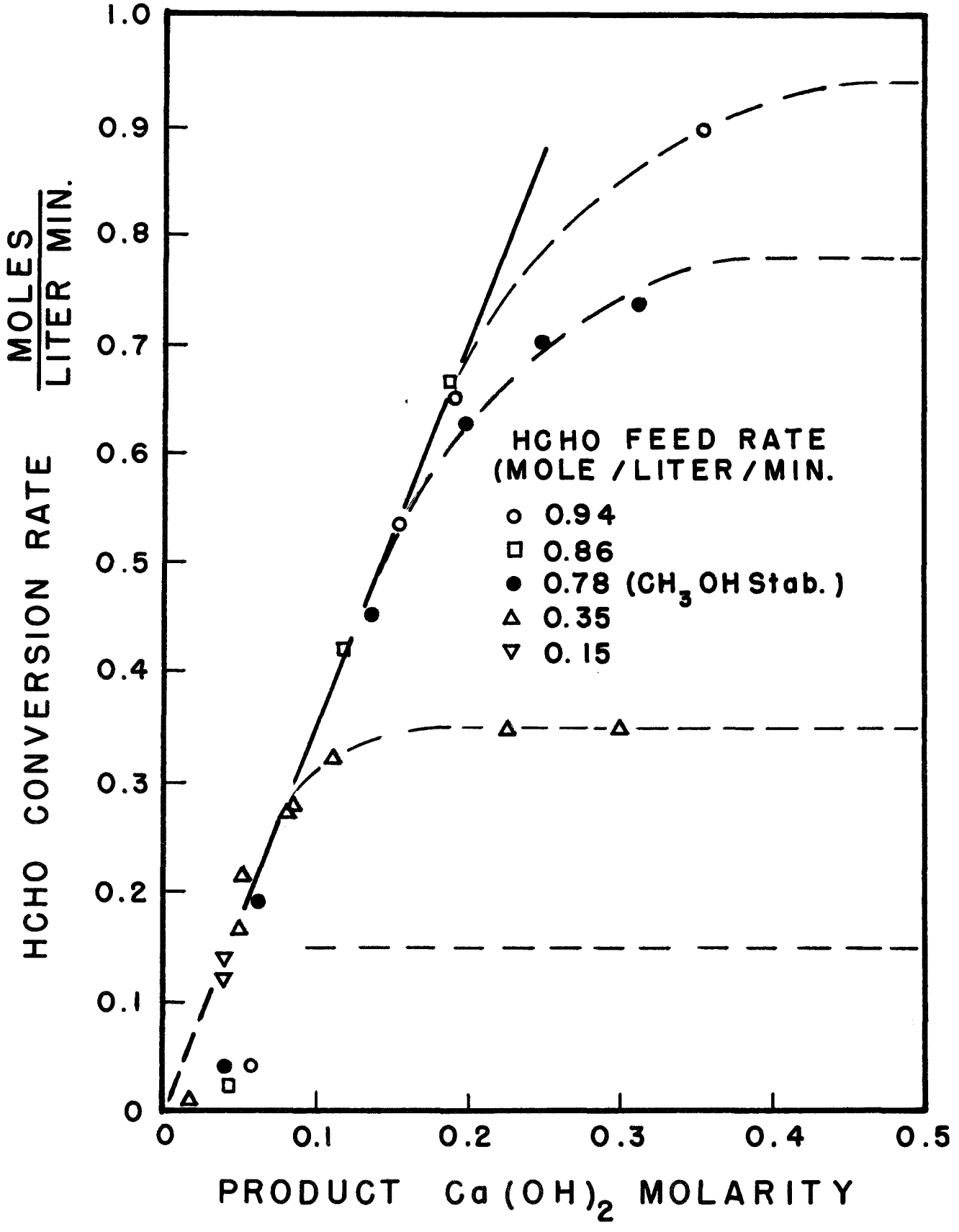


Figure 3

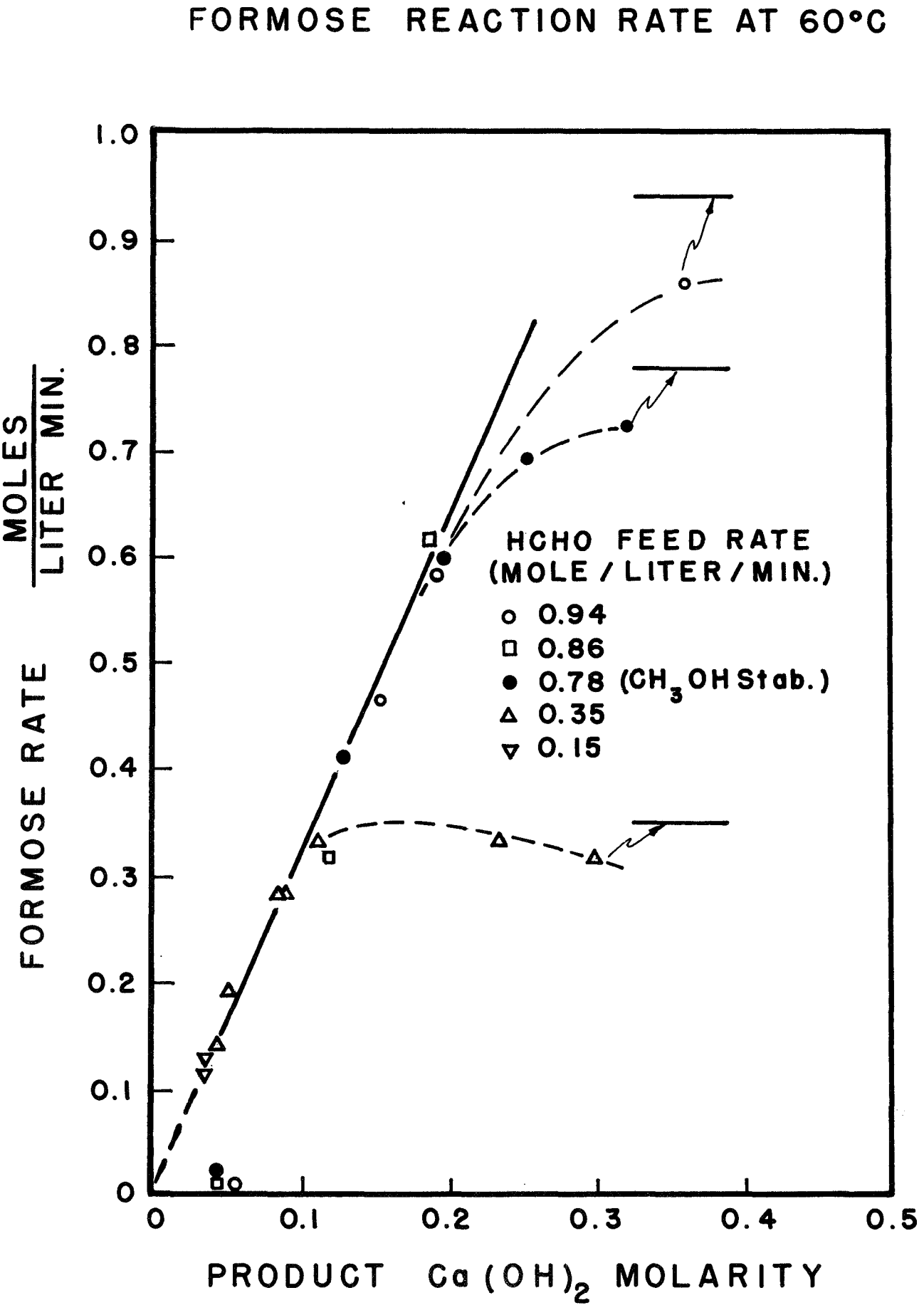

FORMOSE REACTION RATE AT 60°C
FORMOSE RATE
MOLES / LITER MIN.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
PRODUCT Ca(OH)2 MOLARITY
HCHO FEED RATE
(MOLE / LITER / MIN.)
0.94
0.86
0.78 (CH3OH Stab.)
