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13. ABSTRACT

The purpose of this study was to determine analytically the effects of water vapor on the ignition delay process in the burning of gaseous hydrogen in a supersonic flowing vitiated airstream. A low temperature (950 - 1000°K) regime was used so the reaction rates would be dominate over the diffusion rates. In this study two chemical kinetic computer programs were used to analytically predict the ignition delay times using the inputs from seven vitiated-air heater experimental investigative conditions. The analytically calculated ignition delay times, for the seven comparitive clean - air and vitiated-air cases, were then compared to the experimental results to determine the effects of water vapor on the ignition delay time.

It was found that the water vapor shortened the ignition delay time in the temperature regime of this investigation.

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A STUDY OF NONEQUILIBRIUM EFFECTS ON IGNITION DELAY IN A SUPERSONIC AIRSTREAM

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A STUDY OF NONEQUILIBRIUM EFFECTS ON IGNITION DELAY IN A SUPERSONIC AIRSTREAM

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by
Donald M. Teasdale
Lieutenant USAF

Graduate Aerospace-Mechanical Engineering
March 1972

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PREFACE

I would like to thank the members of my thesis committee who helped me with the problems I encountered during this study. I am especially grateful to Major Renaldo M. Jensen who suggested this study and spent many hours giving suggestions and explaining the points that were unfamiliar to me.

Thanks also goes to Mrs. Kelly Stevens who helped type this report. Most of all I would like to thank my wife Sally, son Brandon, and daughter Cheryl for the patience and understanding they gave to me during the course of this study.

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LIST OF SYMBOLS

Symbol	
τ_{ID}	Ignition Delay Time
ϕ	Equivalence Ratio

ABSTRACT

The purpose of this study was to determine analytically the effects of water vapor on the ignition delay process in the burning of gaseous hydrogen in a supersonic flowing vitiated-airstream. A low temperature (950°K - 1000°K) regime was used so the reaction rates would be dominate over the diffusion rates. In this study two chemical kinetic computer programs were used to analytically predict the ignition delay times using the inputs from seven vitiated-air heater experimental investigative conditions. The analytically calculated ignition delay times, for the seven vitiated-air and seven comparitive clean-air cases, were then compared to the experimental results to determine the effects of water vapor on the ignition delay process.

It was found that the water vapor shortened the ignition delay time in the temperature regime of this investigation.

A STUDY OF NONEQUILIBRIUM EFFECTS ON IGNITION DELAY IN A SUPERSONIC AIRSTREAM

I. INTRODUCTION

Supersonic ramjet engines (SCRAMJETS) require large mass flow rates of air to produce desirable thrust. Ground test facilities which could provide air mass flow rates at temperatures, pressures, and velocities necessary for meaningful engine development are virtually non-existent.

Due to floatation and erosion problems associated with high mass flow rates in clean air heaters, vitiated air heaters may be the only solution to achieving high energy fluids necessary for the ground development of SCRAMJET engines.

Combustion type vitiated air heaters are gas generator and nozzle combinations that produce large mass flow rates with inherent high temperatures and pressures as a result of the combustion of propellants. Careful design of these apparatuses can duplicate flight conditions necessary for hypersonic operation of a SCRAMJET engine in a ground test facility. The working fluid generated which is called vitiated air, has the same molecular weight and oxygen content as clean air. Additional species such as water vapor and carbon dioxide may be present due to by-products of the combustion process and are considered contaminants when compared with real air composition. If the effects of these contaminates on the ignition process between fuel and vitiated air could be determined, then the vitiated air heater could be economically used for meaningful engine combustor development in ground test facilities.

The purpose of the study is to determine analytically the effects of water vapor contamination on the ignition process of heated gaseous hydrogen fuel in a Mach 3 vitiated airstream.

Scope of Present Investigation

This study is an extension of the work performed by Major Renaldo M. Jensen at Purdue University as partial fulfillment of the requirements for the Doctor of Philosophy Degree (Ref.6). Jensen's experimental results on the ignition delay phenomenon are included in this thesis as a comparison for the analytical results determined in this study.

The SIL (Simplified Ignition Lag) (Ref.6) computer program that Jensen used to analytically predict the ignition delay lengths in his experimental cases did not allow for a temperature increase during the ignition delay period.

It was felt that some validity in the comparison of his analytical and experimental data was impaired by neglecting this temperature rise. However, in this study the ignition delay lengths of Jensen's experimental cases will be recalculated allowing for the temperature increase during the ignition delay period to determine whether the allowance of this temperature increase improves his correlation between the experimental and analytical results. Additional ignition delay lengths will be computed using clean air rather than vitiated air for the same experimental conditions, to determine the effects of the water vapor on the ignition delay process.

Review of Pertinent Literature

Jensen (Ref. 6). Jensen designed and built a vitiated air heater (Fig. 1, Pg. 4) that reacted a nitrogen (N_2) diluent, nitrogen tetroxide (N_2O_4), and hydrazine (N_2H_4) to generate the vitiated air. The use of nitrogen (N_2) increased the molecular weight to that of real air. The water vapor inherently produced as a combustion product in the gas generation process (19 percent by weight) replaced an equal amount of nitrogen in the vitiated air.

This system was designed to duplicate the temperature (1000°K), pressure (14.7 PSIA), and velocity conditions ($M = 2.9$) of air entering the combustor of a SCRAMJET engine operating at a flight mach number of 6 at an altitude of 80,000 feet. This simulation of a SCRAMJET combustion chamber entrance was further enhanced by using an annular injector at the exit of the gas generator nozzle for the introduction of the heated hydrogen gaseous fuel (590° to 750°K) into the vitiated air stream. Injection was parallel to the flow in order to minimize the recirculation effects between the concentric streams of the free jet. (Fig. 2, Pg.6). Once ignition

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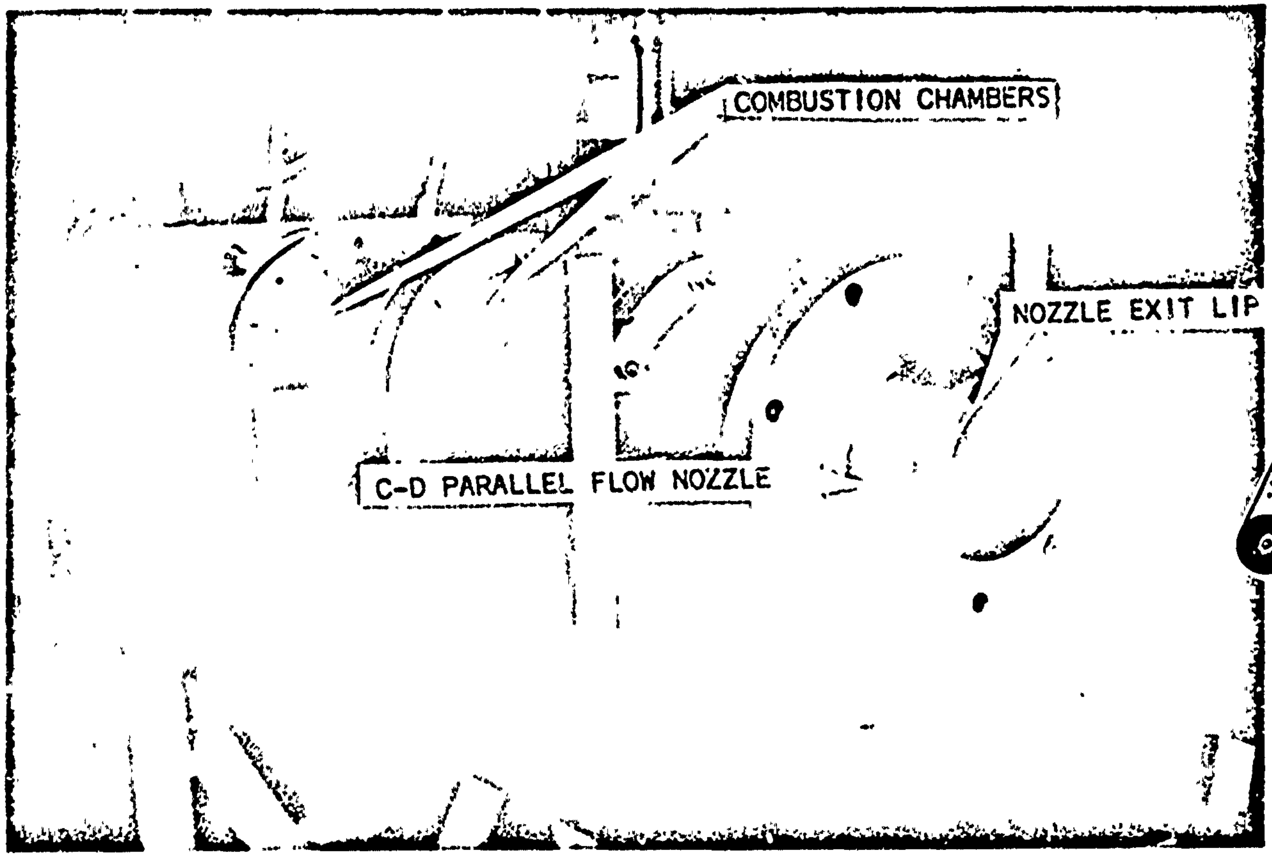

Figure 1. VITIATED-AIR HEATER WITH H_2 INJECTOR REMOVED

occurred in this unconfined flow it was possible to physically measure the ignition delay phenomenon captured by a high speed motion picture (Fastex) camera (550 frames a min.). See Fig 3, Pg.7 and Fig. 4, Pg.8 .

The SIL computer program supplied by NASA Lewis, was used to analytically predict the ignition delay lengths for his experimental cases. It was found that the ignition delay length decreased with increasing hydrogen inlet temperature and that the ignition delay lengths were comparatively independent of the equivalence ratio (Figs. 5 and 6, Pg.9). The results also showed that the presence of water vapor shortened the ignition delay length (Fig. 7, Pg.11).

Snyder, Robertson, Zanders, and Skinner (Ref.8).

In this study the effects of water vapor, nitric oxide, nitrogen dioxide and ammonia on ignition delay were studied using shock tube techniques. The ranges considered were, equivalence ratio .5 to 1.0, temperature from 800°K to 1100°K, and the pressure range from 1.5 PSIA to 130 PSIA.

Their results showed that for an equivalence ratio of 1, pressure of 30 PSIA, and water vapor content of 20 percent, that the water vapor present would shorten the ignition delay if the temperature is higher than 970°K, and would lengthen the ignition delay if the temperature is lower than 970°K (Fig. 8, Pg.13). Their results also showed that nitric oxide (Fig. 8) and nitrogen dioxide had an accelerating effect on the ignition delay. They also indicated that ammonia had very little effect on the ignition delay in this low temperature range.

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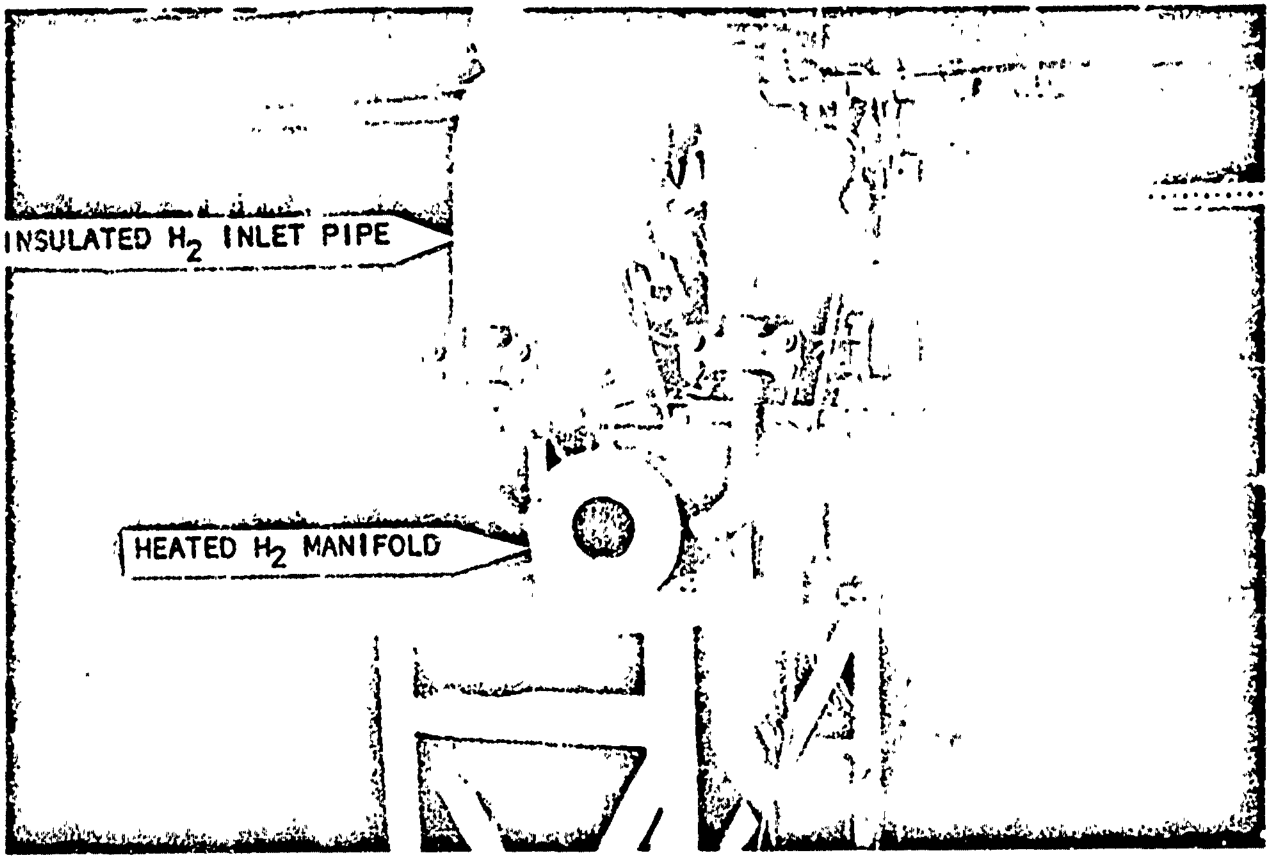

