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AN EXPERIMENTAL INVESTIGATION OF THE SUPERSONIC COMBUSTION OF VITIATED AIR-HYDROGEN MIXTURES

R. E. Davis

ARO, Inc.

May 1970

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FOREWORD

The work presented herein was sponsored by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 62402F, Project 3012, Task 07.

The results of research presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under Contract F40600-69-C-0001. The research was conducted from May 13, 1968 to June 30, 1969 under ARO Projects PW5835 and PW5935, and the manuscript was submitted for publication on January 29, 1970.

This technical report has been reviewed and is approved.

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Colonel, USAF
Director of Plans
and Technology

ABSTRACT

Tests were conducted utilizing the AEDC PWT 5-MW Research Arc Heater as a high enthalpy air source to determine the effects of water vapor contamination on a hydrogen-air supersonic combustion process. A flow apparatus was constructed to permit vitiated, arc-heated airflow to mix coaxially with hydrogen in a constant area duct. The hydrogen was injected at the exit of the vitiated air nozzle which was designed for M = 2.8. Data were obtained in the form of wall pressure distributions and impact pressures and gas samples obtained from nonquenching pitot probes. The enthalpy of the mixture was varied from 1360 to 1860 Btu/lbm and the water vapor mass percent in the vitiated air was varied from 0 to 23.

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NOMENCLATURE

C	Gas sample volume fraction
E	Arc heater voltage, v
I	Arc heater current, amp
H	Stagnation enthalpy referenced to 0°R, Btu/lbm
m	Mass, mg
$\dot{m}$	Mass flow rate, lbm/sec
pc	Chamber or total pressure, psia
pm	Pitot probe impact pressure, psia
pn	Gas flow inlet pressure, psia
ps	Static pressure, psia
R	Normal distance from combustion duct centerline, in.
T	Static temperature, °R
TI	Gas flow inlet temperature, °R
ΔT	Change in cooling water temperature, °R
$\dot{V}$	Gas volume flow rate, cfm
$\dot{V}W$	Cooling water volume flow rate, gpm
X	Distance from exit of stilling chamber nozzle, in.
α	Species mass fraction

SUBSCRIPTS

a	Air
ah	Arc heater

cd	Combustion duct
e	Exit plane of stilling chamber nozzle
h	Hydrogen
n	Reservoir at stilling chamber nozzle
n/cd	4.364 area ratio nozzle and combustion duct
sc	Stilling chamber
wv	Water vapor

SECTION I
INTRODUCTION

Research and development of a supersonic combustion ramjet (SCRAMJET) will require true temperature and true velocity conditions in hypersonic wind tunnels. A high stagnation temperature will be required to achieve the proper static temperature and velocity. Among the various means of obtaining a high temperature is the use of a ceramic storage heater for heating air, followed by the combustion of hydrogen or hydrocarbons with a part of the oxygen in the air. The presence of water vapor, as a product of combustion, in the vitiated air may lead to uncertainties in the interpretation of the test results.

At the request of Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, tests were conducted for the University of Tennessee Space Institute (UTSI) to determine the effects of water vapor vitiation upon a hydrogen-air combustion process at various air enthalpy and vitiation levels. The results of the tests are presented herein.

SECTION II
APPARATUS

2.1 5-MW RESEARCH ARC HEATER

The Research Arc Heater (Fig. 1, Appendix) of the Propulsion Wind Tunnel Facility (PWT), AEDC, is a continuous-flow, Linde N-4000 arc heater. The arc heater can be operated with either air, nitrogen, or argon as a test gas.

2.2 SUPERSONIC COMBUSTION APPARATUS

The UTSI supersonic combustion apparatus consisted of a stilling chamber into which cold air and water vapor were injected and mixed with arc-heated air; an axisymmetric, Mach number 2.8, 4.364 area ratio nozzle (hereafter referred to as the stilling chamber nozzle); an annular sonic nozzle that supplied gaseous hydrogen flow; and a 12-in. constant area combustion duct. The flow apparatus which was attached to the arc heater nozzle assembly and test cell is shown in Fig. 2. The test cell was utilized to establish the required ambient pressure and to provide a means to exhaust the test gases.

The arc heater was equipped with a 0.50-in. axisymmetric sonic nozzle. The 0.50-in. sonic and the 1.033-in. axisymmetric nozzle throat diameters resulted in an arc heater nozzle/stilling chamber pressure ratio favorable for good arc heater jet spreading at the desired test conditions, thereby allowing good mixing of the injected water vapor and cold air with the arc-heated air.

The stilling chamber had four injection orifices around its perimeter at each of the injection locations shown in Fig. 2. The injected flow was directed upstream to provide good penetration into the arc-heated air and enhance the mixing process. A pressure orifice was located at the upstream and downstream end of the stilling chamber to provide total pressure measurements. Pressure orifices were also located at the exit plane of the stilling chamber nozzle and at the hydrogen stilling chamber. The design of the stilling chamber nozzle and sonic hydrogen nozzle was such as to allow an equal static pressure (corresponding to the desired mass flows) at the nozzle exits. Shown in Fig. 3 is a full-scale view of the two nozzles at the exit plane. The 12-in. combustion duct had thirty 0.031-in.-diam pressure orifices equally spaced at 0.375 in. along the duct. The first orifice is 0.65 in. downstream of the nozzle exit plane. A view of the test installation is shown in Fig. 4.

Individual heat loss measurements were made for the arc heater and stilling chamber sections. A single heat loss measurement was obtained for the stilling chamber nozzle and combustion duct section. The heat loss measurements from the arc heater and stilling chamber permitted calculation of the stagnation enthalpy of the gas entering the stilling chamber nozzle, which was one of the primary test variables. The heat loss measurement for the stilling chamber nozzle and combustion duct was not required for flow calculations but was monitored during the test.

2.3 GAS SAMPLING APPARATUS

The gas sampling system consisted of three nonquenching water-cooled, pitot probes equally spaced 0.500 in. apart and mounted on a common base; twenty-one cast steel 470-cc sample container bottles; and associated electronic circuitry used for sequenting operation of solenoid valves controlling admission of gas samples into the bottles. The three-probe arrangement was attached to a milling vice that was worm gear driven by an electric motor and moved so as to sample the flow in the exit of the combustion duct. The position of the milling vice, which reflected the position of the probes, was remotely indicated by means of a potentiometer. During testing, the probes were traversed between two predetermined positions at which gas sample and impact

pressure data were obtained. The two positions corresponded to probe locations of 1.25, 0.75, and 0.25 and 1.00, 0.50, and 0 in., respectively, from the centerline of the combustion duct. In addition to the samples taken through the probes, a wall gas sample was taken from a static pressure orifice located 0.50 in. from the end of the combustion duct. For one test condition seven gas samples could be obtained, and the 21-bottle supply permitted the acquisition of gas samples at three test conditions (vitiation levels) during a test run. The probes are shown positioned for testing at the end of the 12-in. combustion duct in Fig. 5. The basic probe has a 0.125-in. OD and 0.050-in. ID at the tip and is constructed of copper.