0.35
0.15

Figure 4

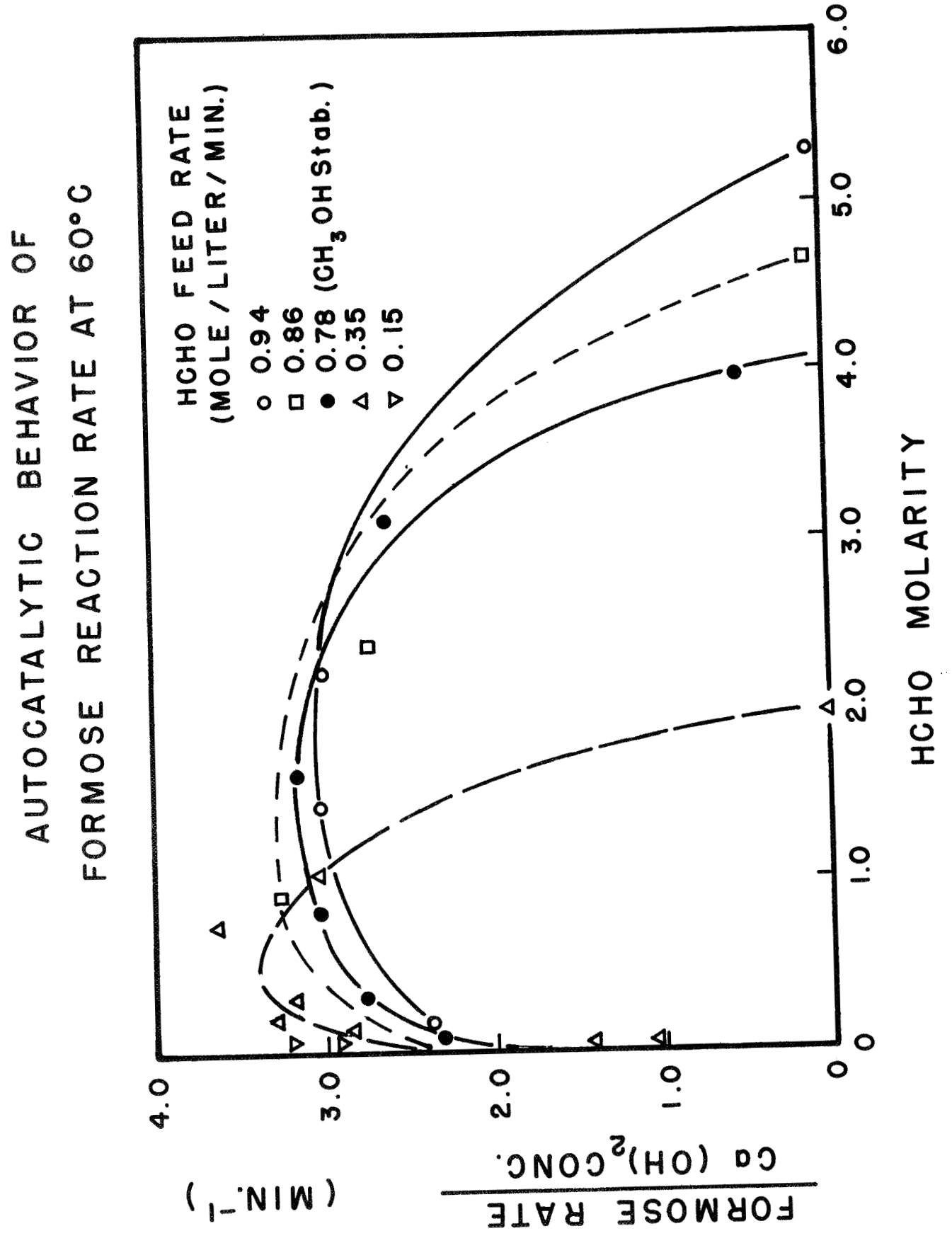

AUTOCATALYTIC BEHAVIOR OF
FORMOSE REACTION RATE AT 60°C
HCHO FEED RATE
(MOLE / LITER / MIN.)
0.94
0.86
0.78 ($CH_3OH$ Stab.)
0.35
0.15
FORMOSE RATE
Ca $(OH)_2$ CONC.
(MIN.$^{-1}$)
HCHO MOLARITY
0
1.0
2.0
3.0
4.0
5.0
6.0