Figure 2. VITIATED-AIR HEATER WITH H_2 MANIFOLD INSALLED

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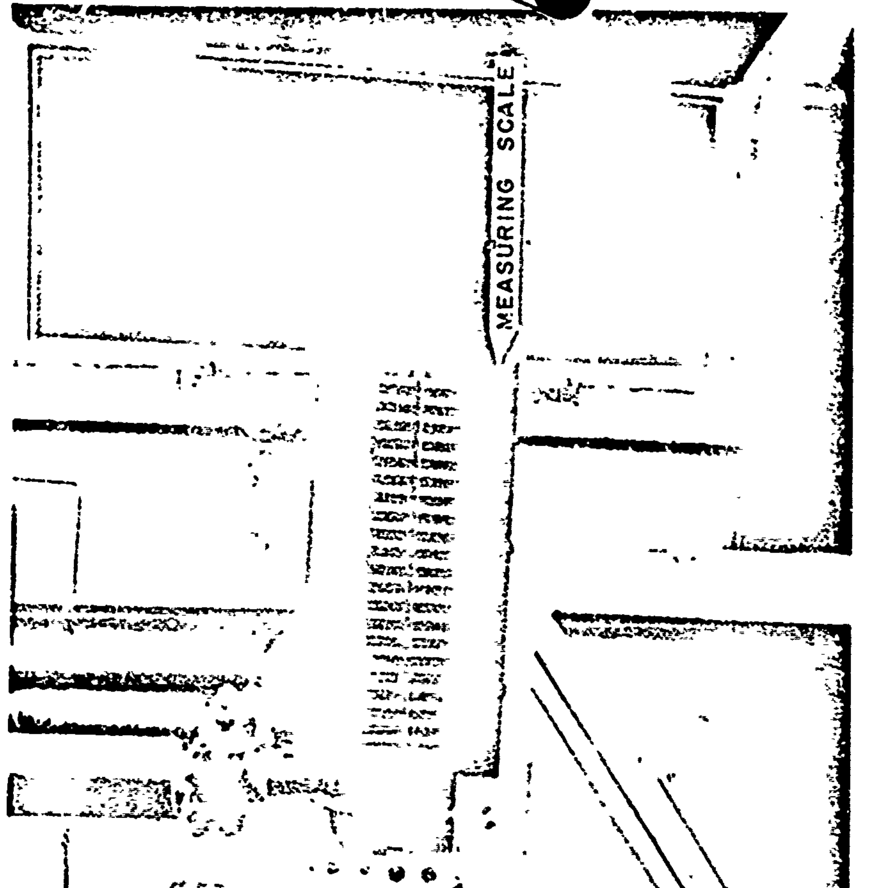

Figure 3 IGNITION DELAY MEASURING APPARATUS

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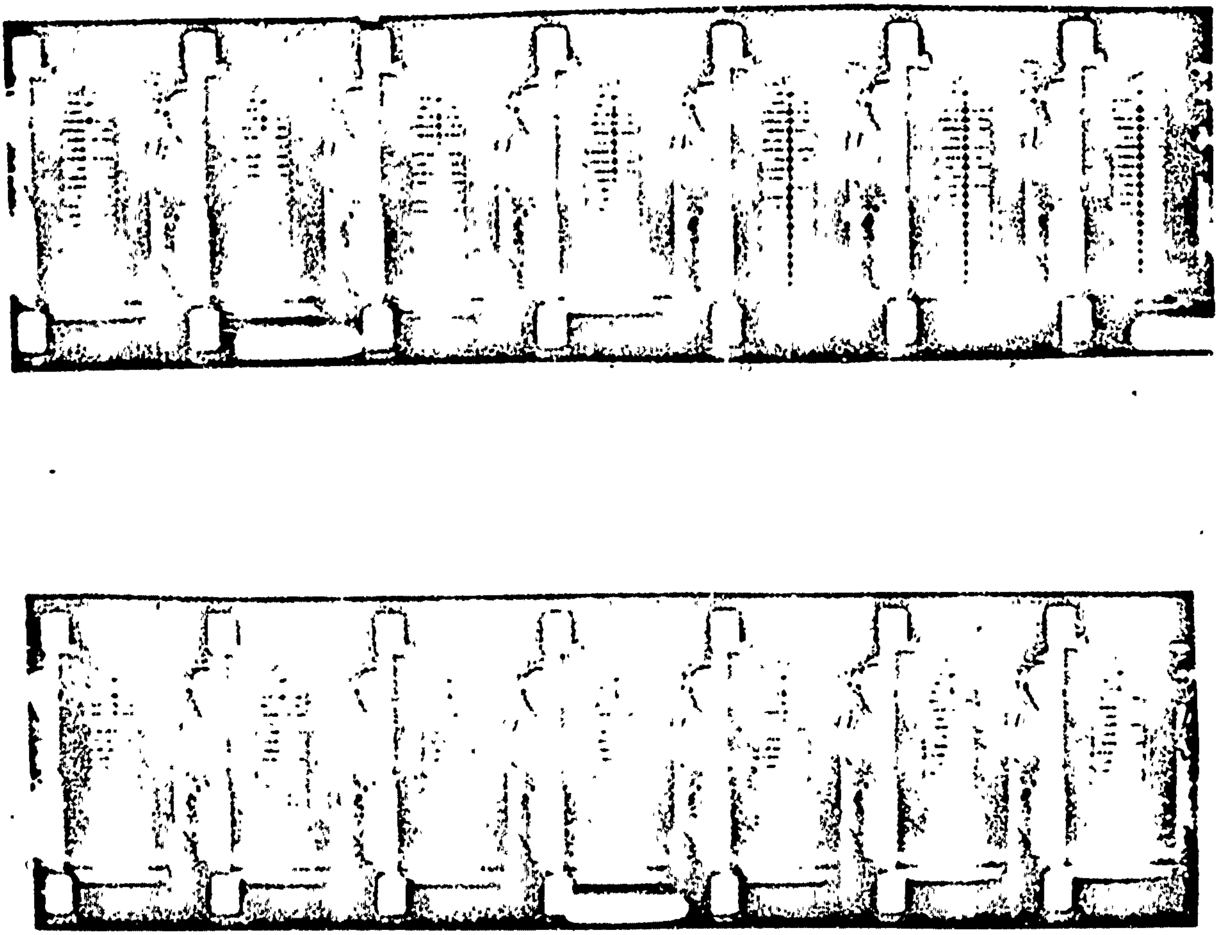
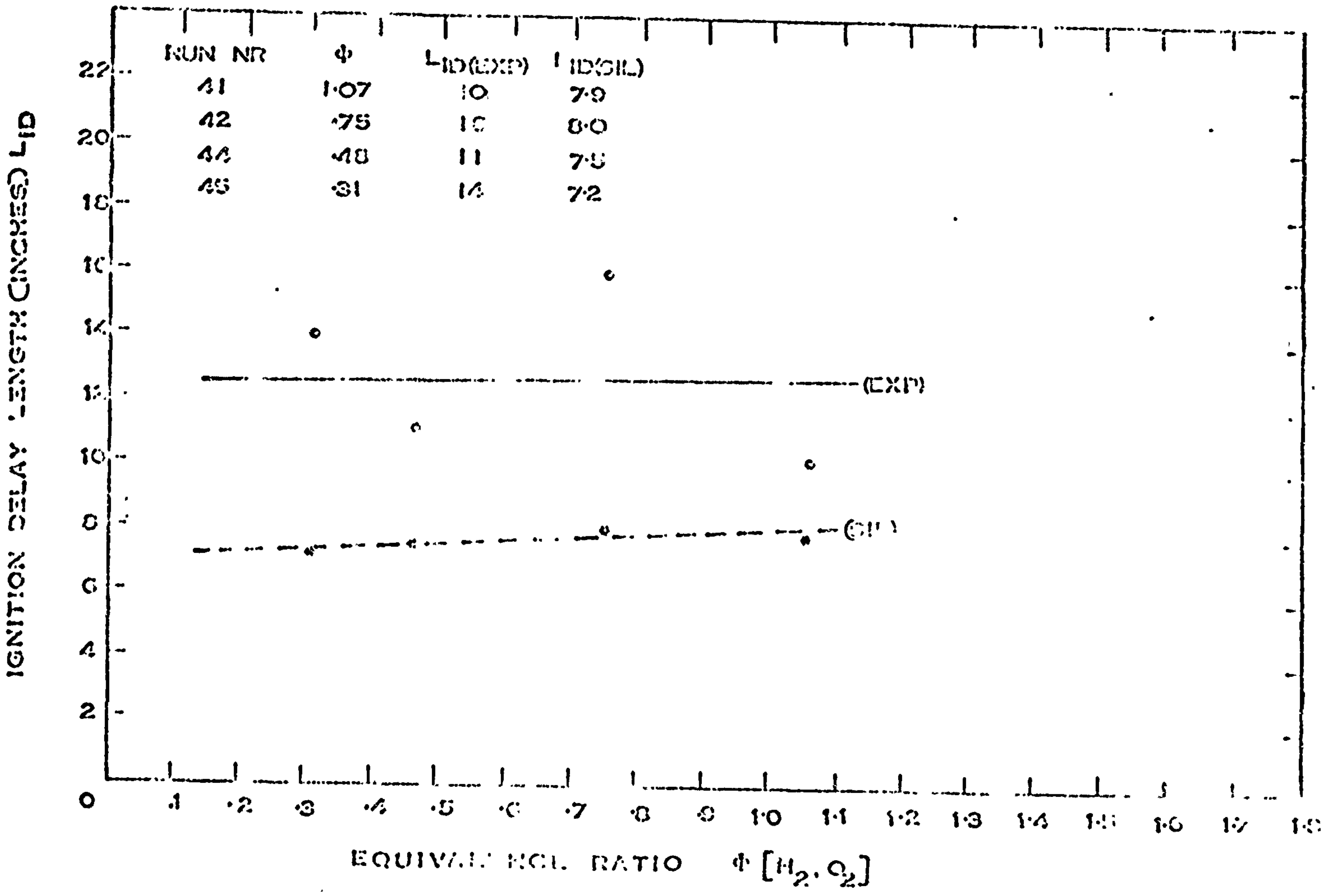
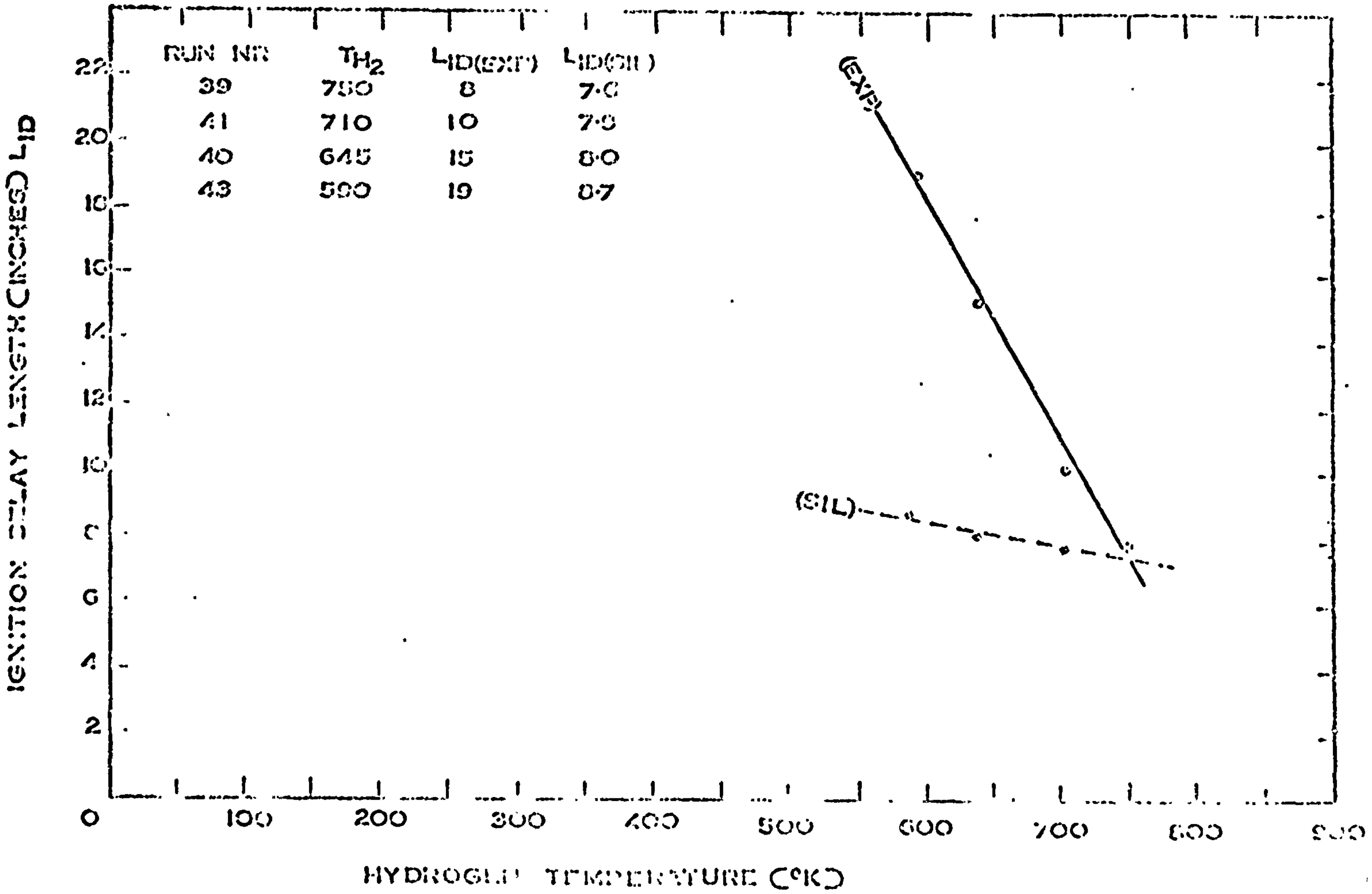