The sampling system valving arrangement and the sampling bottles are shown in Figs. 6 and 7, respectively. The heating coils indicated in Fig. 6 were set at 240°F during testing to help prevent water vapor condensation in the gas sample entering the inlet manifold. The sample lines were not heated from the inlet manifolds to junctions on the test cell wall nor was hot (~190°F) water used for cooling the probe tips and sample line inside the test cell. The additional line heating and hot water cooling would have been desirable but were not feasible with the system. Tests were conducted with helium and oxygen as test gases to determine the purge time required to collect an uncontaminated sample. The tests indicated that an 11-sec purge and an 11-sec fill time would be sufficient to collect an uncontaminated sample.

SECTION III
PROCEDURE

3.1 TEST PROCEDURE

The primary variables controlled during testing were specific enthalpy of the arc heater flow and the vitiation level of the mixture. To establish test conditions, the arc heater air, water vapor, cold air, and hydrogen inlet mass flow conditions were established. Subsequently, water vapor and cold air were injected into the stilling chamber. Then, the arc-heater was brought on line and, after allowing about 20 sec for flow stabilization, hydrogen was injected. The test procedure followed during most of the testing was to operate the arc heater continuously at a constant mass flow of 0.50 lbm/sec and a constant power input for each temperature condition. The mass flow of water vapor and cold air was varied to obtain different vitiation levels. The change in water vapor and cold air mass flows at constant arc heater power input conditions would slightly change the exit

temperature; therefore, some testing was conducted by operating the arc heater at a different power input level for each vitiation level test condition. As previously stated, the arc heater mass flow was held constant at 0.50 lbm/sec for most test conditions, but for some testing, no cold air was injected into the mixing chamber and arc heater mass flow was increased accordingly.

Cold air and water vapor mass flow were varied from 0.0176 to 0.286 and 0 to 0.1442 lbm/sec, respectively, and stilling chamber nozzle mass flow varied between 0.647 and 0.786 lbm/sec. The cold air and water vapor were supplied to the stilling chamber at nominal stagnation temperatures of 535 and 985°R, respectively. The cold air and water vapor inlet pressure to the stilling chamber were sufficient to establish critical flow through the injection orifices at all mass flow rates for both systems. The stilling chamber pressure was a nominal 115 psia during testing. The hydrogen mass flow rate, chamber pressure, and stagnation temperature were maintained at a nominal 0.060 lbm/sec, 7.40 psia, and 540°R, respectively, for all test conditions.

During the test the following data were obtained: stilling chamber (total) pressure, combustion duct static pressure, gas volume flow rate, cooling water volume flow rate, cooling water ΔT, probe impact pressure, and probe gas samples. The numerical data were recorded on magnetic tape at 4-sec intervals. An analog-to-digital converter system processed the data signals for storage on magnetic tape. Each channel of data was sampled 15 times for a 0.20-sec interval and averaged.

The various gas and cooling water flow rates, except arc heater air, were measured by vane-type volume flowmeters together with the inlet pressure and temperature measurements. The arc heater mass flow was determined by means of calibrated orifices. The arc heater air, cold air, and hydrogen mass flow were calculated assuming perfect gas behavior. The water vapor mass flow was calculated using the data of Ref. 1.

The analysis of gas samples was made by first performing a volumetric analysis, at room temperature conditions, for O_2, H_2, and N_2 gases. The remaining volume fraction was assumed to be evaporated water. The gas sample was then heated and all the water vapor was removed from the sample bottle and its mass determined.

3.2 ACCURACY OF THE RESULTS

Based on a confidence level of 95 percent, the errors in the data resulting from instrumentation errors are as follows:

Δpn_{ah}	= ±40.0 psia	$\Delta(\Delta T)$	= ±0.50°F
Δpn_{wv}	= ±10.0 psia	ΔTI_{wv}	= ±5.0°F
Δpn_a	= ±10.0 psia	ΔTI_a	= ±2.0°F
Δpn_h	= ± 2.0 psia	ΔTI_h	= ±2.0°F
Δpc_{ah}	= ±10.0 psia	$\Delta \dot{V}W_{ah}$	= ±3.0 gpm
Δpc_{sc}	= ± 5.0 psia	$\Delta \dot{V}W_{sc}$	= ±1.0 gpm
Δpc_h	= ± 0.15 psia	$\Delta \dot{V}W_{n/cd}$	= ±1.0 gpm
Δps_e	= ± 0.10 psia	$\Delta \dot{V}_a$	= ±0.040 ft^3/sec
Δps_{cd}	= ± 0.15 psia	$\Delta \dot{V}_{wv}$	= ±0.200 ft^3/sec
Δpm	= ± 0.50 psia	$\Delta \dot{V}_h$	= ±0.002 ft^3/sec

ΔE = ±200.0 v

ΔI = ± 10.0 amp

ΔR = ± 0.03 in.

ΔC = ±5% at C = 100 vol. %

The resulting uncertainty intervals for computed results, based upon the work in Ref. 2 where the frequency distribution for all errors is assumed Gaussian, are as follows:

$\Delta \dot{m}_{ah}$	= ±0.010 lbm/sec	ΔH_{ah}	= ±130 Btu/lbm
$\Delta \dot{m}_a$	= ±0.004 lbm/sec	ΔH_a	= ±0.500 Btu/lbm
$\Delta \dot{m}_{wv}$	= ±0.006 lbm/sec	ΔH_{wv}	= ±2.50 Btu/lbm
$\Delta \dot{m}_n$	= ±0.012 lbm/sec	ΔH_n	= ±105 Btu/lbm
$\Delta \dot{m}_h$	= ±0.005 lbm/sec	$\Delta \alpha_{e,wv}$	= ±0.008

SECTION IV
RESULTS AND DISCUSSION

4.1 GENERAL DISCUSSION

The original test plan called for values of nozzle exit static temperatures of 1900, 2100, and 2300°R with vitiation levels of 0, 10, and 20

percent at each temperature at a static pressure of 3.7 psia at the stilling chamber nozzle exit. However, initial test data indicated that no significant combustion was occurring at the test conditions corresponding to and below a nozzle exit static temperature of 2100°R based upon a frozen flow analysis for flow through the stilling chamber nozzle. Therefore, most testing was conducted at conditions where a static temperature of 2100°R and above existed at the nozzle exit.

Shown in Fig. 8 is the envelope of test conditions obtained during the test. The lines of constant nozzle exit static temperature shown in the figure were obtained from a one-dimensional isentropic nozzle expansion program (Ref. 3). The program had the capability for nonequilibrium solutions, but attempts to obtain nonequilibrium solutions for the test conditions of interest were unsuccessful. Therefore, recourse was made to the frozen and equilibrium solutions to aid in the interpretation of test results. The nozzle flow calculations were made for a composition of species O_2, N_2, H_2, A, N, O, H, H_2O, OH, NO, NO^+, and e^-. The vibrational energy was taken to be that of harmonic oscillators for all species except H_2O which was modeled from thermo-fit data. The electronic and vibrational degrees of freedom were assumed to remain in thermodynamic equilibrium. Typically, the computer results revealed that the reservoir temperature corresponding to the test data was high enough that significant dissociation occurred in the reservoir. For an equilibrium expansion to an area ratio of 4.364 corresponding to a nominal Mach number of 2.8, the N_2, O_2, and H_2O species concentrations increased only slightly. Although the N, O, H, OH, NO, and NO^+ concentrations were relatively small at the reservoir, a large percentage decrease occurred in these concentrations during the expansion. As illustrated in Fig. 9 the dissociation and recombination reactions involving N, O, H, OH, NO, and NO^+ had a pronounced effect upon the thermodynamic behavior of the flow through the nozzle. The radicals OH and NO were present at the reservoir in significant amounts to affect results, and calculations of reaction times involving these two species revealed that the reactions were fast and very slow, respectively, when compared to a characteristic flow time based on nozzle length and exit velocity. Therefore, some degree of nonequilibrium was present, and any conclusion about which theoretical solution, shown in Fig. 8, better represents the nozzle exit conditions could not be made with certainty.