Figure 5

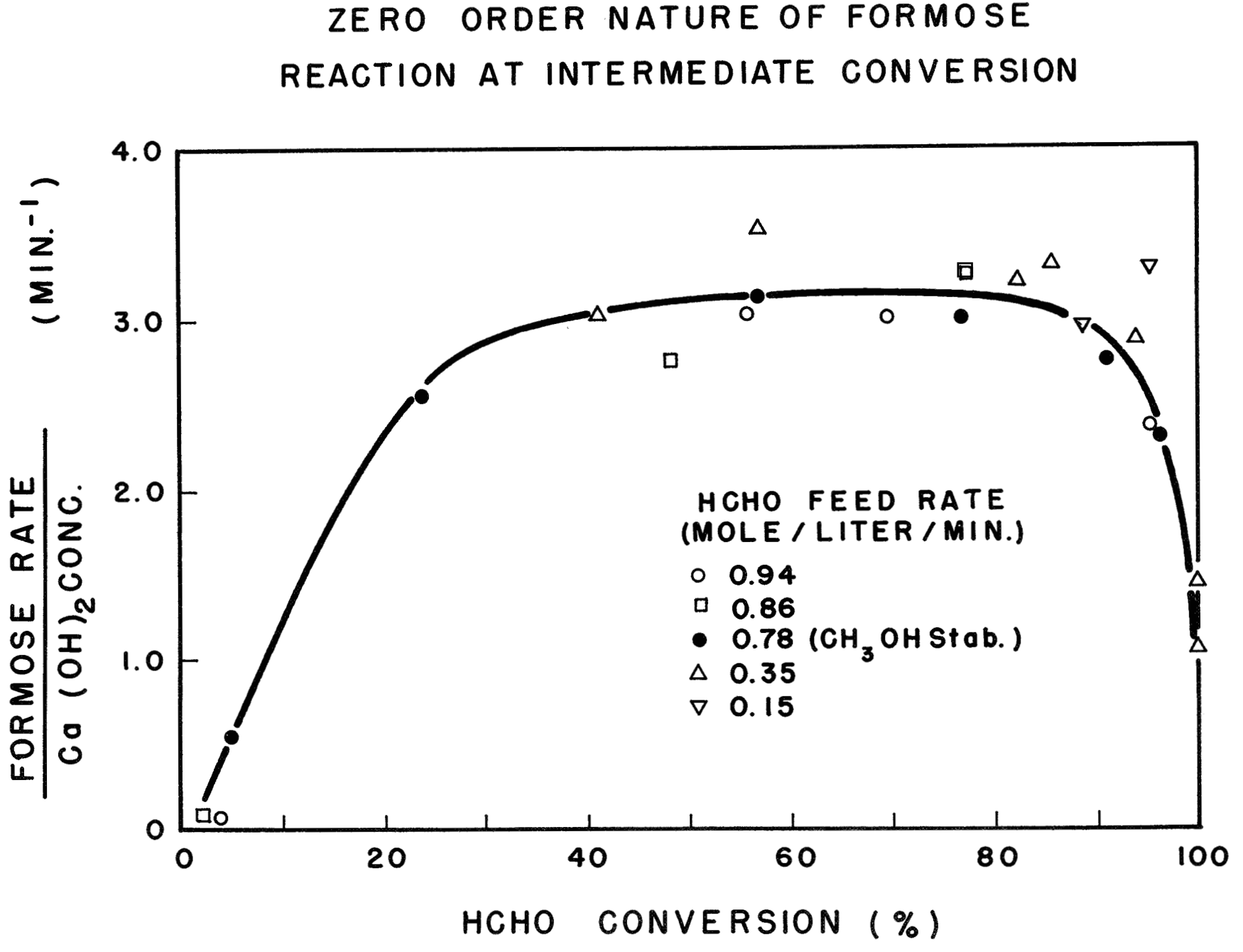

ZERO ORDER NATURE OF FORMOSE
REACTION AT INTERMEDIATE CONVERSION
FORMOSE RATE / Ca (OH)2 CONC. (MIN.-1)
4.0
3.0
2.0
1.0
0
0
20
40
60
80
100
HCHO CONVERSION (%)
HCHO FEED RATE
(MOLE / LITER / MIN.)
0.94
0.86
0.78 (CH3OH Stab.)
0.35
0.15