Figure 4. IGNITION DELAY MEASUREMENT USING HIGH SPEED FASTEX CAMERA



RUN NR	Φ	$L_{ID(EXP)}$	$L_{ID(SIM)}$
41	1.07	10	7.9
42	.75	16	8.0
44	.48	11	7.5
45	.31	14	7.2

FIGURE 5 GRAPHICAL COMPARISON OF ANALYTICAL AND EXPERIMENTAL IGNITION DELAY RESULTS AS FUNCTION OF EQUIVALENCE RATIO



RUN NR	T_{H_2}	$L_{ID(EXP)}$	$L_{ID(SIL)}$
39	750	8	7.6
41	710	10	7.9
40	645	15	8.0
43	590	19	8.7

FIGURE 6 GRAPHICAL COMPARISON OF ANALYTICAL AND EXPERIMENTAL IGNITION DELAY RESULTS AS FUNCTION OF H_2 TEMPERATURE

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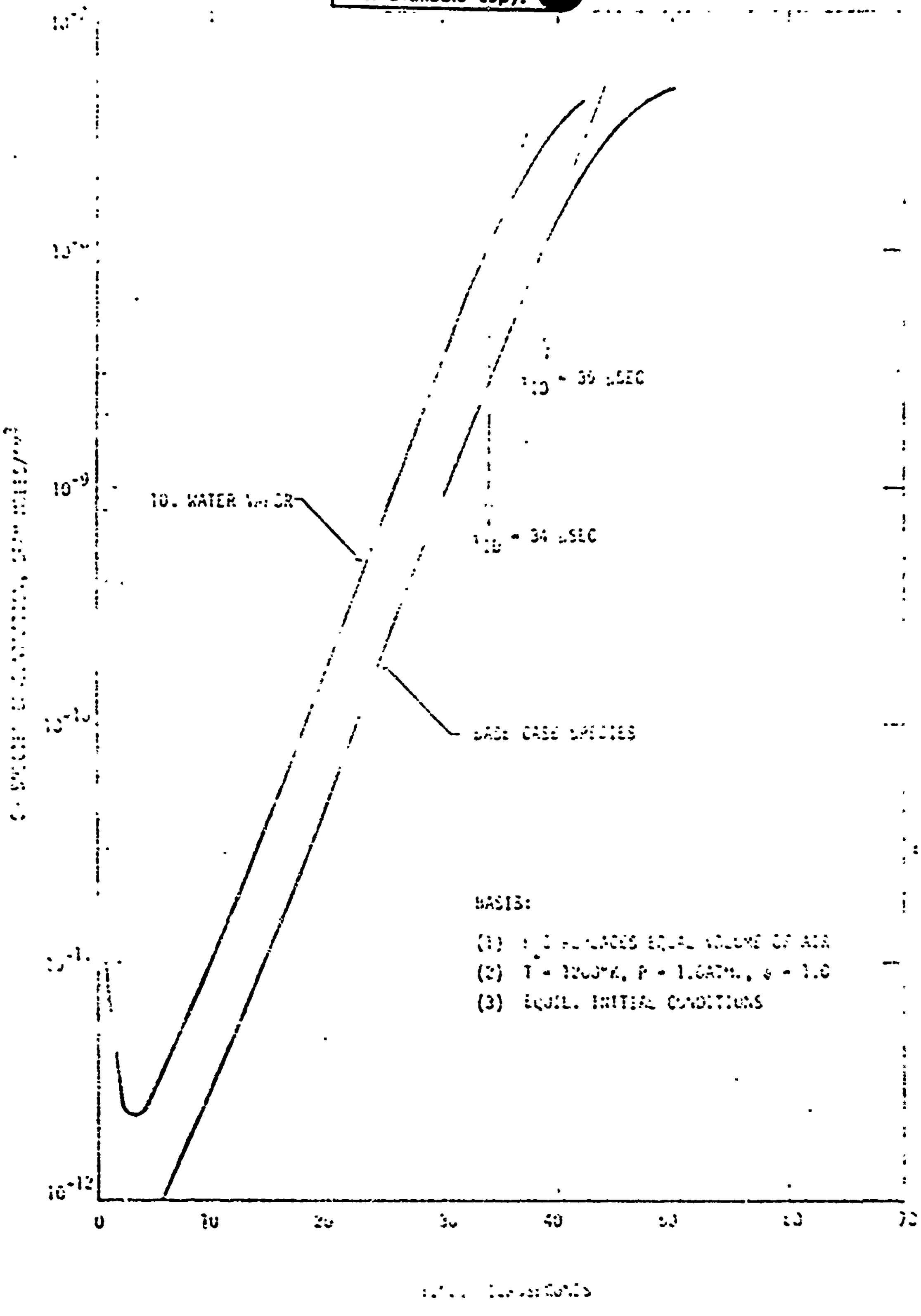

Figure 7 EFFECT OF WATER VAPOR ON IGNITION DELAY

Edelman and Spadaccini (Ref.4). This study was accomplished using preheated air. The air was preheated by burning oil and hydrogen gas. By adding make-up oxygen to a combustion heated true air, (revitalized air), it was possible to obtain vitiated air with the correct proportion of atmospheric oxygen. They concluded from their experimental and analytical results that water vapor and carbon dioxide could either increase or decrease the ignition delay time depending on the initial temperature, pressure, and concentration level.

Approach

The ODFRC (One Dimensional Finite Rate Chemistry) computer program will be used to analytically determine the ignition delay lengths for the seven vitiated air experimental cases. (Ref. 3 & 7). This program was developed by GASL and provided for this research program by NASA Lewis Research Center. It differs from the SIL Computer program used by Jensen in that it takes into account the temperature increase during the induction period.

The GCK (General Chemical Kinetics) computer program will also be used to determine the ignition delay lengths for the seven clean and vitiated air cases. This program was developed by NASA Lewis Research Center (Ref. 2). The GCK program is similar but slightly more sophisticated than the ODFRC computer program in that it has the added ability to allow for up to thirty reactions. Also unlike the other computer programs written for combustion studies, this program internally calculates the step size required for the inte-

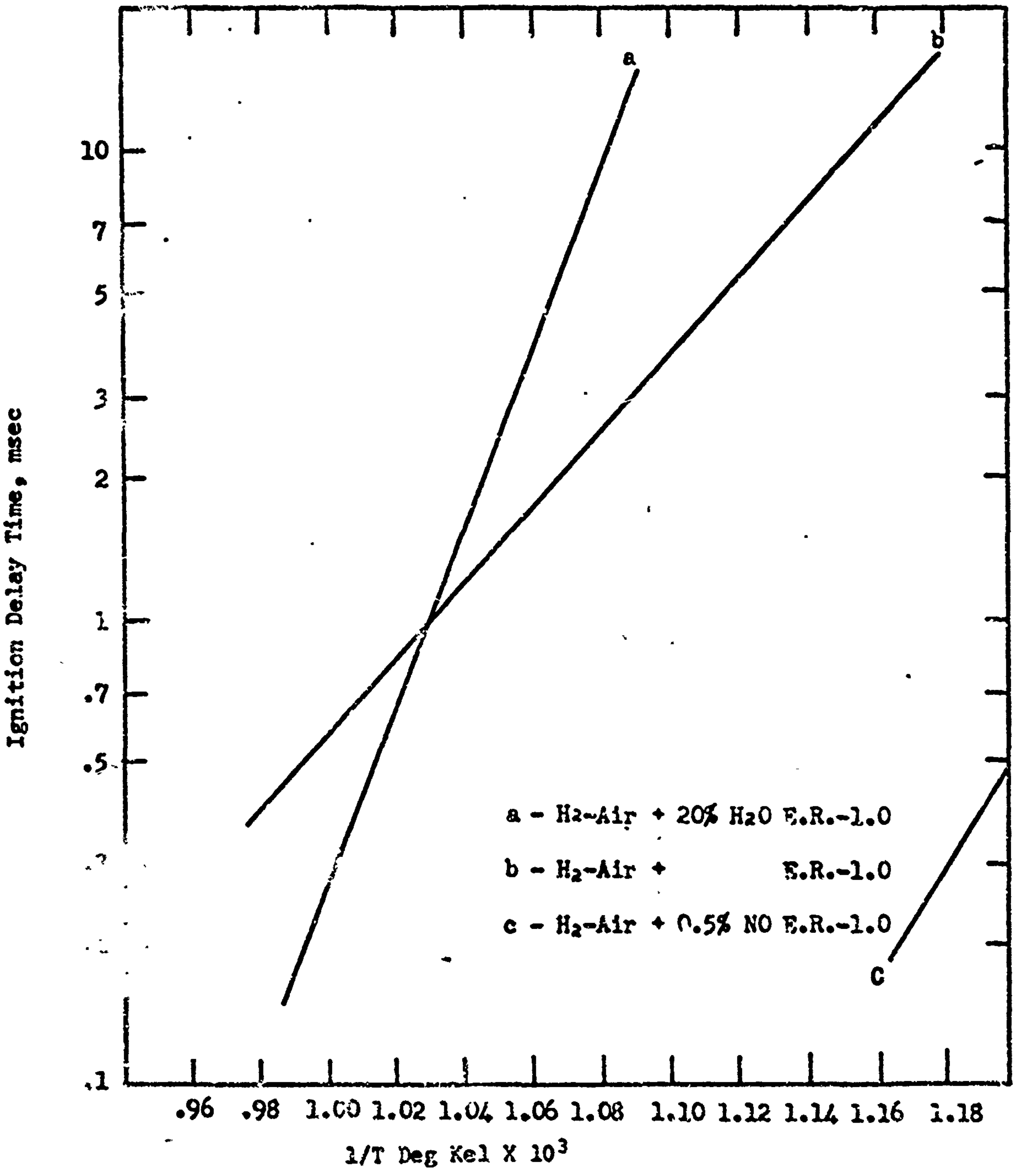

Figure 8. IGNITION CHARACTERISTICS OF H_2-AIR MIXTURES WITH ADDED WATER AND NITRIC OXIDE

gration of the rate equations, which help eliminate the time problem that exists with other integration schemes. Also this program allows for no reactions which are felt to be important in ignition delay calculations.

To determine the nonequilibrium combustor inlet clean and vitiated air species concentration used as the data input to the ODFRC and GCK programs the FRRG (Finite Rate Reacting Gas) computer program will be used. This computer program was developed by TRW Systems for NASA (MSC) under contract NAS-4358 (Ref. 5). It was also used by Jensen to calculate the inlet species concentrations for use in the SIL computer program.

The results of the clean and vitiated air case will be compared to the experimental results to determine the effects of the water vapor on the ignition delay lengths.

Assumptions

In the seven experimental cases, the clean and vitiated air entering the combustor are assumed to be in chemical nonequilibrium. It is also assumed that the airstream entering the combustor is a homogeneous mixture since the computer programs are not designed to handle mixing phenomena.

The assumptions made for the FRRG, ODFRC and GCK computer programs are as follows:

1. The flow is adiabatic.
2. The species behave as ideal gases.
3. Viscous effects are neglected.

4. All internal modes of energy storage are in equilibrium.

II. ANALYTICAL PROGRAM

The author used the FRRG program to analytically determine the nonequilibrium composition, temperature, pressure, and velocity characteristics of the working fluid expanding in the gas generator. The computed outputs were then used as the input data to the ODFRC and GCK programs to analytically predict the ignition delays in the free jet which simulates the ignition process in a SCRAMJET combustor.

Description of Computer Programs

The computer programs indicated in the above section are discussed in the following paragraphs under their individual headings. Included in these discussions are:

1. Program description
2. Input requirements
3. Output
4. Limitations

Finite Rate Reacting Gas (FRRG) Program. The FRRG program was developed by TRW Systems for NASA (MSC) under contract NAS-4358. This program solves the equations for invicid one dimensional flow of a reacting gas mixture (Ref. 5). To minimize computer time during the integrations of the chemical relaxation equations, the program uses an implicit integration scheme for near equilibrium flow, and explicit integration scheme for near equilibrium flow, and explicit integration for flow distant from equilibrium.

Required data inputs are the nozzle geometry, propellant data, and reaction rate information. The reaction rate expressions and rate constants used in this program are listed in Table 1, pg. 18. Only the forward rates are required input since the reverse reaction rates are internally calculated from the forward reaction rate and the equilibrium constant by the following expression:

$$k_b(J) = k_f(J)/K_c(J)$$

Also when the reaction equations used were the same as in the FRRG, ODFRC, and GCK programs, identical input reaction rate data was used to maintain continuity in the results.

This program has the option of performing either equilibrium or finite rate calculations. Output from this program are temperature, pressure, mach number, velocity, density, enthalpy, gas molecular weight, heat capacity, ratio of specific heats, and species concentrations. The finite rate calculation was employed since this option more closely duplicated the experimental conditions.

Output species concentrations are printed in mole fractions and mass fractions. Mass fraction units were chosen since the ODFRC program requires that the species concentrations be input in terms of mass fractions.

One Dimensional Finite Rate Chemistry (ODFRC) Program. The ODFRC program, supplies by NASA Lewis Research Center, solves

TABLE 1

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REACTION RATES FOR FRNG PROGRAM

J	Reaction	A(J) (gr. cm.)	B(J) (kcal/mole)	N(J)
1	$H_2O + M \rightleftharpoons OH + H + M$	1.9×10^{18}	119.9	-1.278
2	$H_2 + M \rightleftharpoons H + H + M$	3.2×10^{15}	102.9	-1.5
3	$N_2 + M \rightleftharpoons N + N + M$	1.0×10^{16}	--	-1.0
4	$NO + M \rightleftharpoons N + O + M$	5.0×10^{16}	--	-0.5
5	$OH + M \rightleftharpoons O + H + M$	2.0×10^{18}	--	-1.0
6	$O_2 + M \rightleftharpoons O + O + M$	3.59×10^{17}	118.0	-2.5
7	$H_2O + H \rightleftharpoons H_2 + OH$	1.43×10^{14}	20.94	--
8	$H_2O + O \rightleftharpoons OH + OH$	2.9×10^{14}	18.7	--
9	$H_2 + O \rightleftharpoons OH + H$	4.0×10^{13}	10.2	--
10	$H_2 + O_2 \rightleftharpoons OH + OH$	2.5×10^{12}	38.9	--
11	$N_2 + O \rightleftharpoons NO + N$	1.5×10^{13}	--	--
12	$N_2 + O_2 \rightleftharpoons NO + NO$	1.0×10^{13}	79.5	-2.5
13	$NO + H \rightleftharpoons OH + N$	5.3×10^{11}	5.62	0.5
14	$NO + O \rightleftharpoons O_2 + N$	1.3×10^{5}	6.0	1.5
15	$O_2 + H \rightleftharpoons OH + O$	1.0×10^{14}	16.[illegible]	--

where

$$k_f(J) = A(J)\, T^{N(J)} \exp[-B(J)/RT]$$

and

$$k_b(J) = k_f(J)/k_c(J)$$

for the rate of growth of the free radicals as a function of time by using a standard matrix technique. These rates are then integrated to give the species concentrations at that instant of time. Unlike the SIL program used by Jensen (Ref. 6), this program allows for the temperature increase during the ignition delay period caused by certain reactions being slightly more exothermic than the other reactions are endothermic.

During the development of the ODFRC program, modifications were made by NASA Lewis Research Center to the original program to allow the computation to run though the steep temperature rise following ignition.

The program has the option of using pressure vs. distance, area vs. distance, or radius vs. distance for combustor geometry conditions. The pressure vs. distance option was chosen to duplicate the constant pressure experimental conditions of a free jet burning in the atmosphere. Other inputs include initial temperature, pressure, velocity, area, distance, time, species concentrations, and reaction rate constants. Reactions, rates, and constants used are listed in table 2, page 21. Species considered were H, O, H_2O, H_2, O_2, OH, N_2, HO_2, and H_2O_2.

Output from this program includes time, temperature, density, pressure, enthalpy, velocity, area, distance, and species concentrations for the nine species listed above. The author modified the program to include a calcomp plotting subroutine to plot O H concentration vs. time, H concentration vs. time, and temperature vs. time. The plots which are used to determine the ignition delay, will be discussed in a later section.

General Chemical Kinetics (GCK) Program. The GCK computer program was supplied by NASA Lewis Research Center for this study. Unlike the ODFRC Program, the GCK program allows for reactions involving NO which possibly could have an accelerating effect on the ignition delay.

The program solves the reaction equations by means of an implicit integration technique. This implicit solution scheme was combined with a new step-size optimization method. This new integration technique which is efficient for both very slow and very fast (near-equilibrium) chemical reactions (Ref.2). Step-size control decreases the computation time required.

Input conditions for this program allow for 30 reactions. The reactions and reaction rate constants used in this program are listed in table 3, pg.23 . Reverse reaction rates are calculated internally from the relation:

$$K_b(J) = k_f(J) / K_c(J)$$

In addition to the chemical species which are required by the given reactions, the user can include one or more inert species, but the total number of species considered cannot exceed 25 (Ref.2). For each dissociation-recombination reaction, the user can specify a set of third-body efficiencies (Ref.2). To maintain continuity between the computer programs, the same efficiencies were used in the GCK program as in the ODFRC program where possible. If the third-body efficiencies are not specified they are assumed to have a value of one.