The experimental values of nozzle exit static pressure ranged from 3.02 to 3.67 psia for all tests. The computer results for frozen and equilibrium flow gave a static pressure 0.3 to 0.7 psia higher than the experimental value. This was probably due in part to the fact that nozzle heat losses, typically about 140 Btu/lbm, were not considered in the

nozzle flow program. Comparison of the experimental value of nozzle mass flow with the calculated value for frozen and equilibrium flow indicates that equilibrium flow exists up to the nozzle throat.

Information supplied by UTSI predicted no, slight, and significant reaction at 1900, 2100, and 2300°R, respectively. Figure 8 illustrates that for frozen flow (the most conservative case) a reaction, as suggested by a significant pressure rise in the combustion duct, did not consistently occur at a temperature above 2100°R. Only about 20 percent rather than 100 percent of the stilling chamber and supersonic nozzle wall surfaces were flame sprayed with zirconium oxide for the purpose of maintaining a high recovery wall temperature. It is reasonable to assume that without the oxide coating a strong traverse enthalpy gradient would exist in the stilling chamber with a resulting relatively low wall temperature at the nozzle exit, possibly explaining the absence of reaction at some test conditions. If the enthalpy gradient thickness and the nozzle radius are of the same order of magnitude at the exit plane of the nozzle and the inner core flow static temperature is favorable to reaction, then reaction may be delayed until mixing has progressed toward the duct centerline. Review of some motion-picture data indicated that a flame definitely existed at the end of the combustion duct when the pressure data showed no significant pressure rise. The possibility then exists that slight combustion was occurring in the inner core of the flow, and traverse static pressure gradients existed in the reacting flow. Motion-picture data also indicate that a much brighter flame existed at the combustion duct exit for zero as compared to the 20-percent vitiation level.

In Fig. 8, at 1575 Btu/lbm and nine-percent vitiation, reaction did not occur until some time after the hydrogen flow had been established. Possibly, reaction at this test condition could have been induced by a flow contaminant such as an eroded metal particle. However, at 1540 Btu/lbm and 10-percent vitiation, combustion was not delayed and is not readily explainable in view of the absence of reaction at other test conditions. There were also inconsistencies concerning reaction at zero-percent vitiation where for two sets of data at a nominal enthalpy of 1775 Btu/lbm a combustion duct pressure rise did and did not occur.

4.2 COMBUSTION DUCT PRESSURE DISTRIBUTION

During the test, one run was made at a low nozzle enthalpy level (1440 Btu/lbm) where negligible reaction was expected, to determine the effect, shown in Fig. 10, of hydrogen mass flow on the pressure distribution in the duct. The nonuniform pressure distribution was probably the result of the finite lip thickness at the nozzle exit plane and the

hydrogen and vitiated air exit static pressure not being exactly equal. A progressive increase in hydrogen mass flow tended to shift and raise the low point of the pressure distribution at the 8.0-in. station, but the general shape remained the same. The range of hydrogen mass flow represents an exit static pressure below and above the prevailing vitiated air nozzle exit static pressure of 3.25 psia. Therefore, a lip induced oblique shock structure probably exerts the strongest influence on the pressure distribution which is seemingly only slightly affected by the static pressure ratio across the two nozzles.

Insufficient data were obtained where reaction occurred at a nominally constant exit temperature to make firm conclusions about the effect of vitiation on reaction. The combustion duct pressure distributions for some of the data at nominal vitiation levels of 0, 10, and 20 percent are shown in Fig. 11. The data in Fig. 11 do indicate that vitiation level and nozzle enthalpy level did not significantly affect the maximum pressure or pressure distribution in the duct when reaction did occur and also that the ignition delay time was short as indicated by the continuous pressure rise proceeding from the nozzle exit.

4.3 GAS SAMPLE CONCENTRATION AND IMPACT PRESSURE DISTRIBUTIONS

Combustion was not expected at a nozzle exit static temperature of 1900°R, and gas samples were to be collected to evaluate turbulent mixing theories. The thermodynamic properties of the flow at 1900°R should not differ greatly from flow properties at 2100 and 2300°R where combustion was expected. Considerable difficulty was experienced with probe failures, however, and gas sample data were obtained at only one test condition. The gas sample and impact pressure data were obtained for test conditions corresponding to a nozzle exit temperature above 2200°R (based on a frozen flow analysis). Possible conclusions regarding the turbulent mixing phenomena were consequently negated since combustion upstream of the probe might have occurred at 2200°R.

Shown in Fig. 12 are the species volume fraction together with the total mass of water present in the sample. A gas sample of 1.25 in. from the combustinn duct centerline and at the wall was not obtained because the corresponding probe and orifice pressures were lower than the sampling line pressure maintained by the vacuum pump.. Mention should also be made of other factors that may invalidate some of the gas composition data. The possibility exists that water vapor condensation occurred in the unheated and water-cooled sections of the lines while samples were being taken, thereby introducing errors in the immediate and following samples. The sample bottles were made of cast steel,

and hydrogen gas absorption at the bottle walls could have occurred. Therefore, some of the data presented may be significantly in error. As indicated by the N_2 volume fraction data in Fig. 12, the undisturbed flow seems to extend to at least 0.25 in. from the flow centerline at 12 in. from the nozzle exit. However, even for the zero-percent vitiation test condition water, less than 21 percent O_2 and negligible H_2 were present at the centerline which would indicate that the mixing region had migrated to the centerline and some reaction had occurred. The gas sample data for the three vitiation levels were obtained over a range of nozzle enthalpy which, in view of the inconsistent trends in the results of Fig. 12 and the uncertainty as to whether reaction occurred upstream of the probe tip, makes any conclusion as to the effect of vitiation on reaction suspect. For all three test conditions shown in Fig. 12, significant reaction at 0.75 in. from the centerline, whether upstream or downstream of the probe tip, is indicated by the presence of a significant amount of water, a small amount of oxygen, and a nitrogen concentration which is significantly more than the nitrogen/oxygen ratio for the vitiated air.

The measured impact pressure distribution is shown in Fig. 13. However, the pressure at 0 and 0.50 in. from the centerline is believed to be greater than that indicated in the figure. The reason is that when the probe was moved to the positions 0, 0.5, and 1.0 in., data recording commenced before the reduced pressure, caused by the previous purge and fill operation at the other positions, was able to reach the higher level. The centerline pressure is thought to be equal to or greater than the pressure at 0.25 in. from the centerline. Noting the variation in the stilling chamber pressure, the different pressure levels in the centerline region seem reasonable.