Figure 6

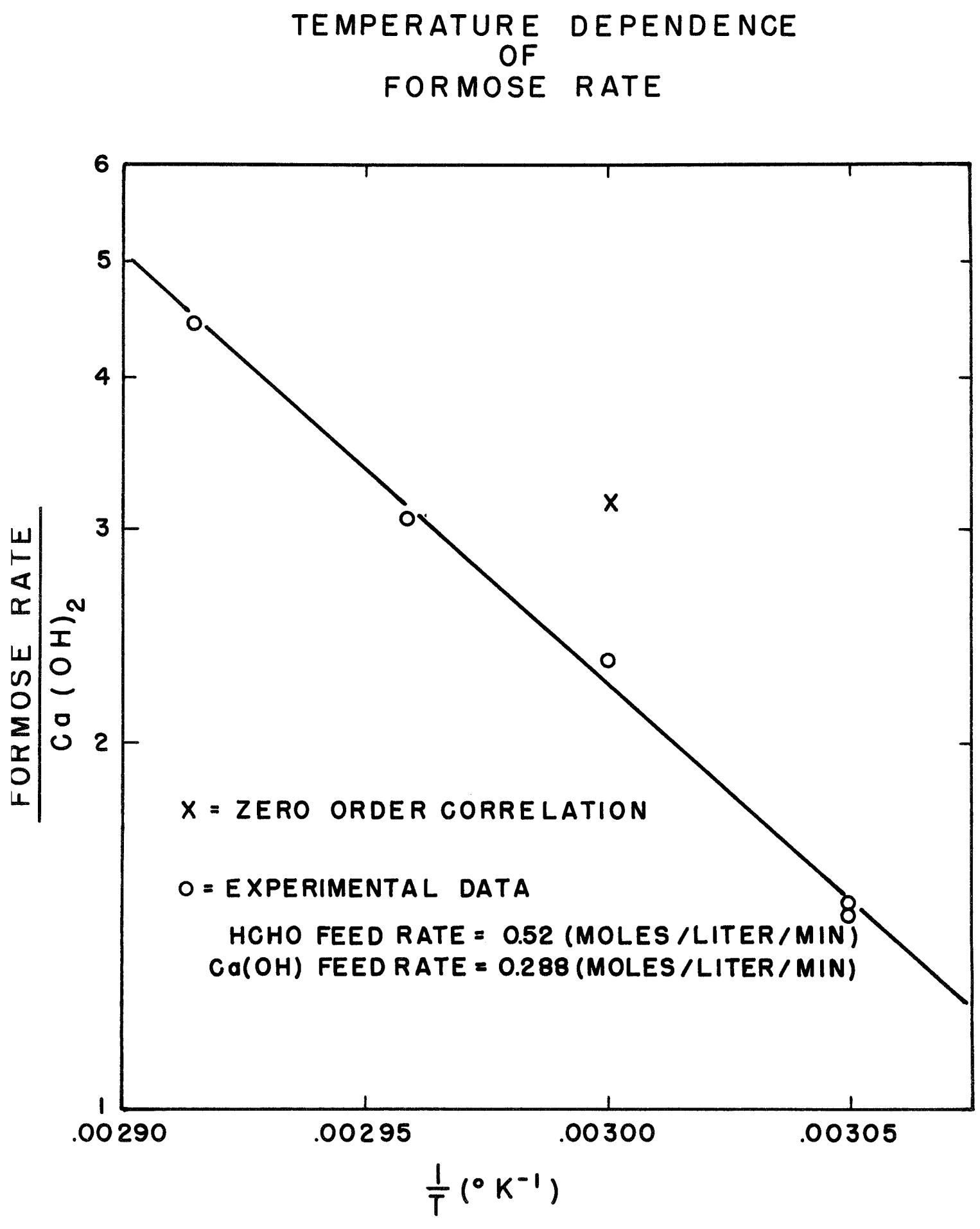

TEMPERATURE DEPENDENCE
OF
FORMOSE RATE
FORMOSE RATE / Ca(OH)2
6
5
4
3
2
1
X
X = ZERO ORDER CORRELATION
O = EXPERIMENTAL DATA
HCHO FEED RATE = 0.52 (MOLES/LITER/MIN)
Ca(OH) FEED RATE = 0.288 (MOLES/LITER/MIN)
.00290
.00295
.00300
.00305
1/T (°K⁻¹)

Figure 7

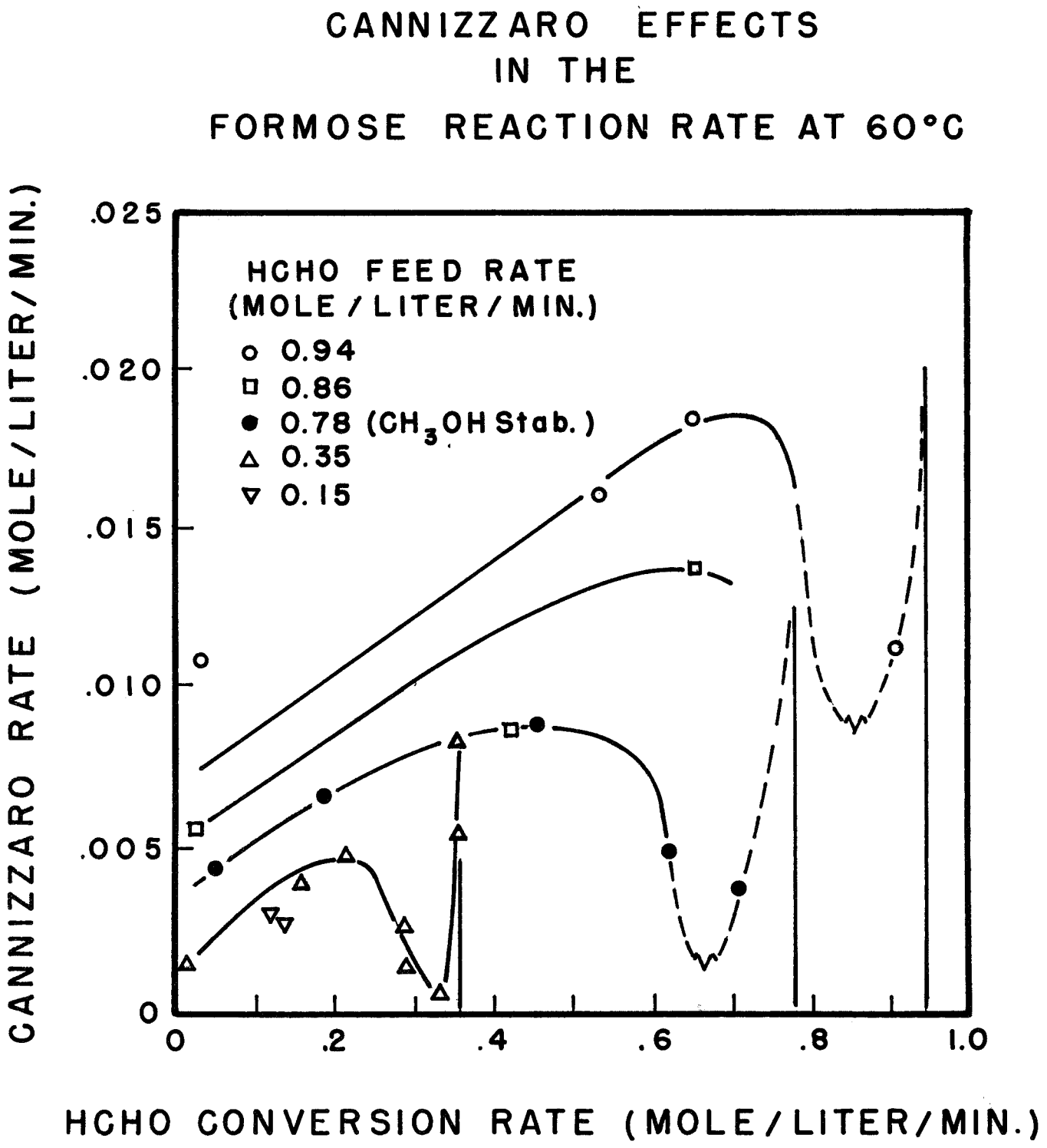

CANNIZZARO EFFECTS
IN THE
FORMOSE REACTION RATE AT 60°C
HCHO FEED RATE
(MOLE / LITER / MIN.)
0.94
0.86
0.78 (CH3OH Stab.)
0.35
0.15
CANNIZZARO RATE (MOLE/LITER/MIN.)
.025
.020
.015
.010
.005
0
0
.2
.4
.6
.8
1.0
HCHO CONVERSION RATE (MOLE/LITER/MIN.)