TABLE 2

REACTION RATES FOR CDFRC PROGRAM

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J	Reaction	A(J) (gr. cm.)	B(J) (kcal/mole)	N(J)
1	$H + O_2 \rightleftharpoons OH + O$	1.0×10^{14}	16.0	--
-1		4.16×10^{12}		0.41
2	$O + H_2 \rightleftharpoons H + OH$	4.0×10^{13}	10.2	--
-2		1.85×10^{13}	8.39	--
3	$H_2 + OH \rightleftharpoons H + H_2O$	2.3×10^{13}	5.2	--
-3		1.43×10^{14}	20.94	--
4	$O + H_2O \rightleftharpoons OH + OH$	2.3×10^{14}	18.7	--
-4		2.03×10^{13}	1.13	0.26
5	$H_2 + M \rightleftharpoons 2H + M$	3.15×10^{16}	102.9	-1.5
-5		9.18×10^{15}	-0.97	-1.5
6	$H_2O + M \rightleftharpoons OH + H + M$	1.86×10^{13}	119.9	-1.278
-6		7.5×10^{16}	--	-1.0
7	$O_2 + M \rightleftharpoons 2O + M$	3.59×10^{17}	118.0	-2.5
-7		8.9×10^{15}	-1.57	-2.074
8	$H + O_2 + M \rightleftharpoons HO_2 + M$	4.3×10^{15}	-1.28	--
-8		8.9×10^{15}	46.12	-0.28
9	$H_2 + HO_2 \rightleftharpoons H_2O_2 + H$	2.0×10^{13}	23.72	--
-9		1.0×10^{14}	9.82	--
10	$H_2 + O_2 \rightleftharpoons OH + OH$	2.5×10^{12}	38.95	--
-10		4.77×10^{13}	19.87	--
11	$H_2O_2 + M \rightleftharpoons 2OH + M$	1.17×10^{17}	45.57	--
-11		8.4×10^{14}	-5.31	--
12	$H + HO_2 \rightleftharpoons OH + OH$	7.0×10^{13}	--	--
-12		4.37×10^{12}	39.2	--
13	$HO_2 + HO_2 \rightleftharpoons H_2O_2 + O_2$	1.8×10^{12}	--	--
-13		8.1×10^{12}	42.19	--
14	$H + H_2O_2 \rightleftharpoons H_2O + OH$	3.18×10^{14}	9.0	--
-14		5.6×10^{13}	78.0	--
15	$OH + H_2O_2 \rightleftharpoons H_2O + HO_2$	1.0×10^{13}	0.997	--
-15		2.3×10^{13}	32.76	--

where $k(J) = A(J)\, T^{N(J)} \exp[-B(J)/RT]$

Initial conditions required are:

1. Time and axial position.
2. Velocity (or mach number).
3. Density (or pressure).
4. Temperature.
5. Species concentrations

Also pressure or area profile must be input if the problem under consideration is a flow problem. (Ref.2)

Outputs from this program are temperature, time pressure, velocity, mach number and species concentrations. The output can be in CGS, FPS, or SI units. The CGS option was chosen to maintain continuity with the results of the other programs.

Analytical Determination of the Ignition Delay Time.

The FRRG program was used to calculate the species concentrations, velocity, temperature and pressure conditions at the exit of the vitiated air heater. The exit of the vitiated air heater is considered the inlet of the combustor in this study. The species mass fractions were recalculated allowing for the H_2 gas that is supplied at the combustor inlet. These species mass fractions, mixing cup temperature, and velocity conditions are used as the input to the ODFRC and GCK programs. The ODFRC and GCK calculate the temperature, velocity, and species concentration as a function of time. See Fig. 9, pg. 24.

The end of the ignition delay period is characterized by a rapid increase in termperature (Fig. 10, Pg.26). During the

TABLE 3

REACTION RATES FOR GCK PROGRAM

J	REACTION	A (J) (gm.cm)	B(J) (kcal/mole)	N(J)
1	$H + O_2 = OH = O$	1.25×10^{14}	16.3	----
2	$O + H_2 = OH + H$	1.7×10^{13}	9.45	----
3	$H_2 + OH = H_2O + H$	2.19×10^{13}	5.15	----
4	$O + H_2O = OH + OH$	5.75×10^{13}	18.0	----
5	$H_2 + HO_2 = H_2O_2 + H$	9.6×10^{12}	24.0	----
6	$H_2 + O_2 = OH + OH$	1.0×10^{13}	43.0	----
7	$H + HO_2 = OH + OH$	7.0×10^{13}	----	----
8	$2HO_2 = H_2O_2 + O_2$	1.8×10^{12}	----	----
9	$H + H_2O_2 = H_2O + OH$	3.1×10^{14}	9.0	----
10	$OH + H_2O_2 = H_2O + HO_2$	1.0×10^{13}	1.8	----
11	$M + H + OH = H_2O + M$	7.5×10^{16}	----	-2.6
12	$M + H + O_2 = HO_2 + M$	1.59×10^{15}	-1.0	----
13	$M + H + H = H_2 + M$	1.0×10^{18}	----	-1.0
14	$M + O_2 + O = O + M$	2.75×10^{19}	118.7	-1.0
15	$M + H_2O_2 = OH + OH$	1.17×10^{17}	45.5	----
16	$M + N + N = N_2 + M$	2.8×10^{17}	----	-.75
17	$M + N + O = NO + M$	5.4×10^{16}	----	-.5

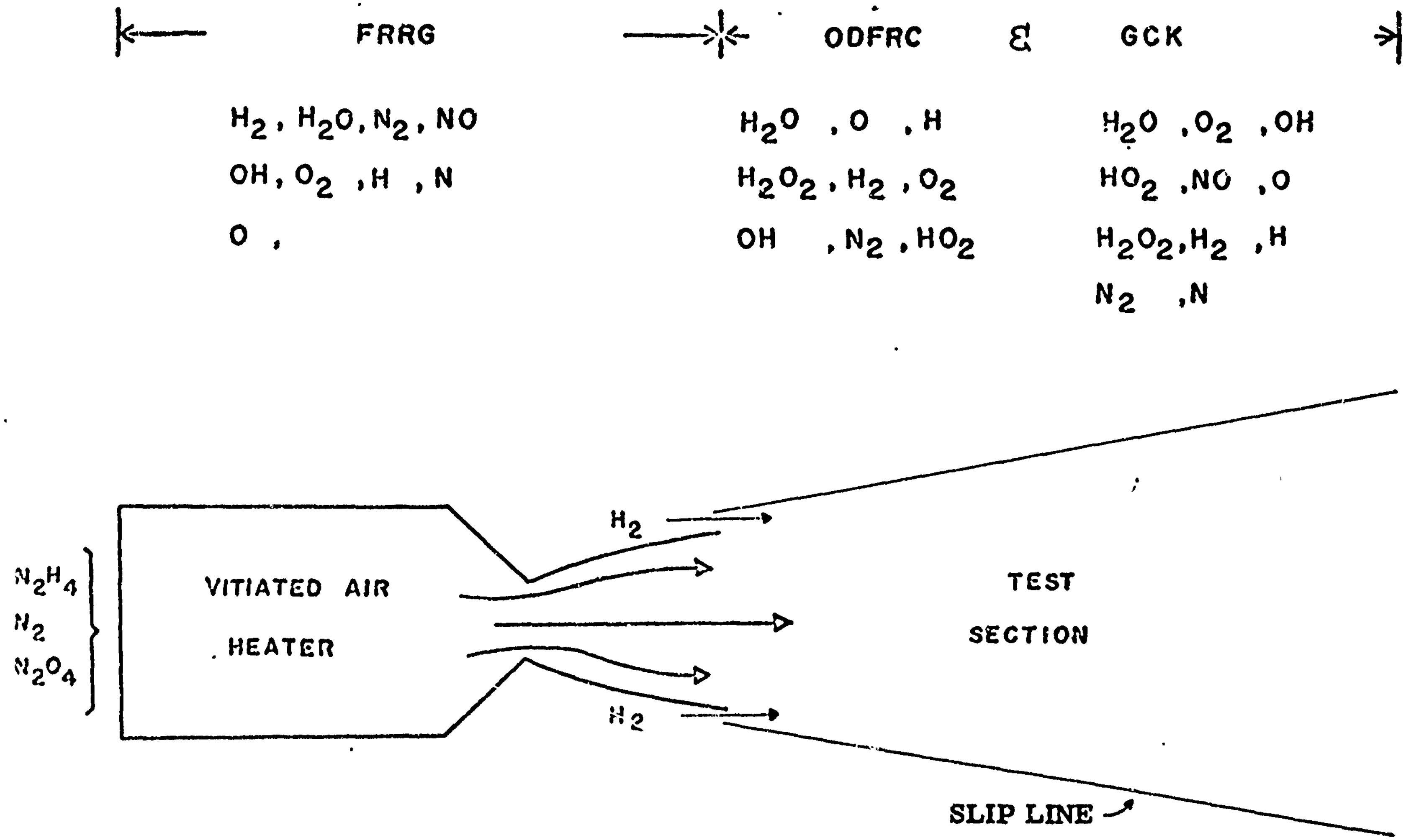

Figure 9. PROGRAM APPLICATION

ignition delay region the net results of the reactions are slightly exothermic. This accounts for the slight temperature increase during the ignition delay period. At the point where the temperature increases rapidly, the recombination reactions are the controlling reactions. Since the recombination reactions are exothermic, the temperature increases rapidly (Fig. 10, 26).

The following criteria were used to determine the time at which the ignition delay period ended.

1. Intersection of the linear slope temperature line in the ignition delay zone, with the linear slope temperature line of the reaction zone. (Fig. 11, Pg. 27)
2. Deviation from the linear portion of the OH vs. time curve (Fig. 12, Pg. 28)
3. Deviation from the linear portion of the H vs. time curve (Fig. 13, Pg. 29)
4. One half of the initial H_2 concentration.

All four methods yield essentially identical delay times so all methods appear applicable.