SECTION V
CONCLUDING REMARKS

The combustion duct pressure distribution is apparently dominated by the geometry of the lip separating the air and hydrogen flow when reaction does not occur. The absence of reaction between the vitiated air-hydrogen mixture at an air static temperature where reaction is expected would suggest that flame quenching might have occurred in the flow or that the static temperature in the mixing region, reduced as a result of wall cooling upstream of the stilling chamber nozzle, was not high enough to initiate reaction. Any future experimental program should consider means of maintaining a high recovery wall temperature along the flow channel and the possibility of flame quenching in the mixing region.

The combustion duct maximum pressure and pressure distribution were not significantly affected by temperature or vitiation level for the data where reaction did occur. Where reaction did occur, the value of the maximum pressure and the pressure distribution in the combustion duct were not significantly affected by the vitiation level.

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APPENDIX
ILLUSTRATIONS

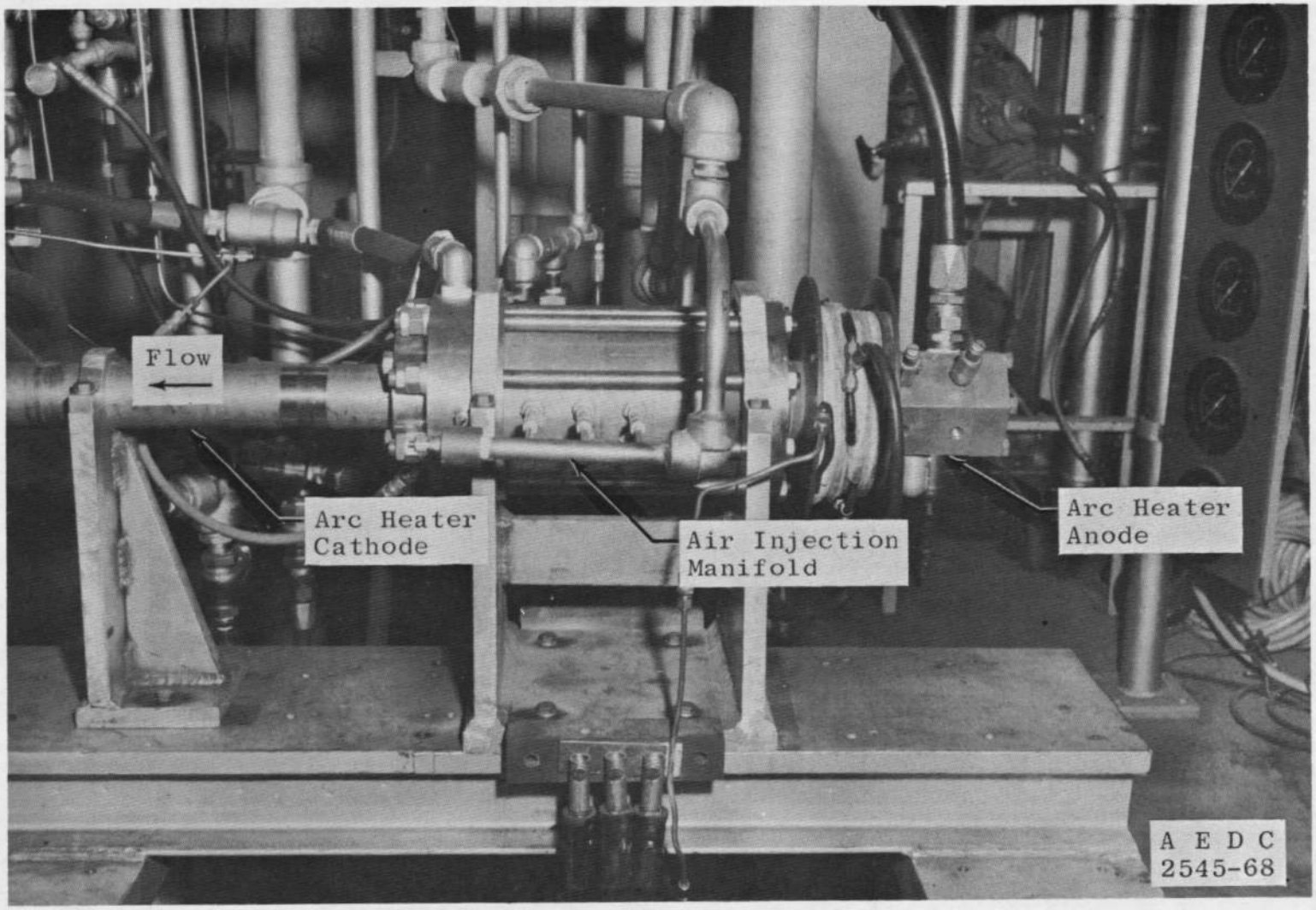

Fig. 1 5-MW Research Arc Heater

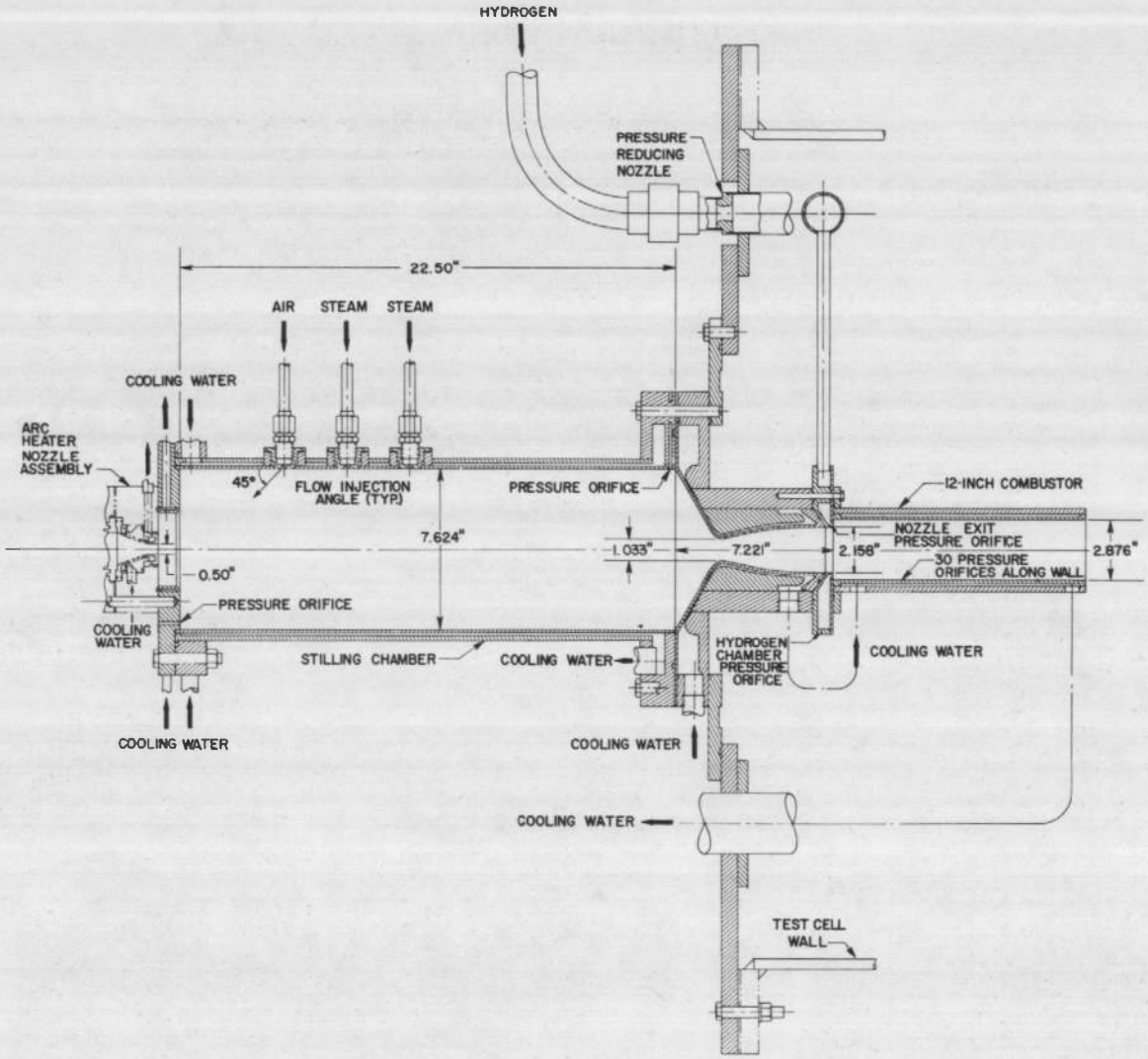

Fig. 2 Supersonic Combustion Apparatus Details

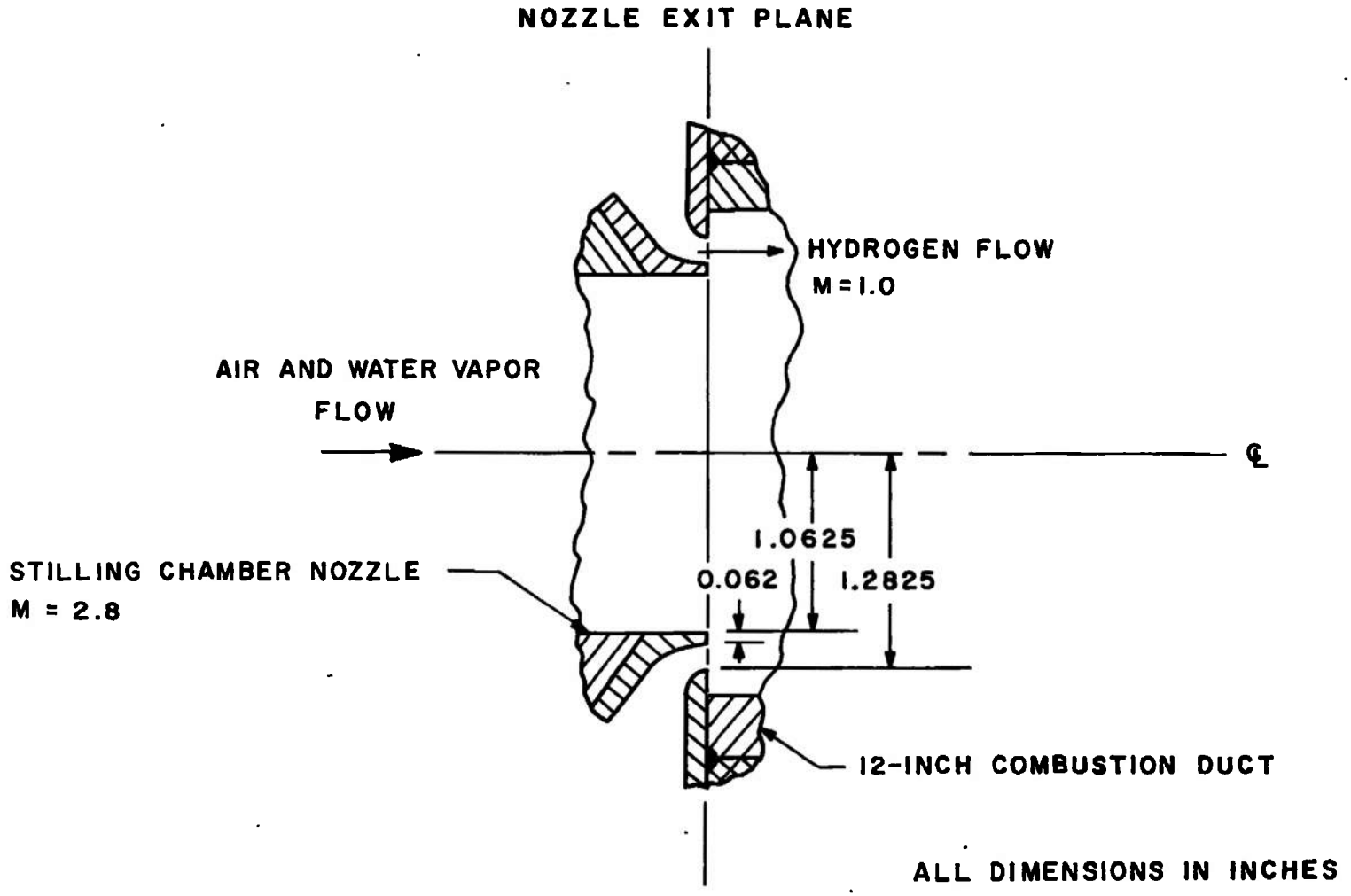

Fig. 3 Vitiated Air and Hydrogen Nozzles Exit Details

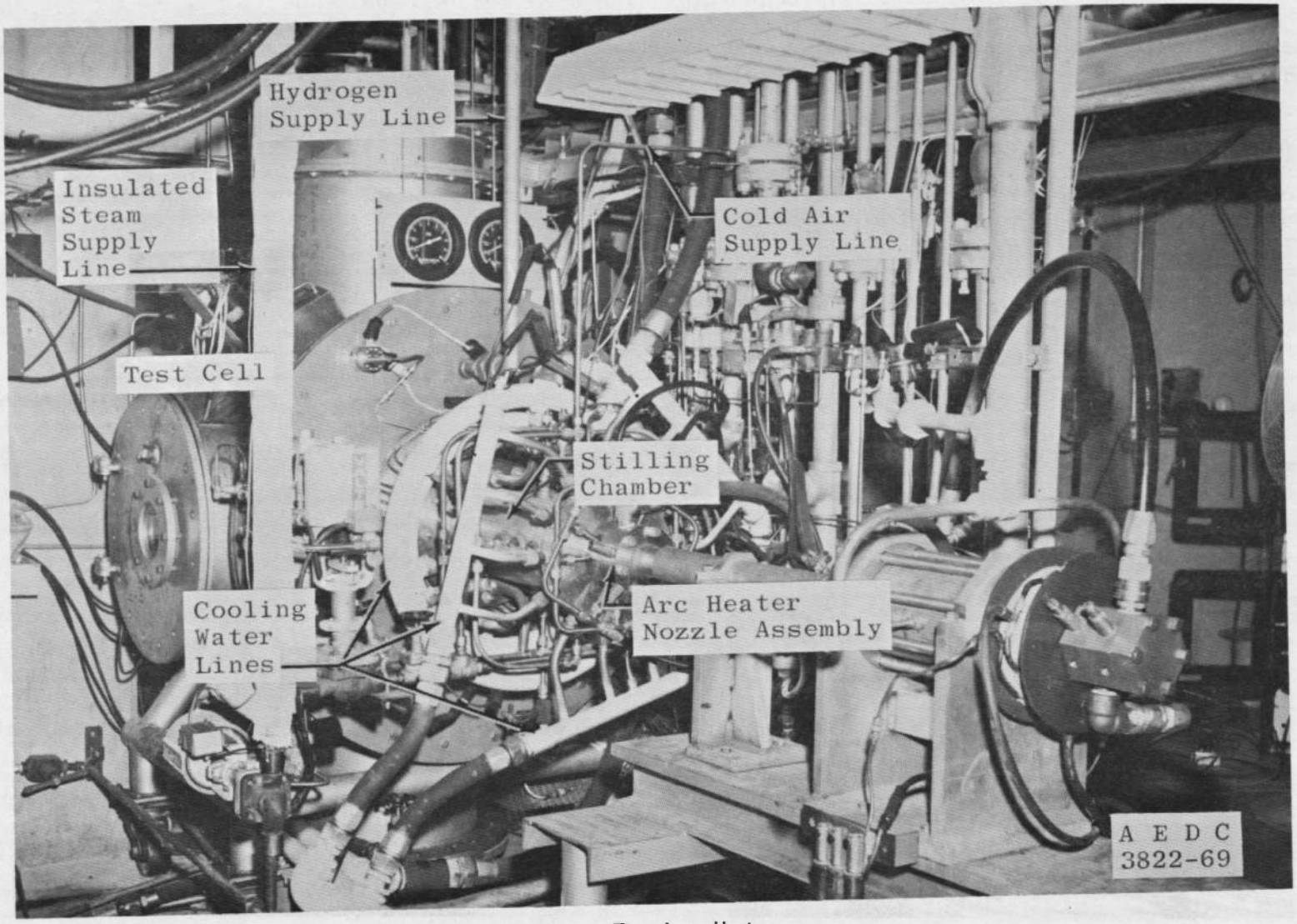

Fig. 4 Test Installation

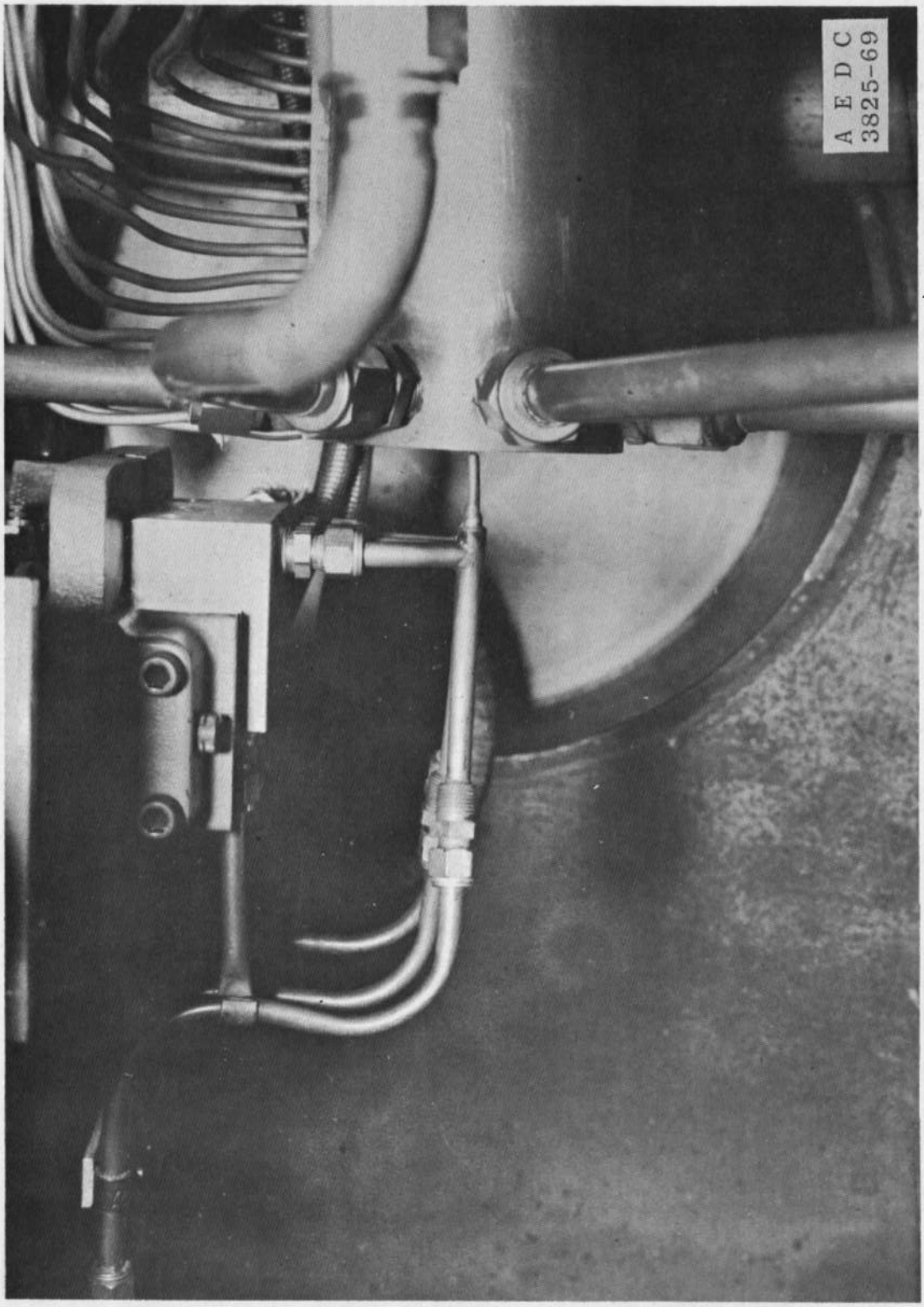