Figure 8

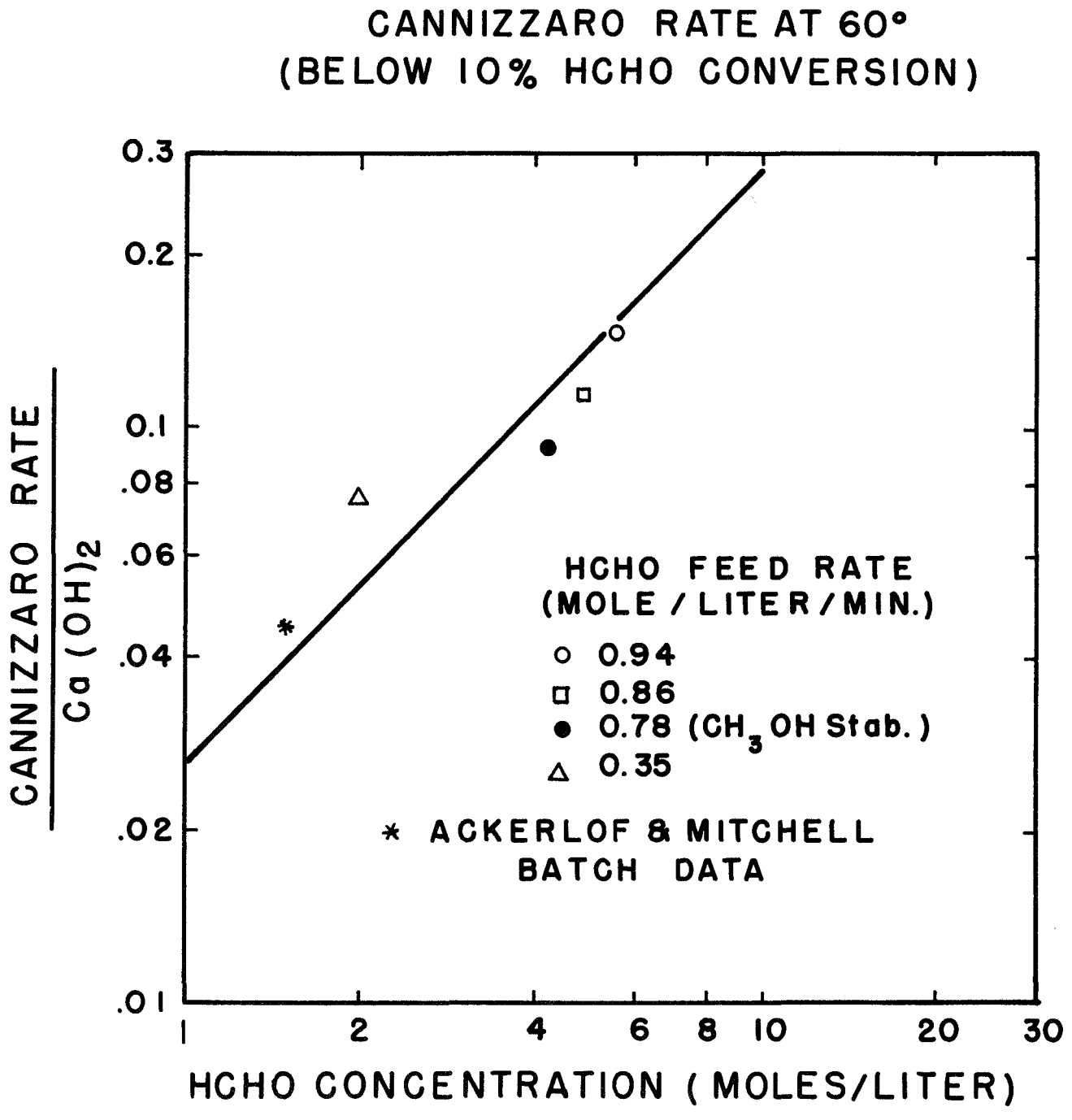

CANNIZZARO RATE AT 60°
(BELOW 10% HCHO CONVERSION)
CANNIZZARO RATE / Ca(OH)2
0.3
0.2
0.1
.08
.06
.04
.02
.01
1
2
4
6
8
10
20
30
HCHO CONCENTRATION ( MOLES/LITER)
HCHO FEED RATE
(MOLE / LITER / MIN.)
0.94
0.86
0.78 (CH3OH Stab.)
0.35
* ACKERLOF & MITCHELL
BATCH DATA