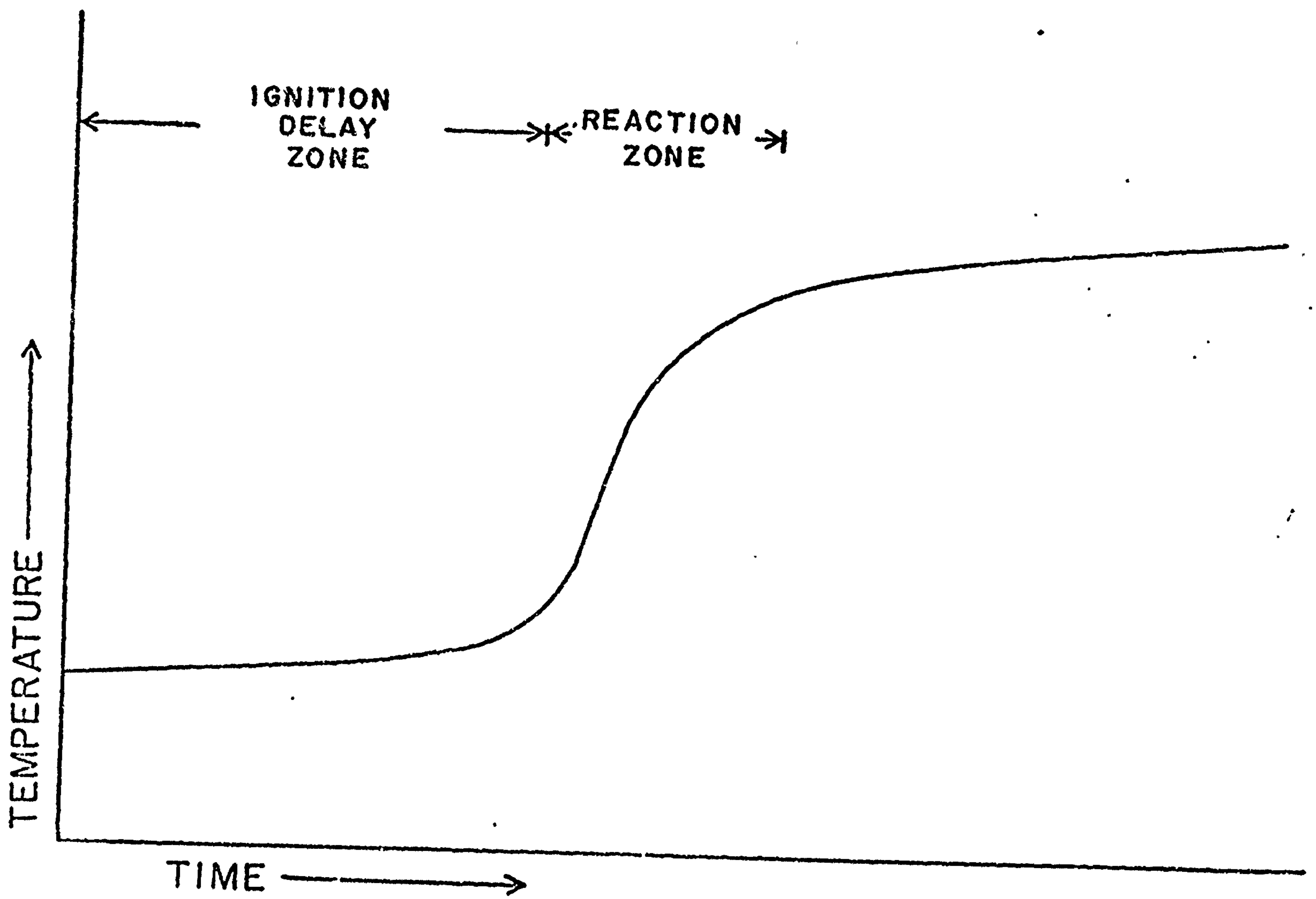

Figure 10. TEMPERATURE HISTORY DURING IGNITION

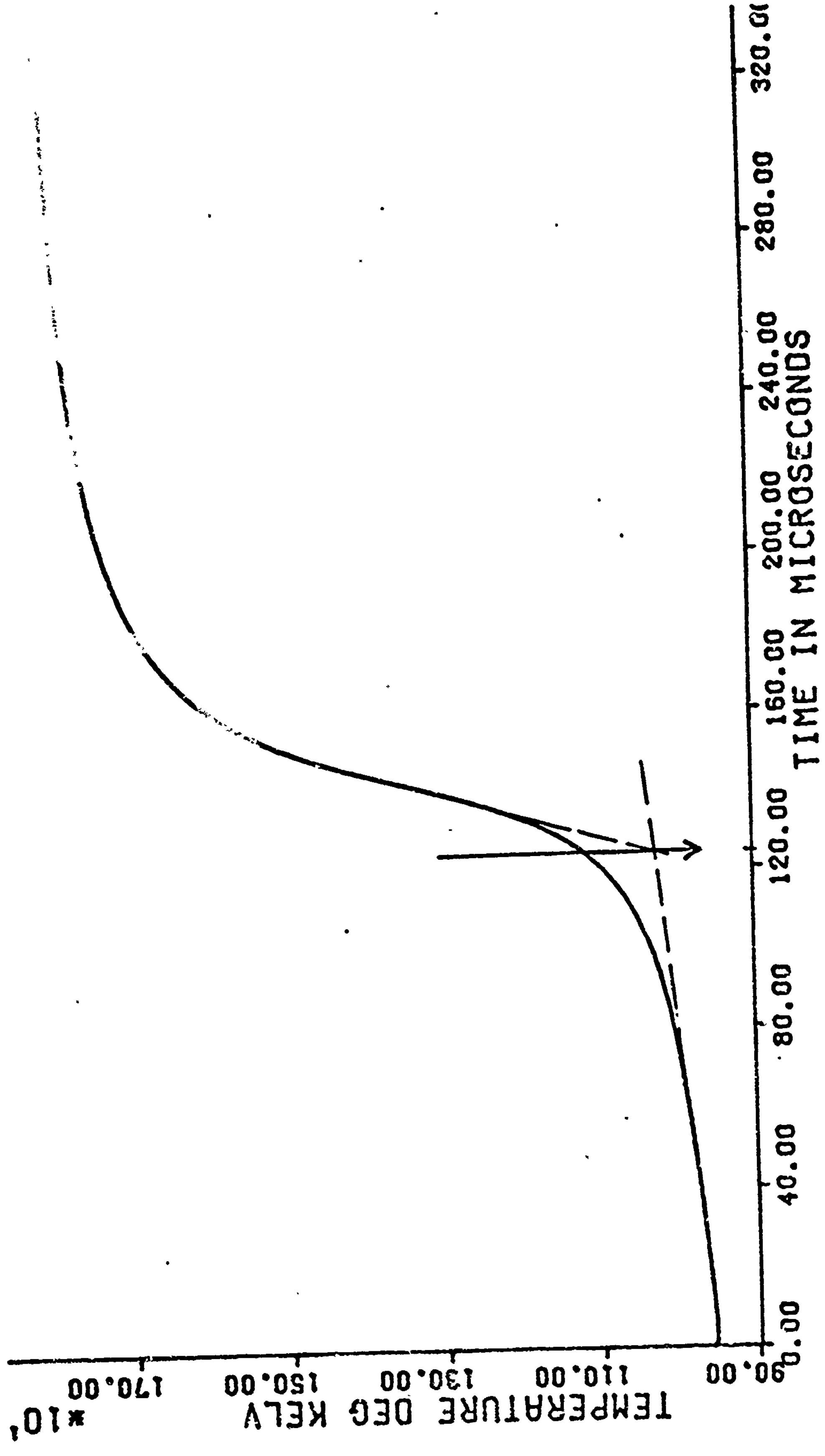

Figure 11. GRAPHICAL REPRESENTATION OF IGNITION DELAY USING TEMPERATURE CRITERIA

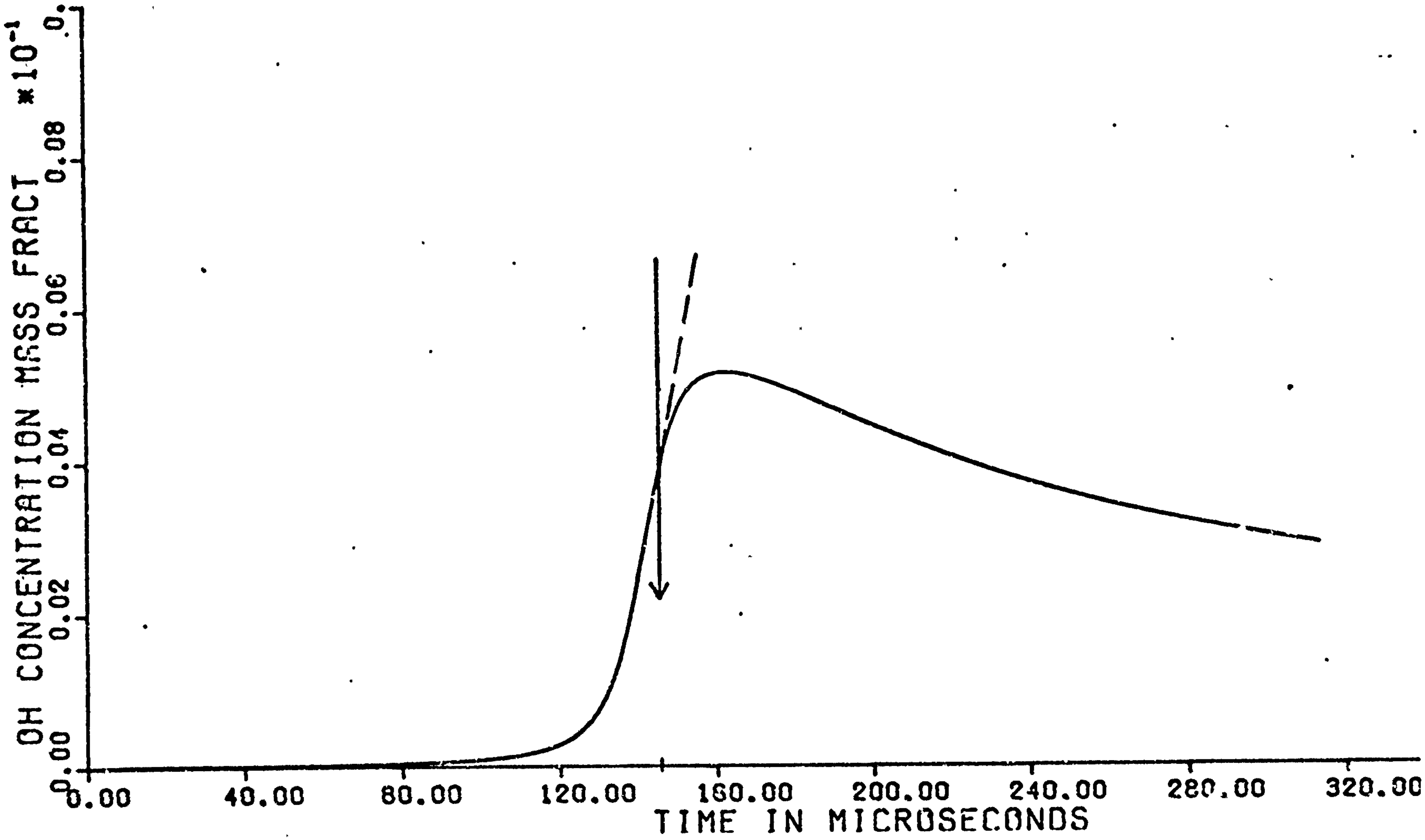

Figure 12. GRAPHICAL REPRESENTATION OF IGNITION DELAY USING OH CRITERIA

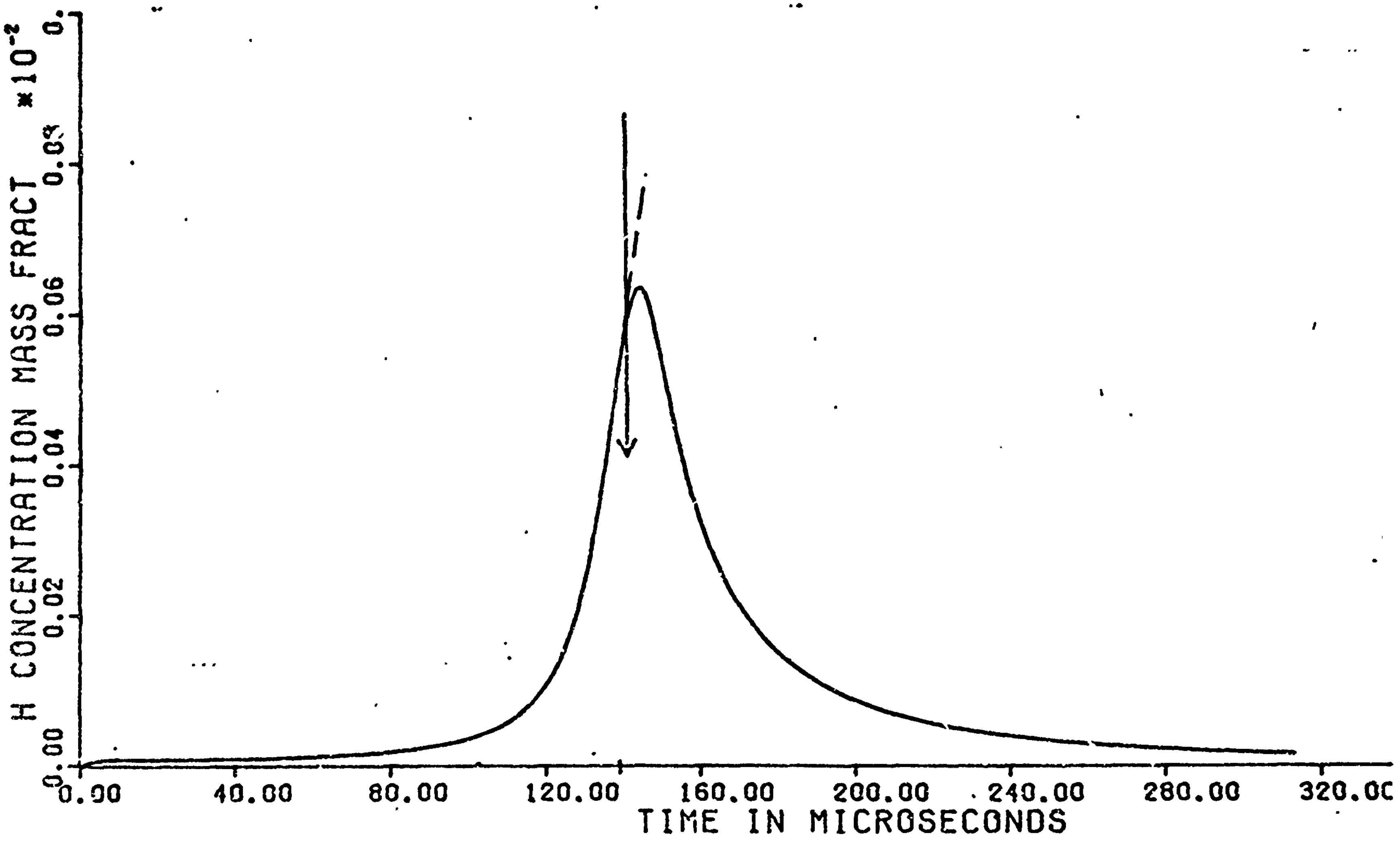

Figure 13. GRAPHICAL REPRESENTATION OF IGNITION DELAY USING H CRITERIA

III. DATA REDUCTION

Analytical results were obtained by using the OH concentration, H concentration, H_2 concentration, and the temperature slope criteria as discussed in section II. Due to the data similarity, only the OH concentration criterion results will be discussed at length. Graphical data based on the remaining criteria are given in the appendix. Discussion of OH data results is considered under the following headings:

1. ODFRC program results
2. GCK program results

ODFRC Program Results

The ODFRC results obtained by holding the equivalence ratio constant (1) and varying the inlet hydrogen gas temperature are shown in Fig. 14, Pg. 31. The results obtained by holding the inlet hydrogen temperature constant (710°K) and varying the equivalence ratio are shown in Fig. 15, Pg. 32. Note that the data points for the analytically calculated clean and vitiated-air cases are from 50% to 100% lower than the experimental values. Results for the seven cases were analytically recalculated using a lower temperature to see if the ignition delay times could be increased. All the analytical data failed to indicate ignition at these lower temperatures.