Figure 9

# ANALYSIS OF HCHO IN REACTOR EFFLUENT

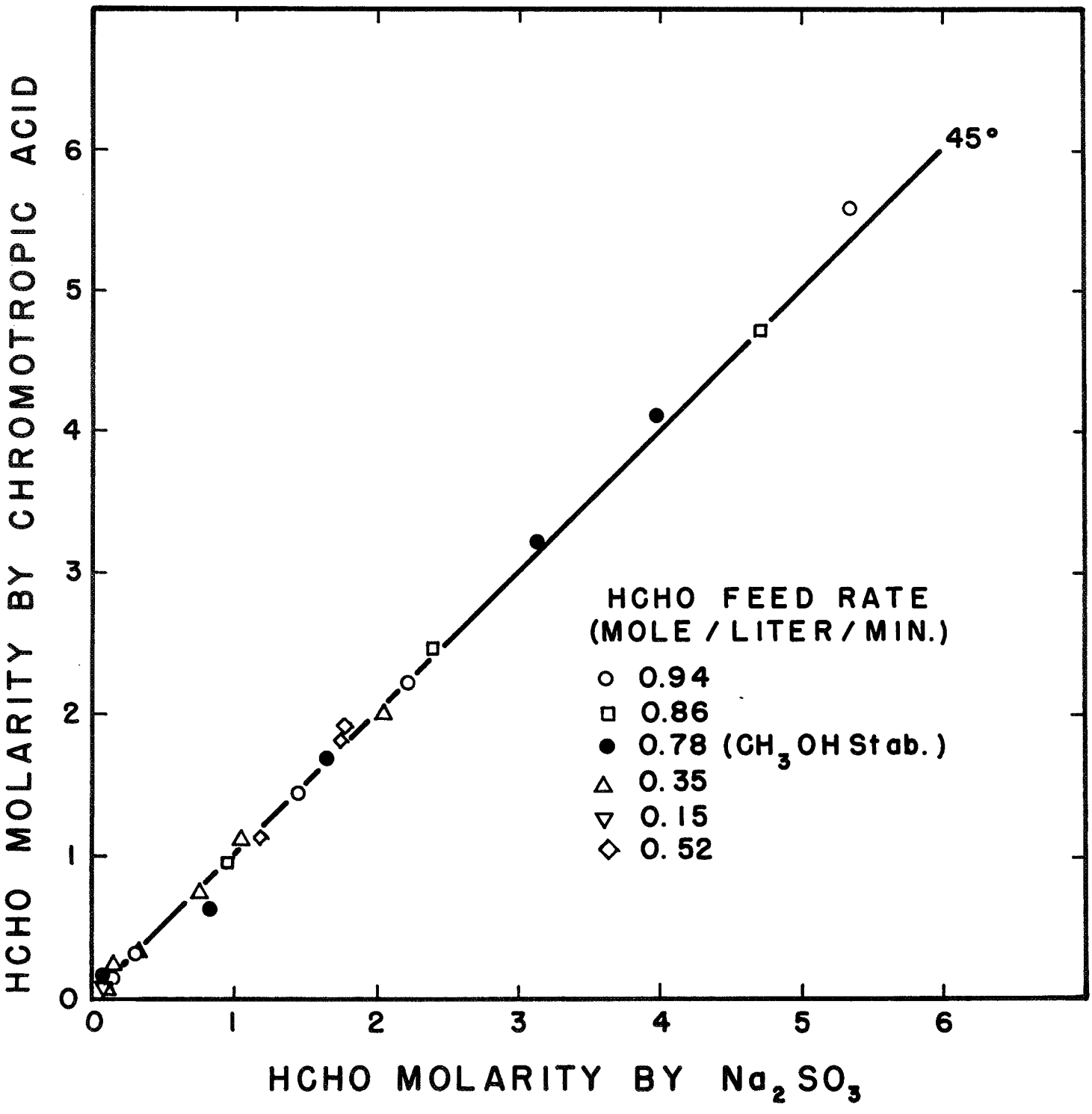


Figure 10

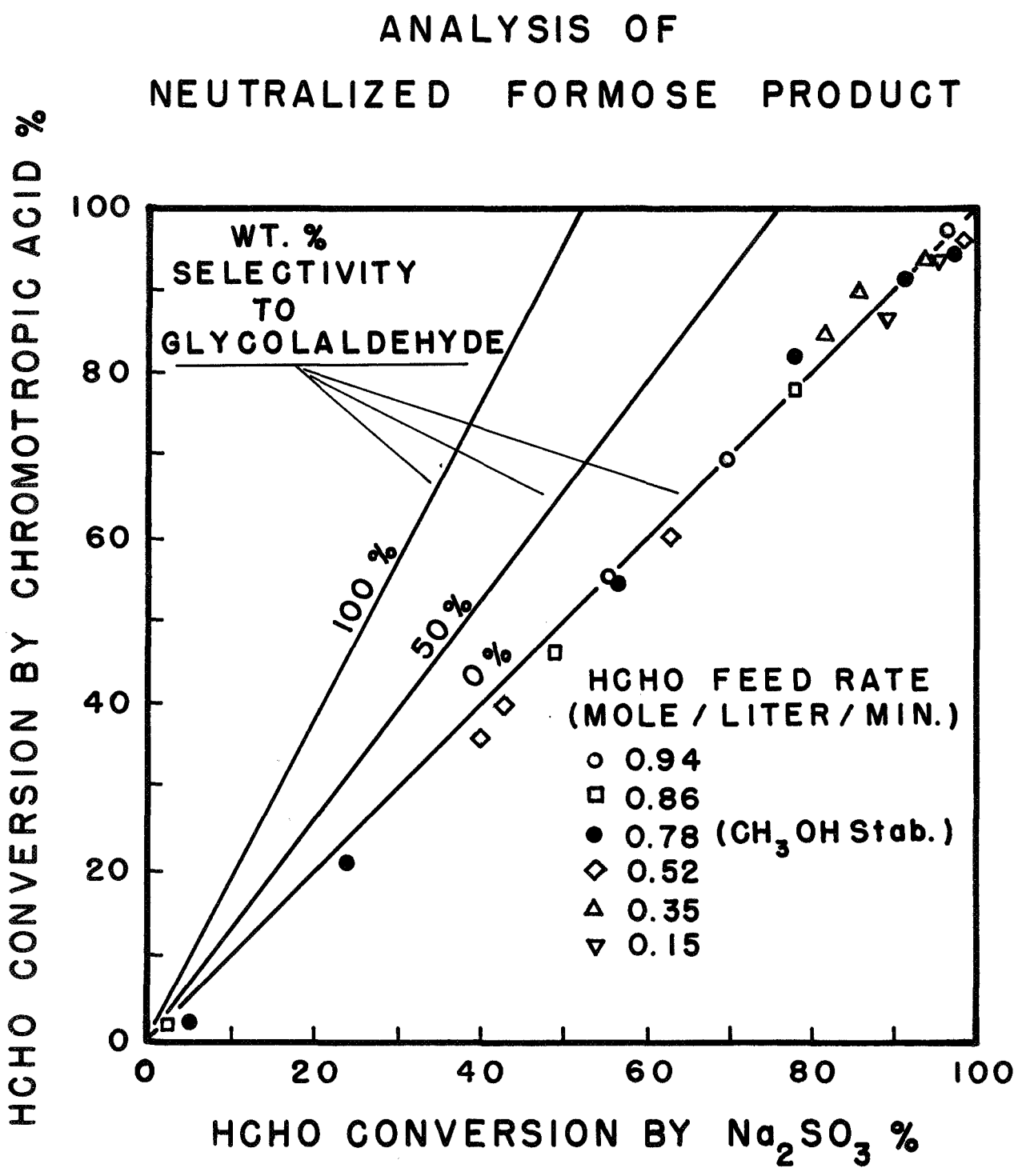

ANALYSIS OF
NEUTRALIZED FORMOSE PRODUCT
HCHO CONVERSION BY CHROMOTROPIC ACID %
HCHO CONVERSION BY $Na_2SO_3$ %
WT. % SELECTIVITY TO GLYCOLALDEHYDE