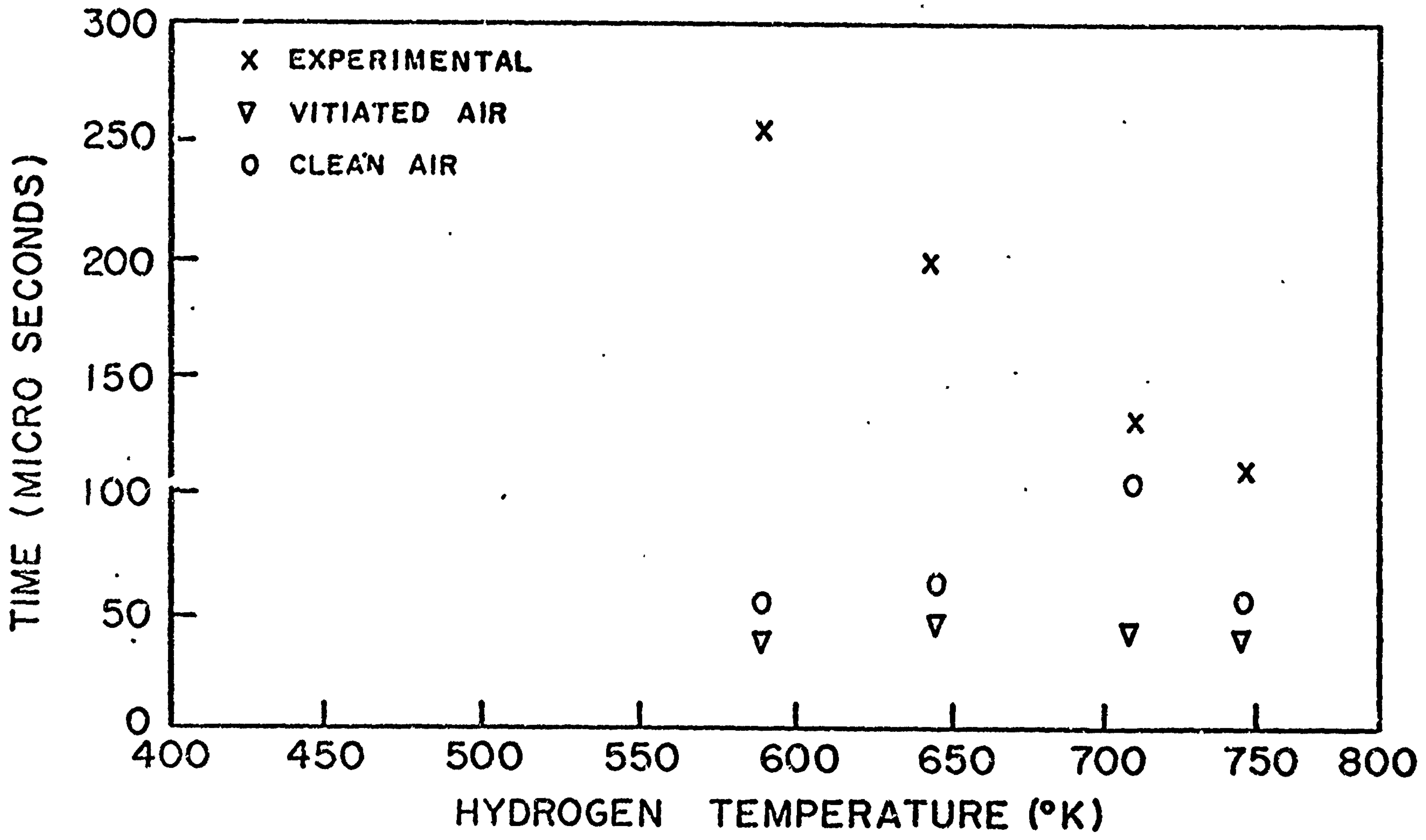

Figure 14. ODTRC IGNITION DELAY HISTORY USING OH CRITERION

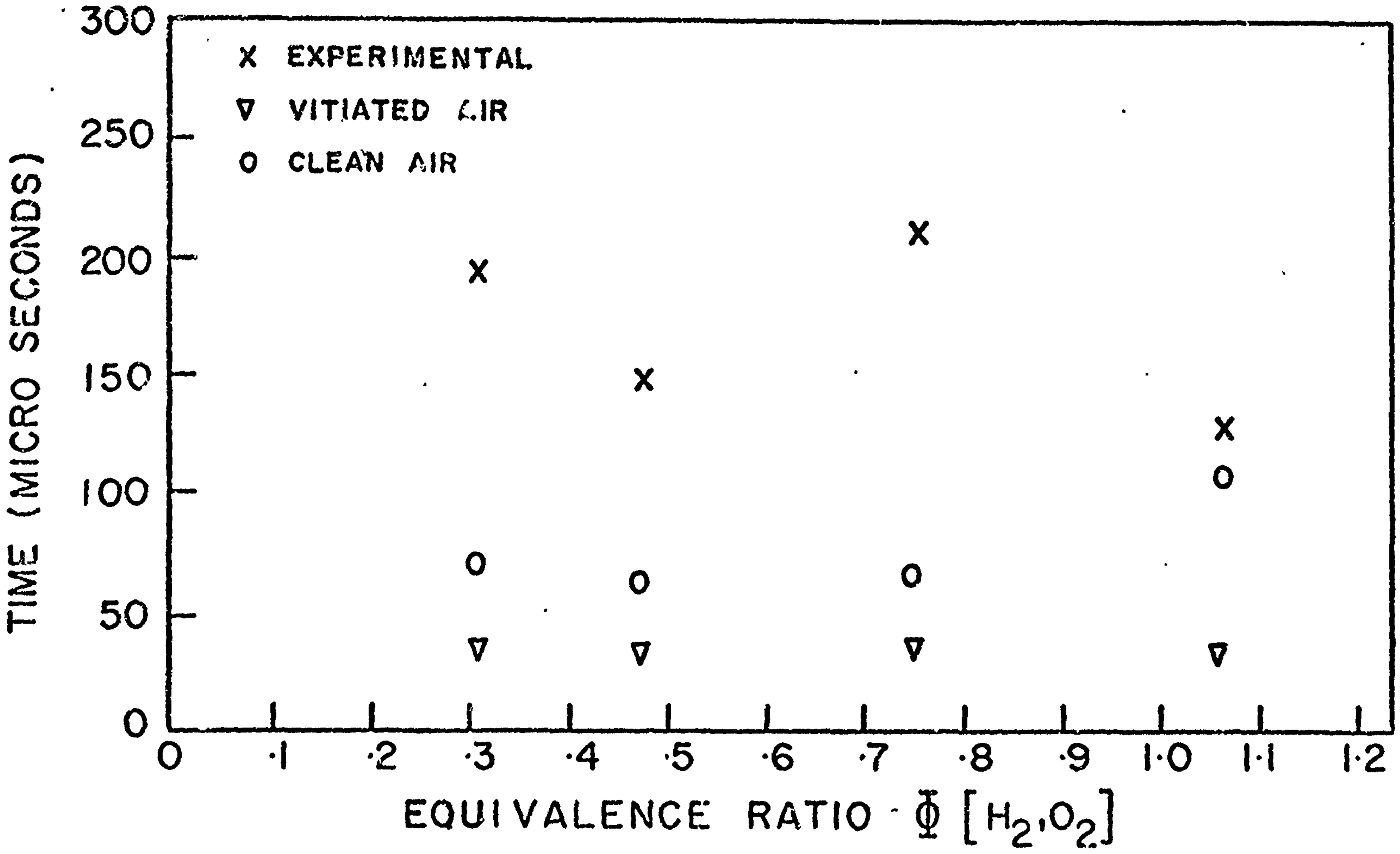

Figure 15. ODFRC IGNITION DELAY HISTORY USING OH CRITERION

Results from the ODFRC program, when comparing clean and vitiated-air results, show that the presence of water vapor shortened the ignition delay time (Figs. 14 and 15). However, due to the deviation between the analytical and experimental data points and the added sophistication, the GCK computer program was used in an attempt to analytically predict a more favorable comparison between the analytically calculated vitiated-air and the seven experimental cases.

GCK Program Results

Fig. 16, Pg. 35 and Fig. 17, Pg. 36 show the computed results obtained from the GCK program. These values compare favorably with the results of the ODFRC program, but were still much lower than the experimental points. The mixing cup termperature, which simulates the rate of diffusion of the H into the working fluid, was decreased to the value that would compare with the 40% mixing conditions assumed by Jensen (Ref. 6). The results obtained (Fig. 18 and 19) were closer to the experimental results than the values obtained from the ODFRC program, but the slope of the vitiated-air ignition delay curve was much less than the slope of the experimental curve. A possible explanation is that diffusion rates are much slower at low temperatures than at high temperatures (Ref. 1). Decreasing the diffusion rate at the lower temperatures would increase the slope of the vitiated-air ignition delay values on the constant equivalence ratio curve (Fig. 18) and increase the ignition delay values for the vitiated-air cases on the constant temperature curve (Fig. 19). The vitiated-air values would then be closer to the experimental values. These results are essentially the same as the analytic results Jensen (Ref. 6) obtained using the SIL computer program with the 40% mixing assumption.

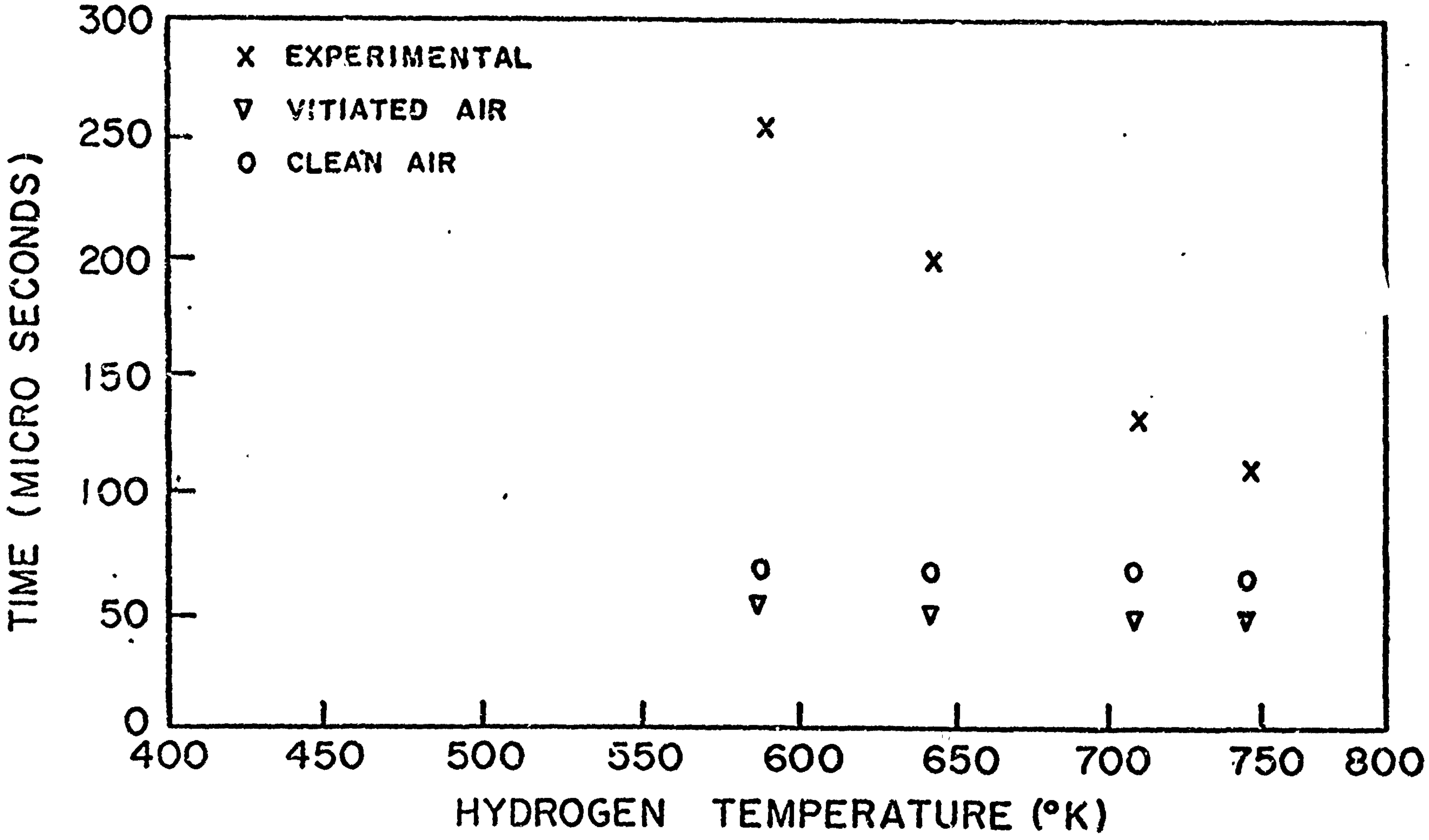

Figure 16. GCK IGNITION DELAY HISTORY USING OH CRITERION

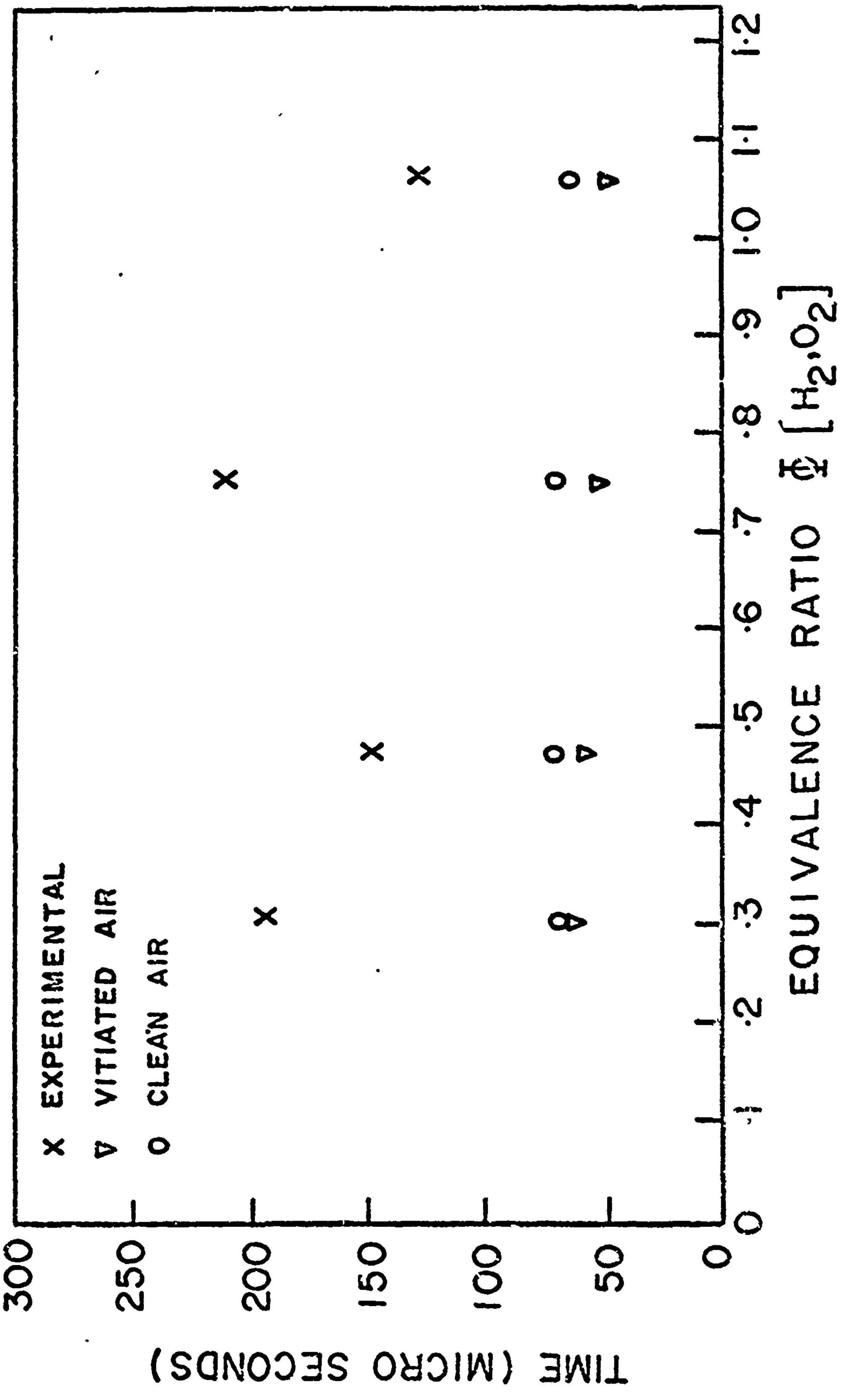

Figure 17. GCK IGNITION DELAY HISTORY USING OH CRITERION

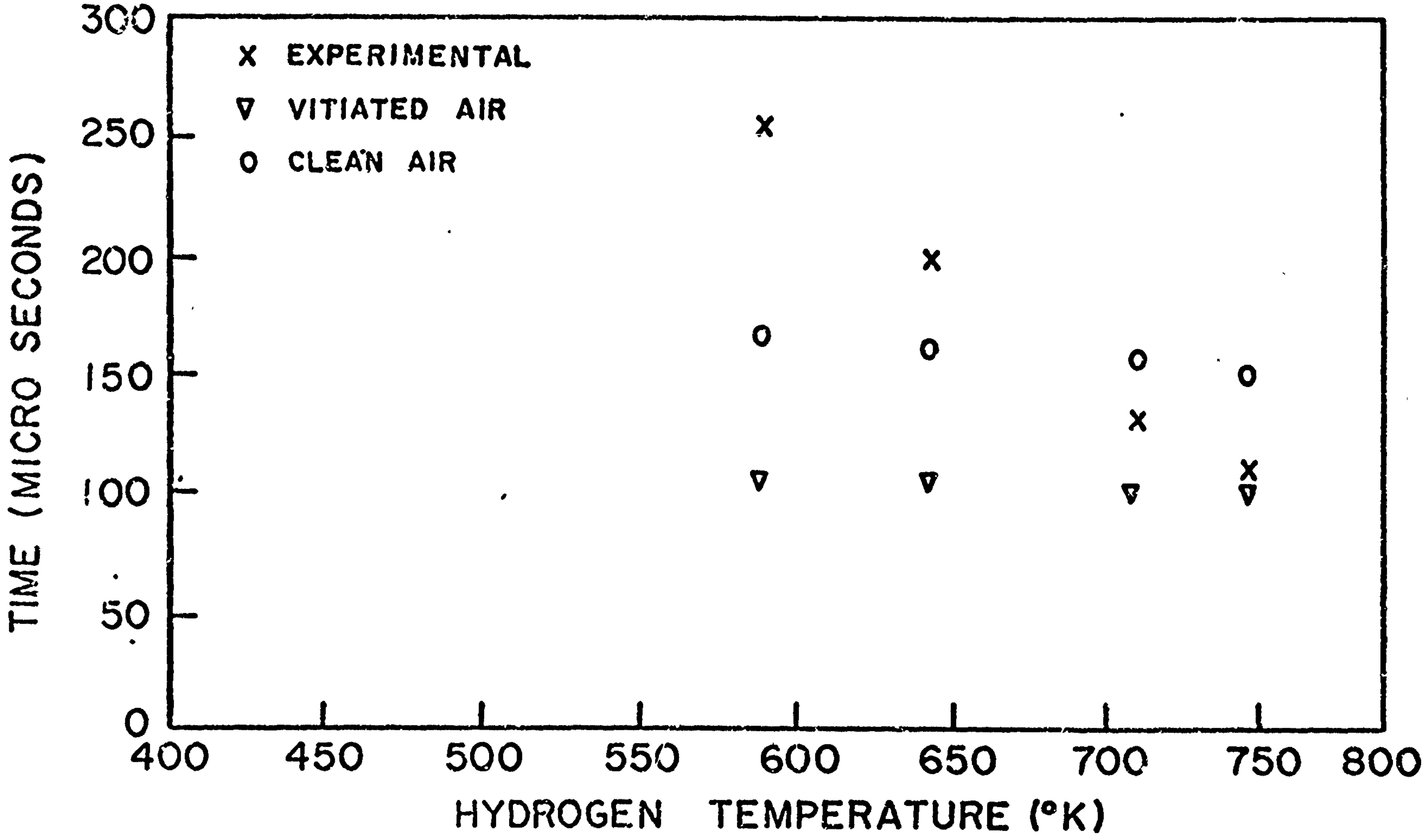

Figure 18. GCK IGNITION DELAY HISTORY USING OH CRITERION (40% MIXING)