100 %
50%
0%
HCHO FEED RATE (MOLE / LITER / MIN.)
0.94
0.86
0.78 ($CH_3OH$ Stab.)
0.52
0.35
0.15
0
20
40
60
80
100

Figure 11

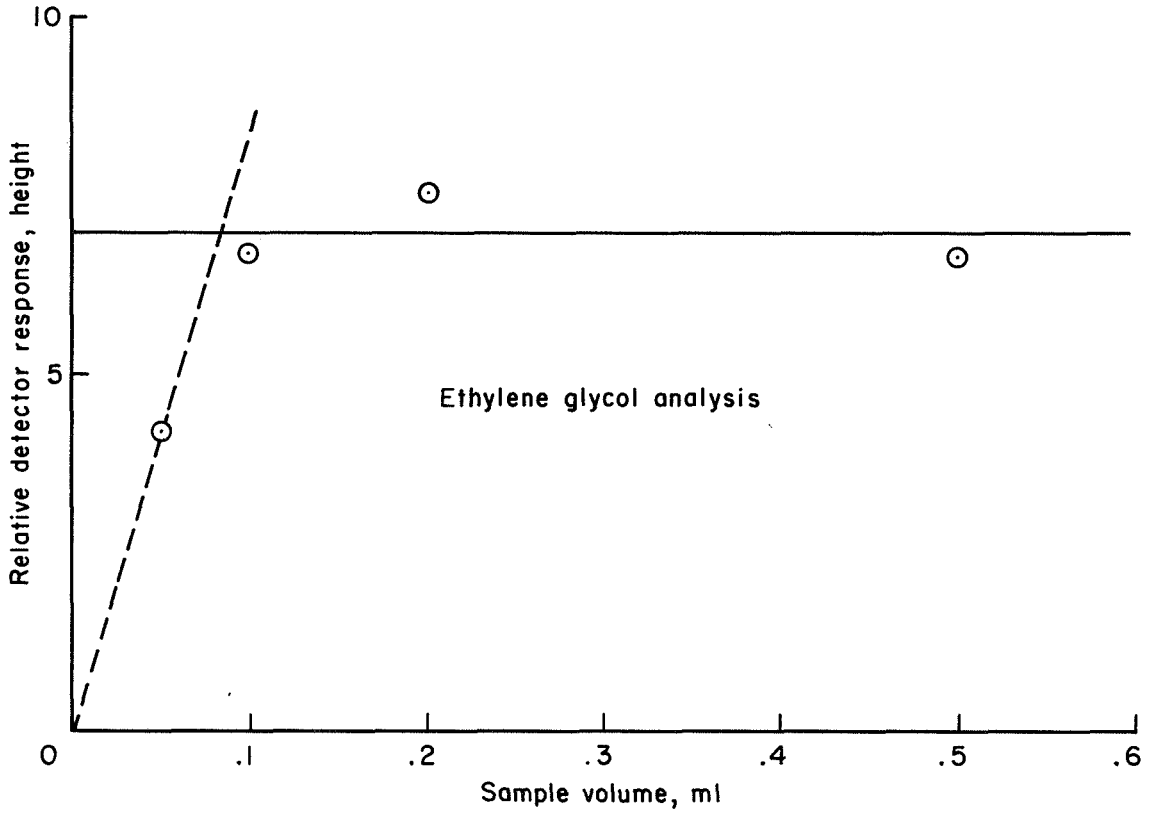



Figure 3. Silylating capacity of reagents
Silylation: 2.0 ml acetonitrile
1.0 ml HMDS
.5 ml TMCS

Figure 12

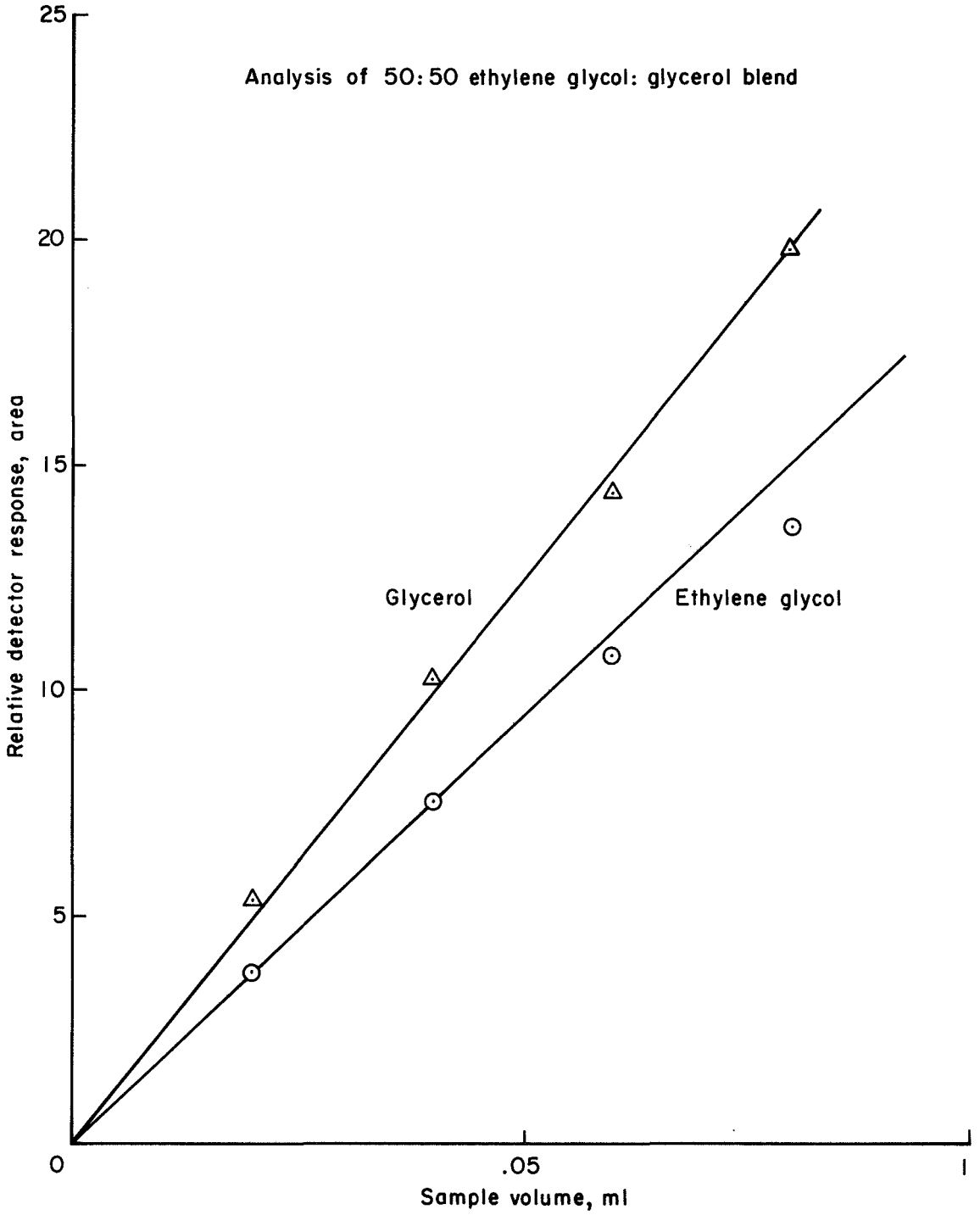



Figure 4. Linear response to sample volume
Silylation: 2.0 ml pyridine
1.0 ml HMDS
.5 ml TMCS

Figure 13

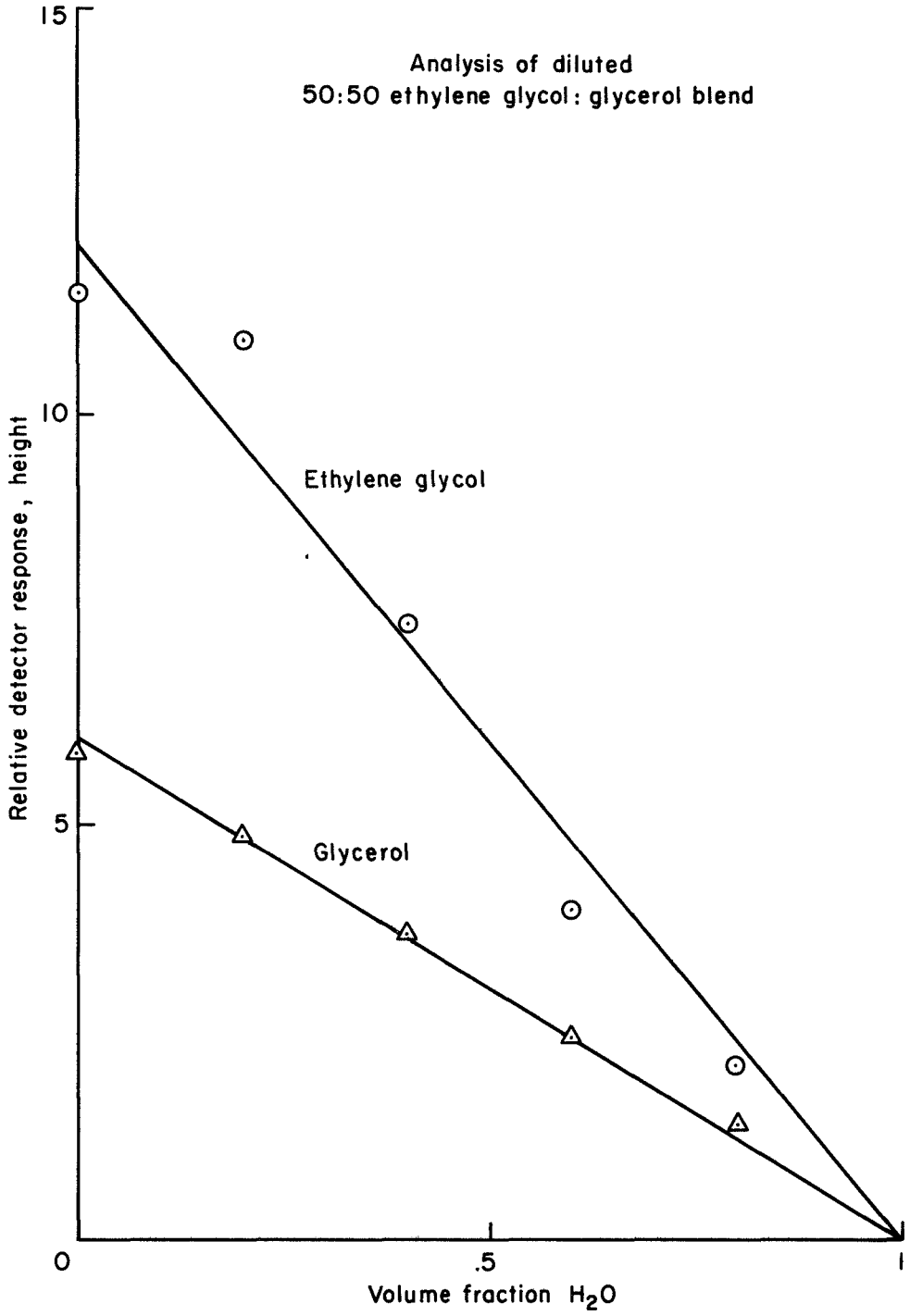



Figure 5. Linear response of diluted samples
Silylation: 2.0 ml pyridine
1.0 ml HMDS
.5 ml TMCS
.1 ml diluted blend