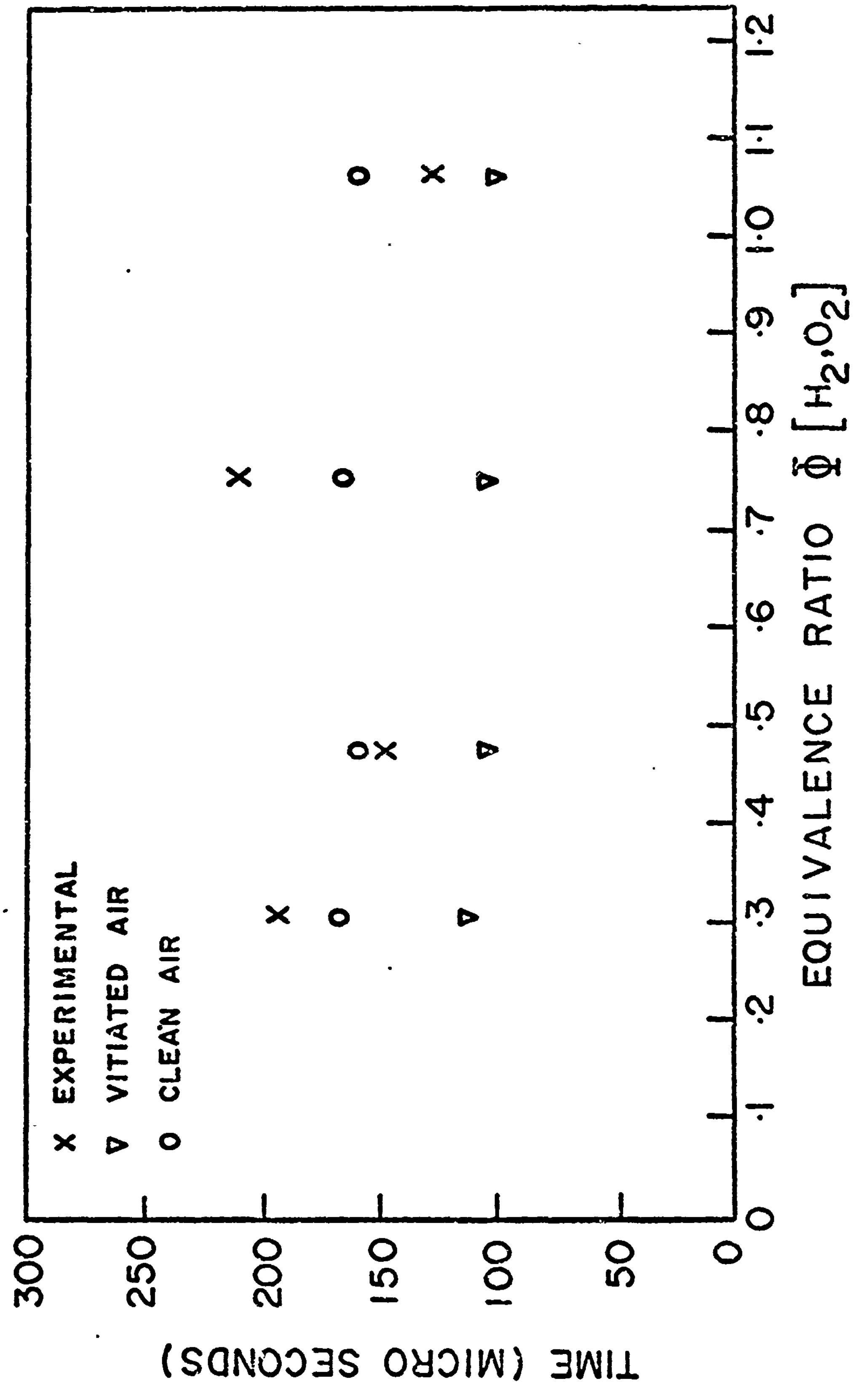

Figure 19. GCK IGNITION DELAY HISTORY USING OH CRITERION (40% MIXING)

IV. CONCLUSIONS

Analytical calculations were made for seven vitiated and clean-air investigative cases. These results were compared to the seven low temperature supersonic experimental data points obtained by Jensen. Based on the results in section III, the following conclusion was made:

> Ignition delay time is decreased if water vapor is present at the inlet to the combustor. Water vapor acts as a third body which promotes recombination of the free radical species causing the exothermic termination reactions to become dominent.

V. RECOMMENDATIONS

As a result of this study, the following recommendations are offered:

1. Obtain experimental inputs and results from vitiated-air heater ignition delay studies for a wider temperature range and analytically predict the ignition delay times. Results of this study would determine the temperature regime in which the water vapor shortens ignition delay times.

2. Determine the rate at which the [illegible] into the working fluid for different temperature [illegible]es. Results from this study could be used to more accurately predict ignition delay times.

3. Develop a kinetic scheme which would allow for more accurate evaluations of the effects of nitric oxide (NO).

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APPENDIX

Ignition Delay History Curves

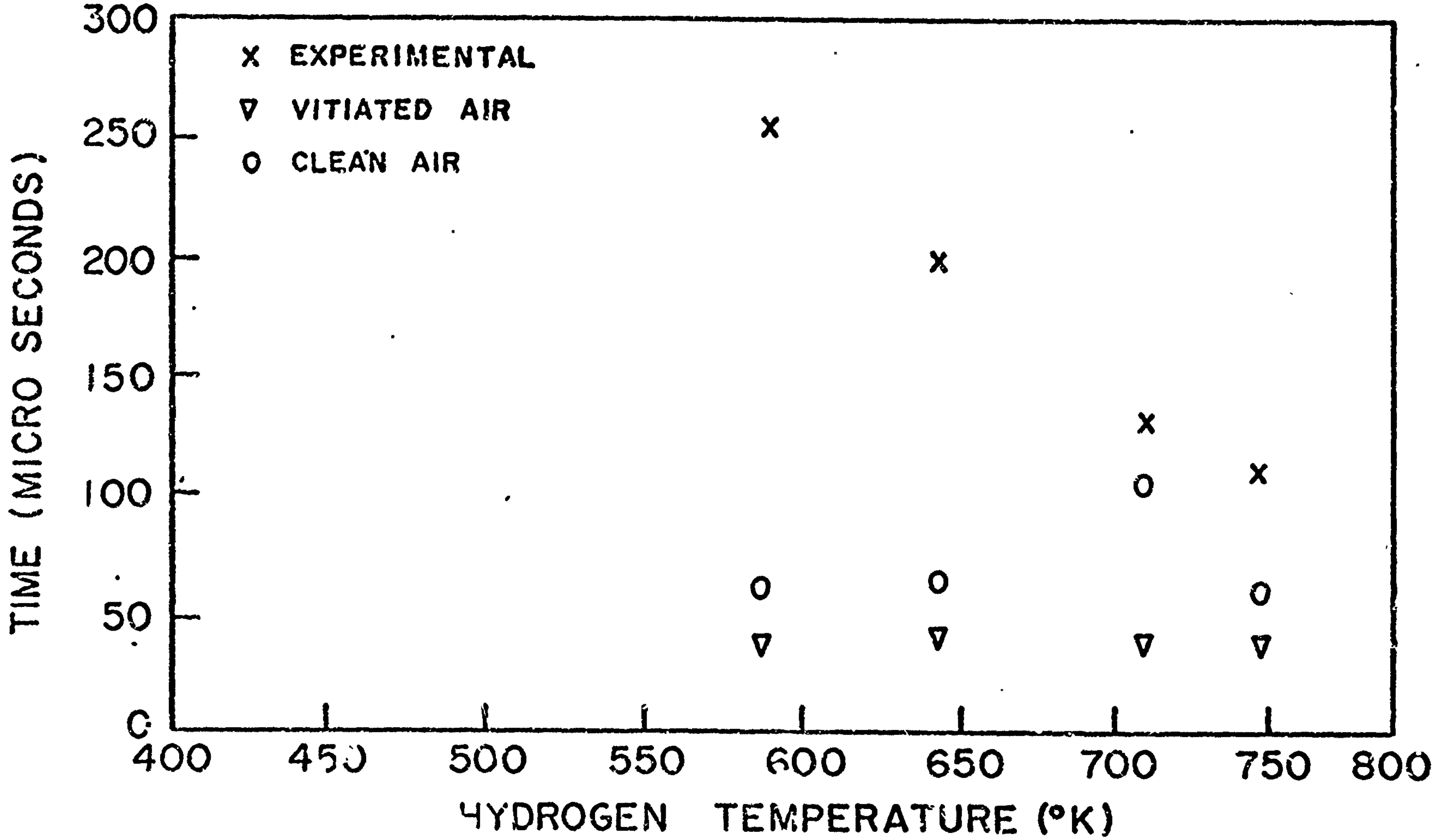

Figure 20. ODFRC IGNITION DELAY HISTORY USING H CRITERION

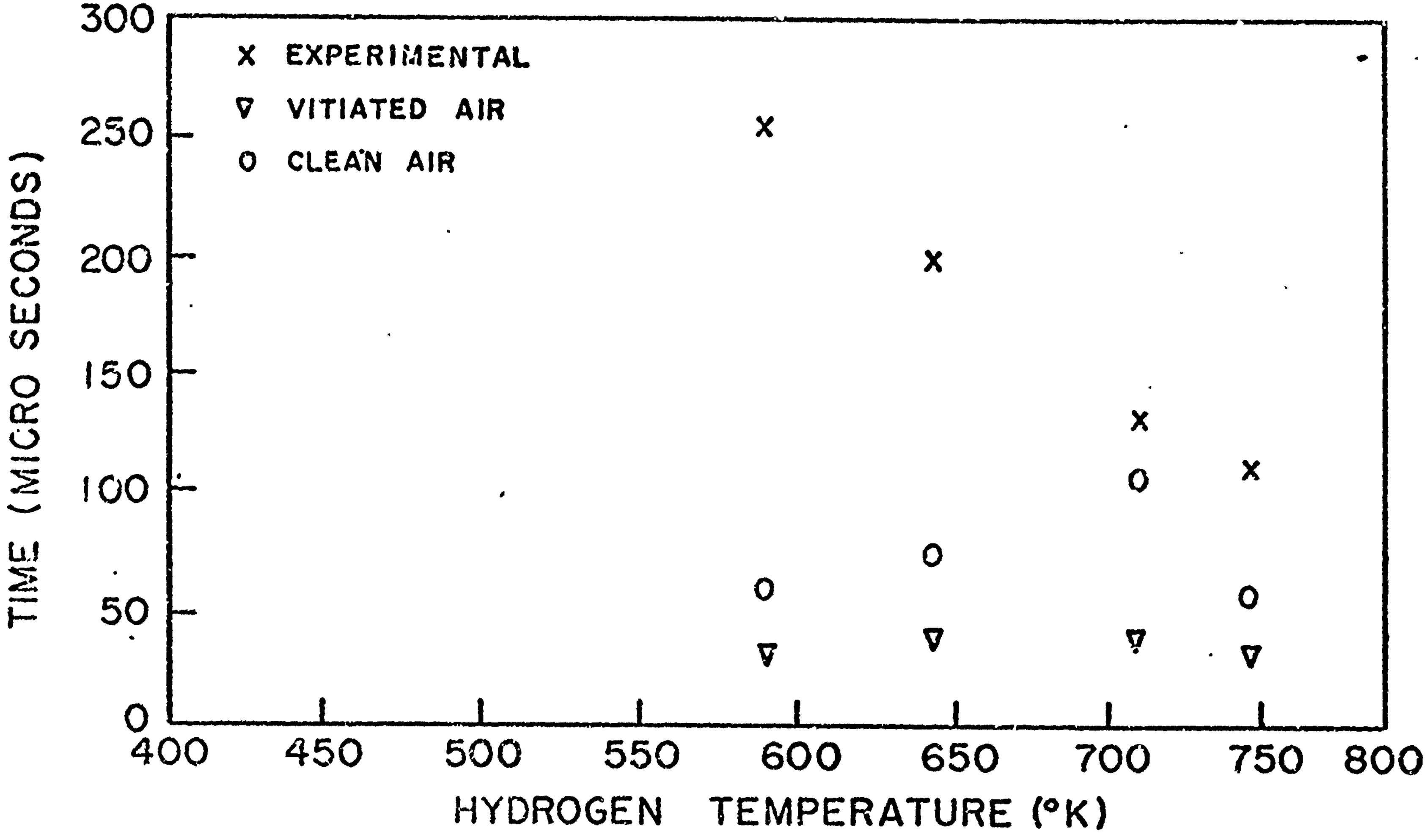

Figure 21. ODFRC IGNITION DELAY HISTORY USING 1/2 H_2 CRITERION

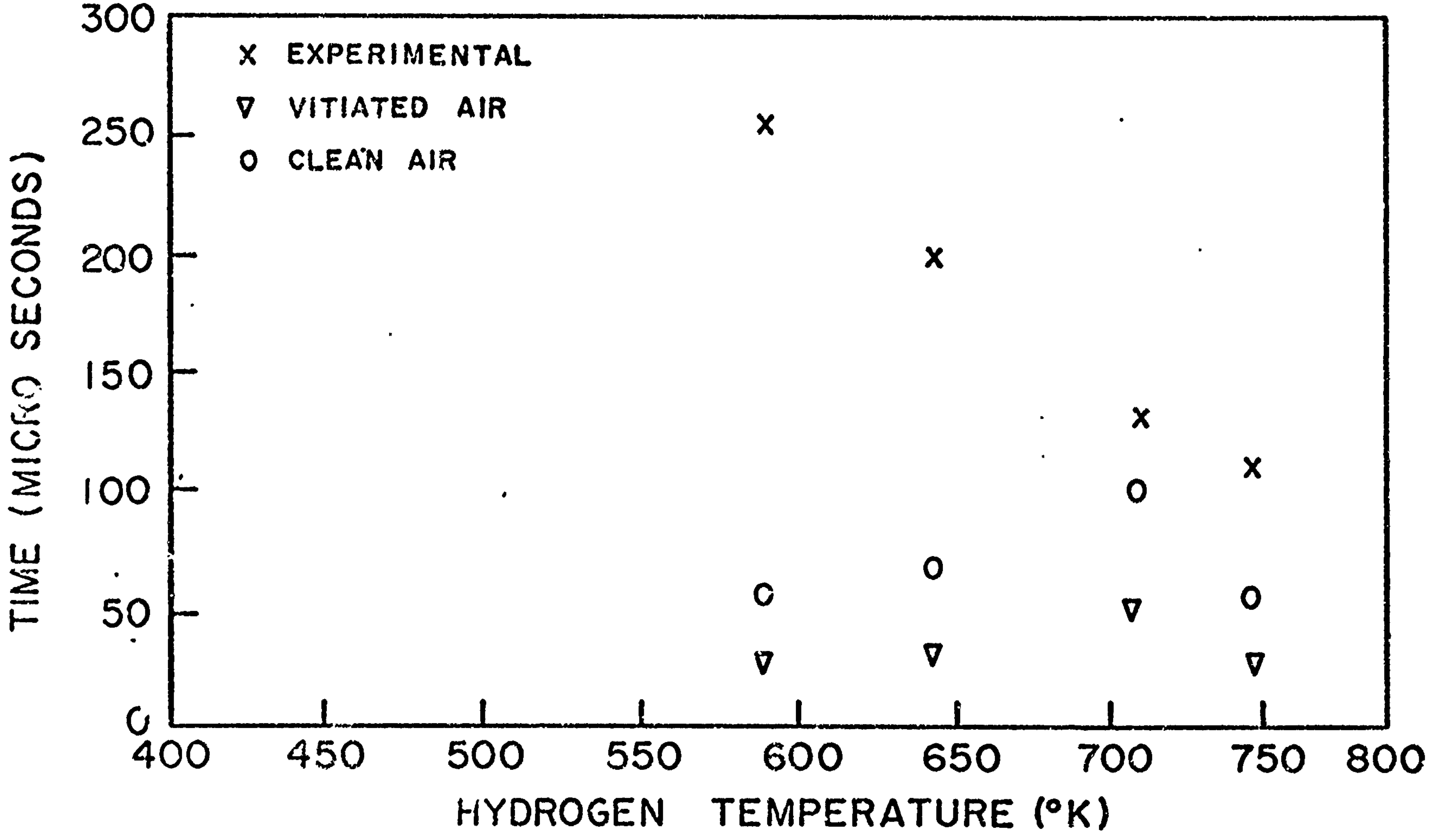

Figure 22. ODFRC IGNITION DELAY HISTORY USING TEMPERATURE SLOPE CRITERION

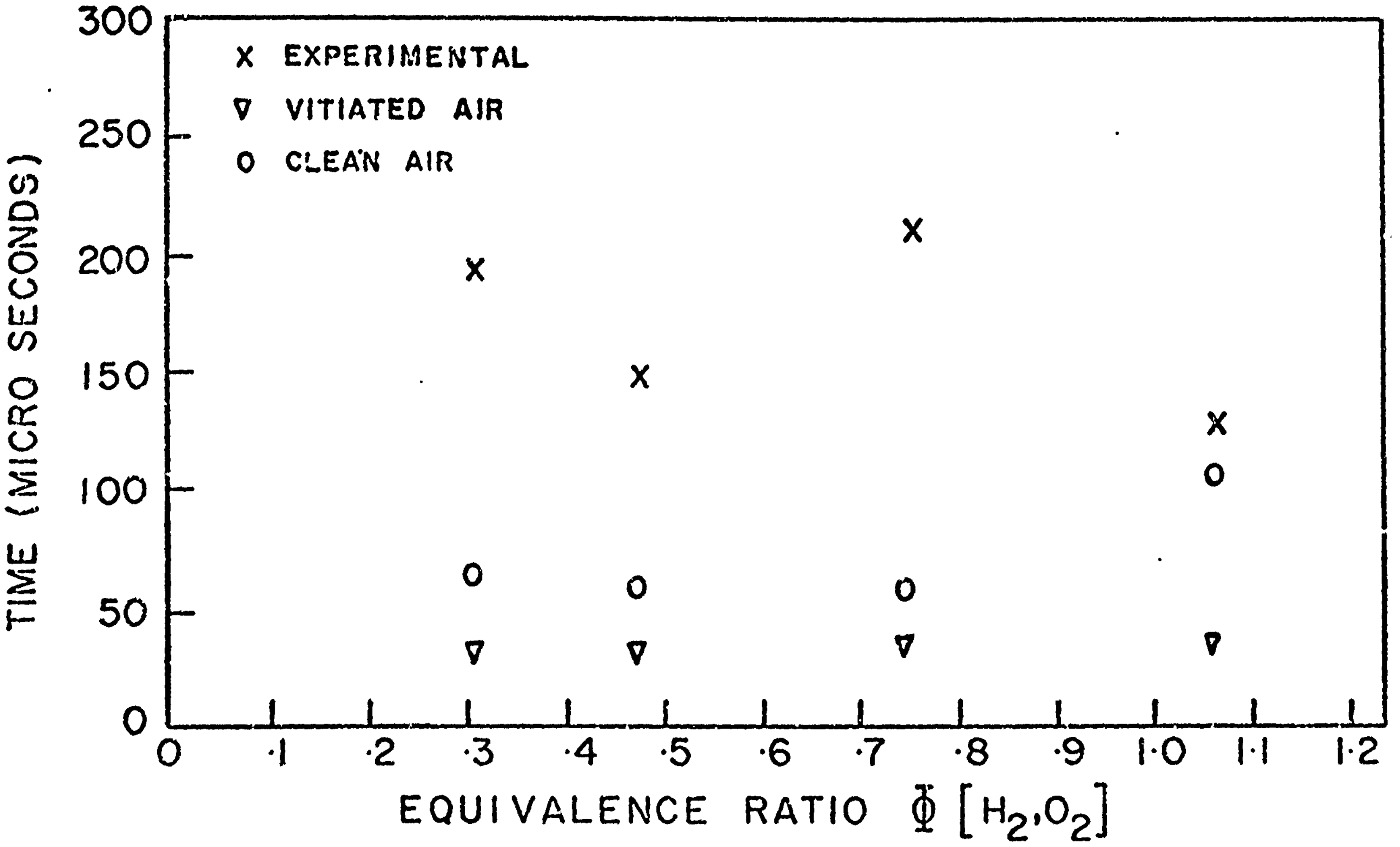

Figure 23. ODFRC IGNITION DELAY HISTORY USING H CRITERION

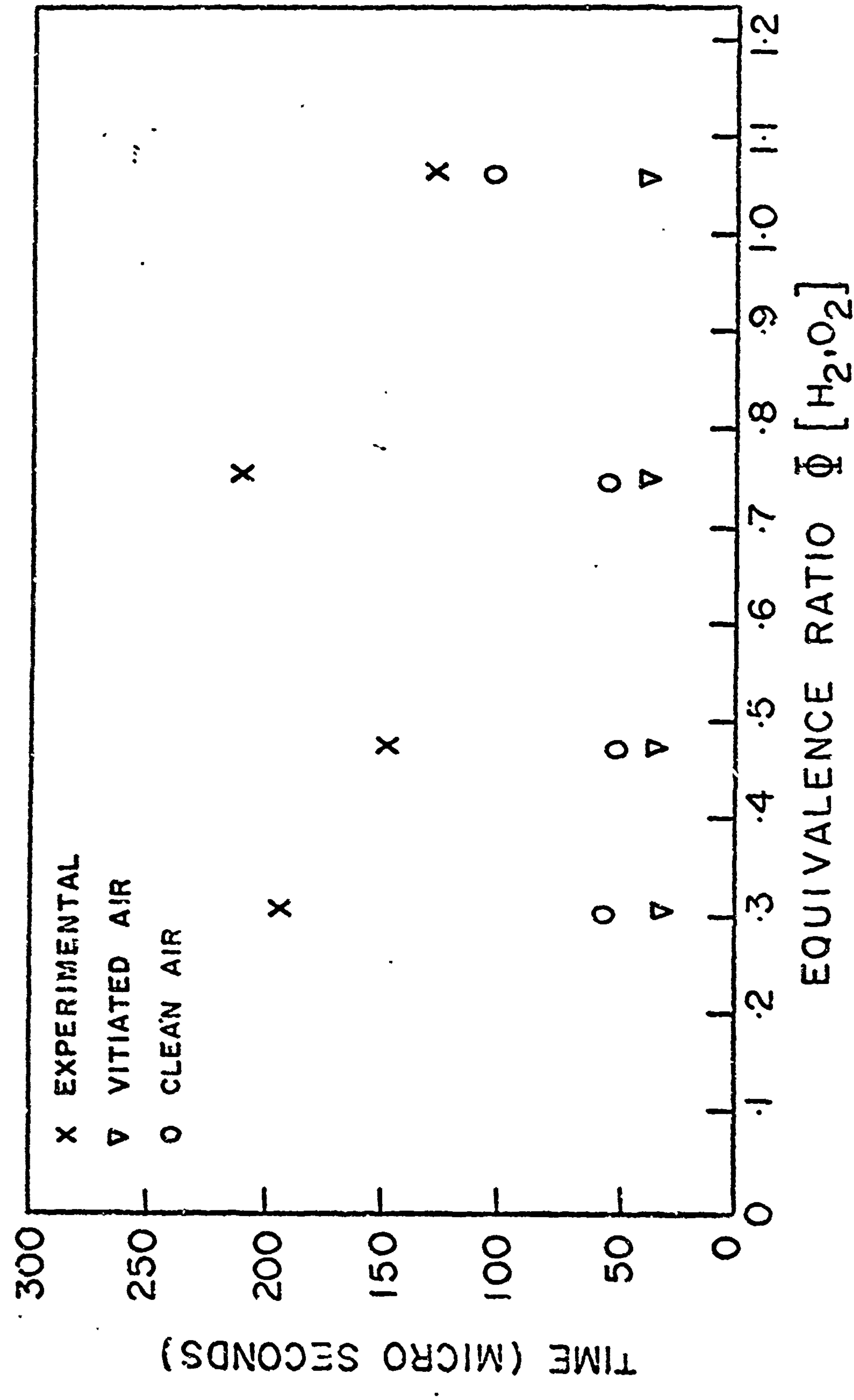

Figure 24. ODFRC IGNITION DELAY HISTORY USING 1/2 H_2 CRITERION

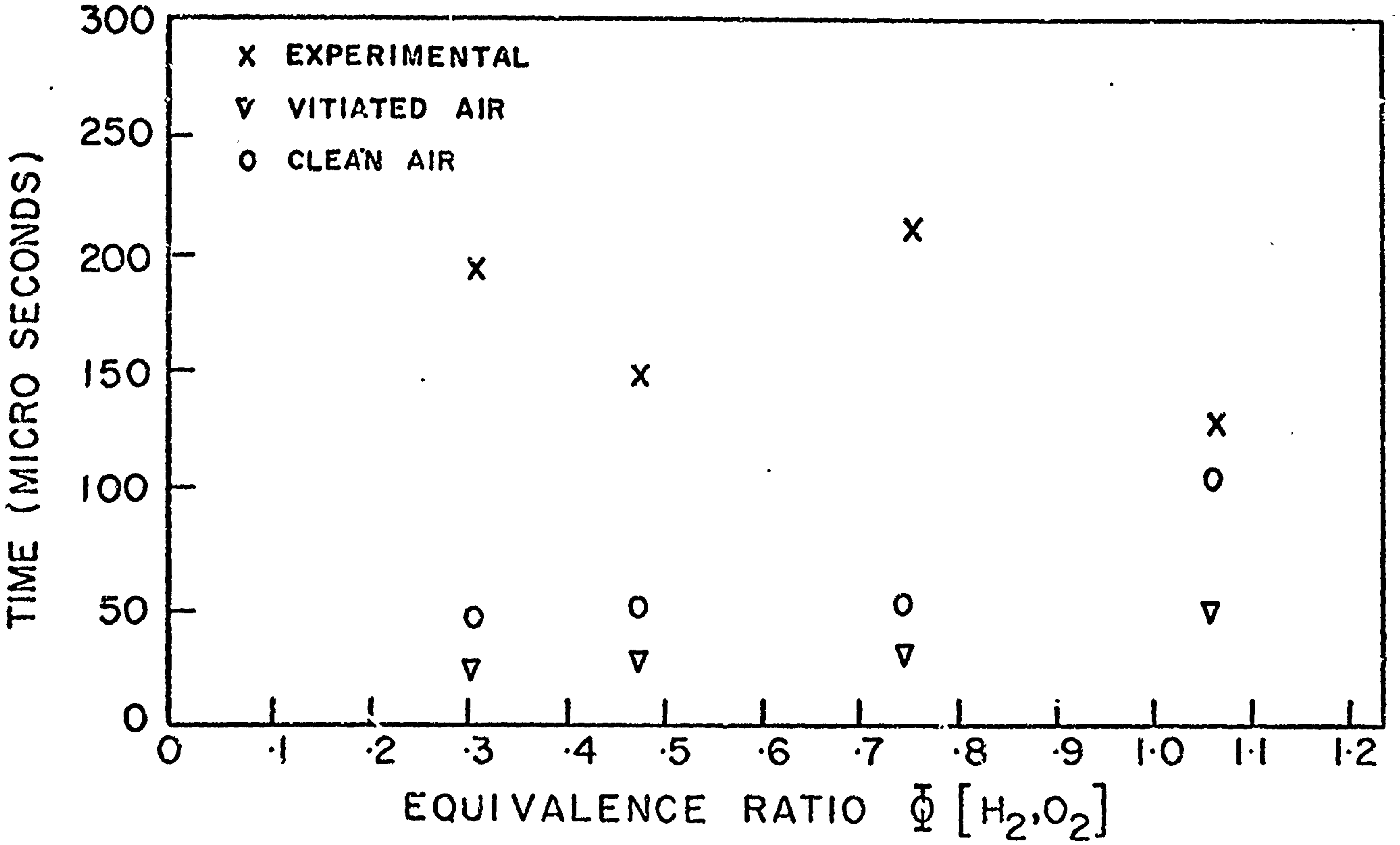

Figure 25. ODFRC IGNITION DELAY HISTORY USING TEMPERATURE SLOPE CRITERION

VITA

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