Fig. 5 Sample Probe Installation

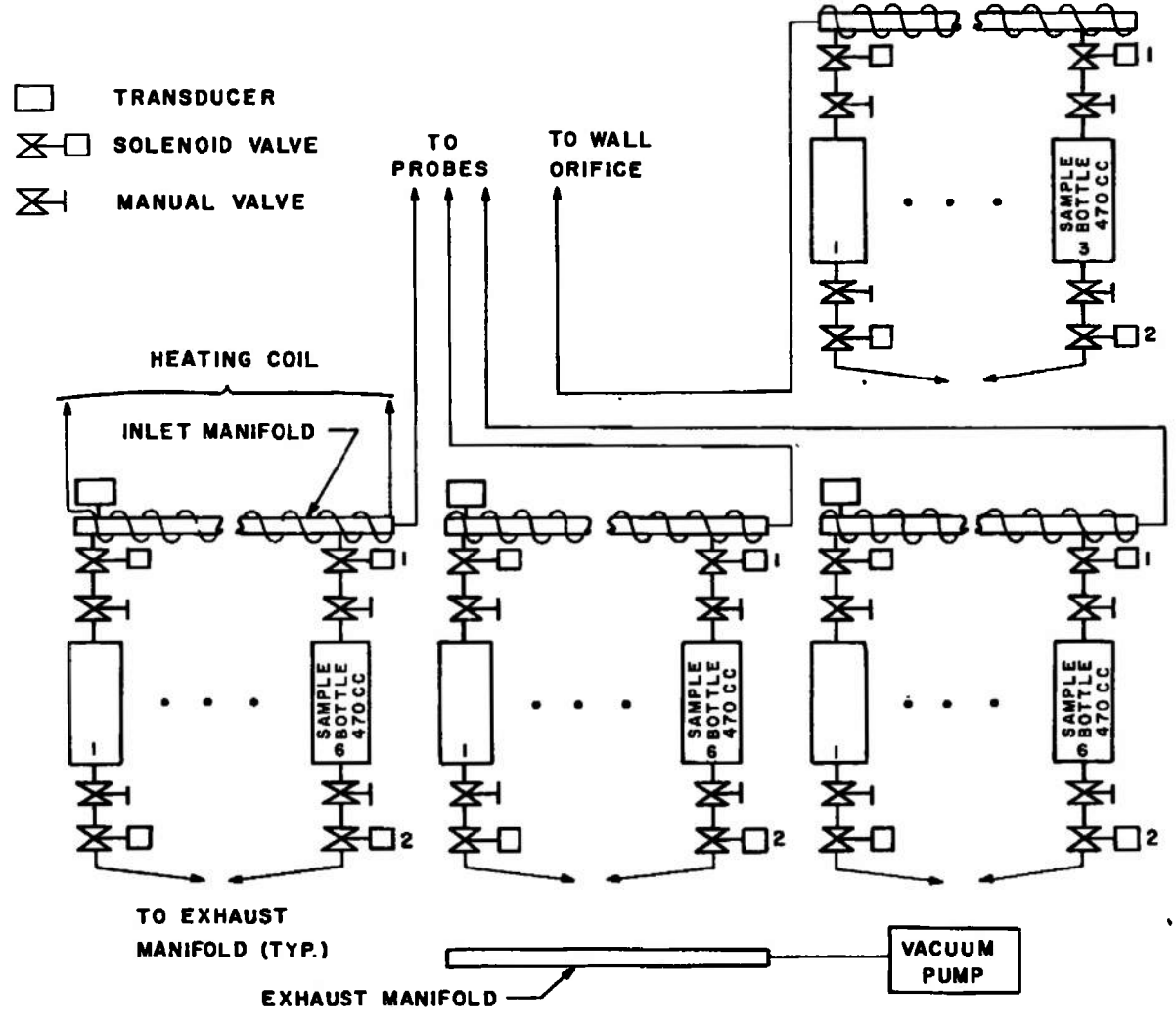

Fig. 6 Gas Sampling Apparatus Details

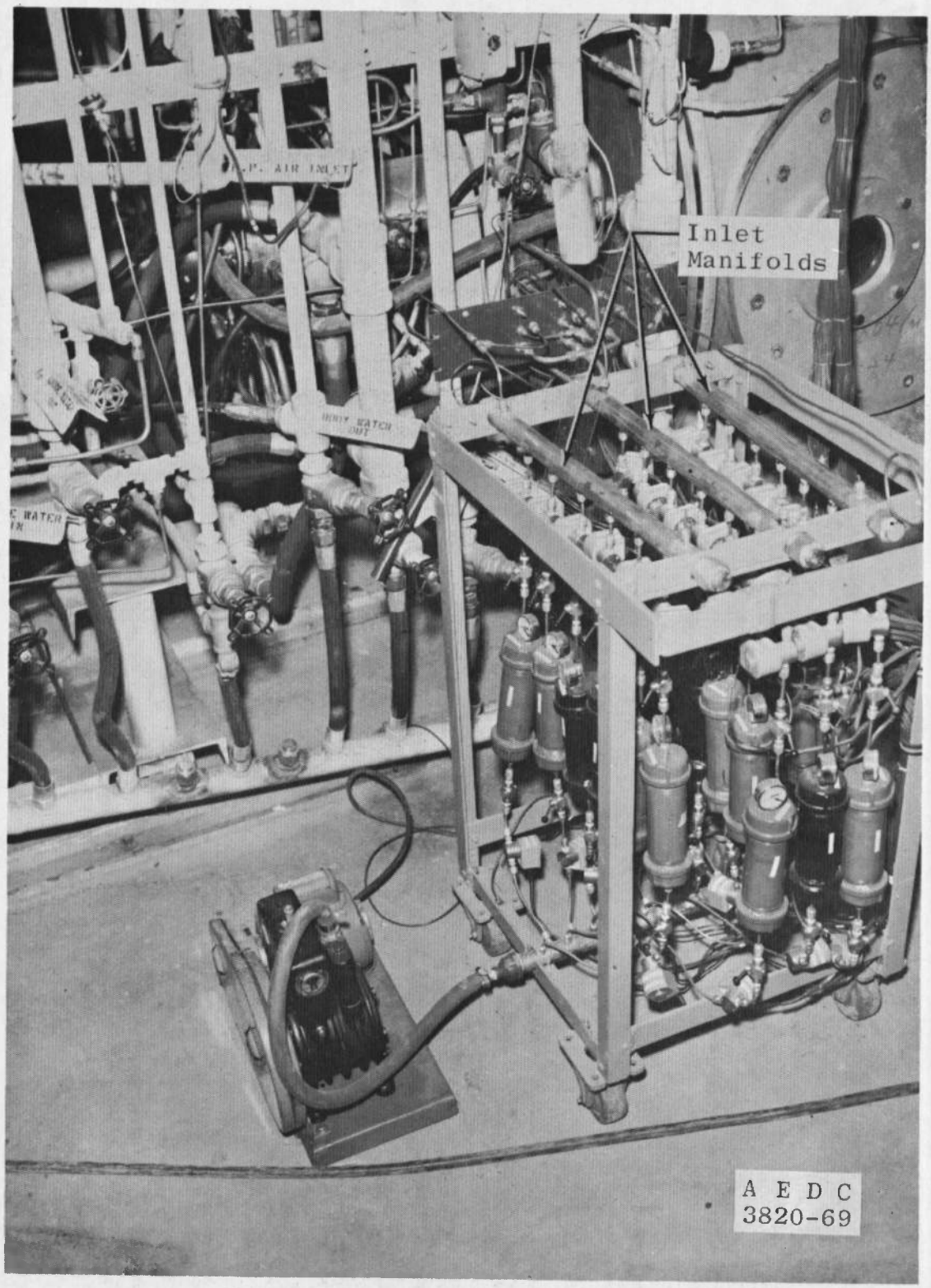

Fig. 7 Gas Sampling Bottle Installation

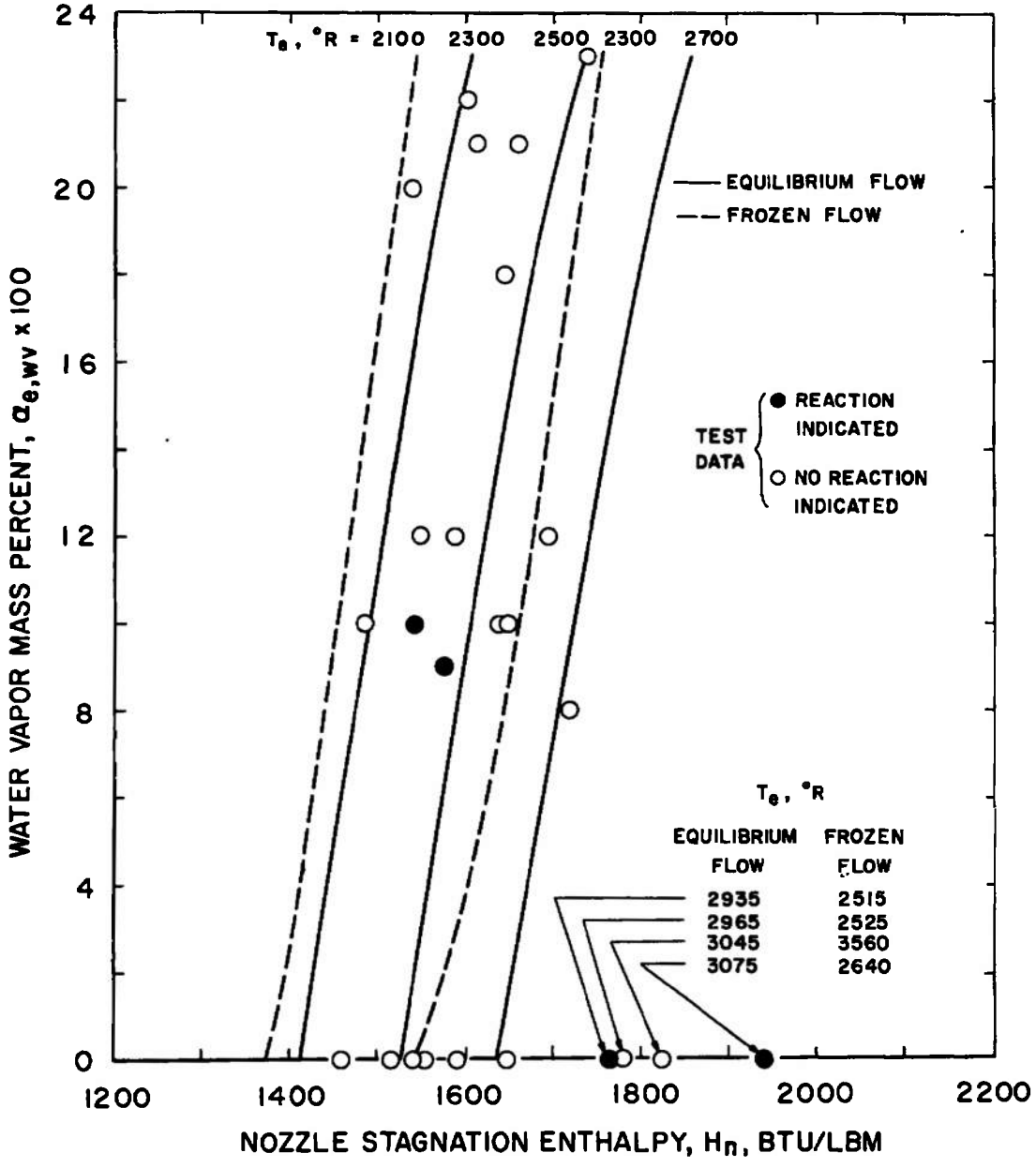

Fig. 8 Test Conditions

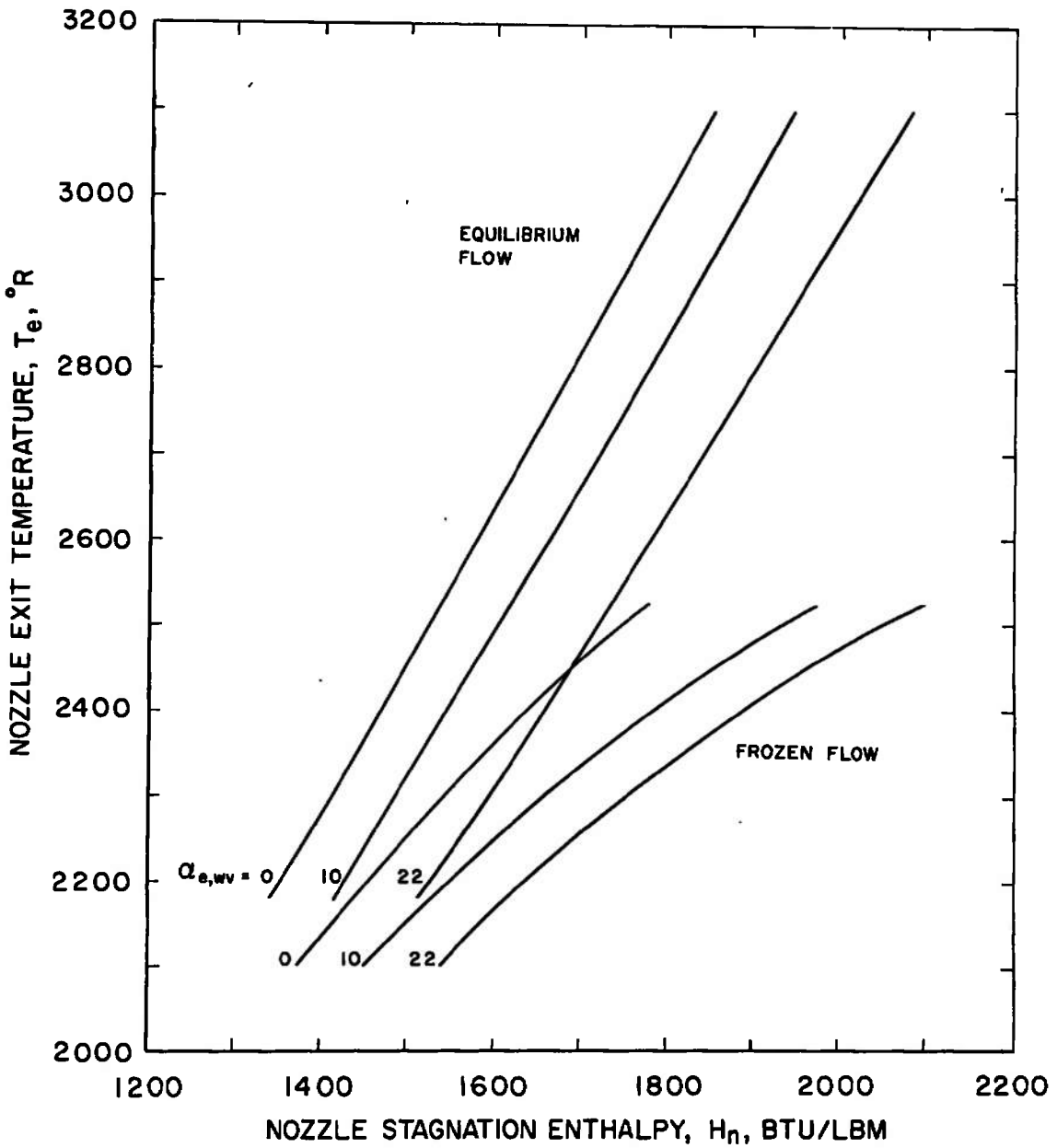

Fig. 9 Effect of Relaxation Rate on Nozzle Exit Static Temperature

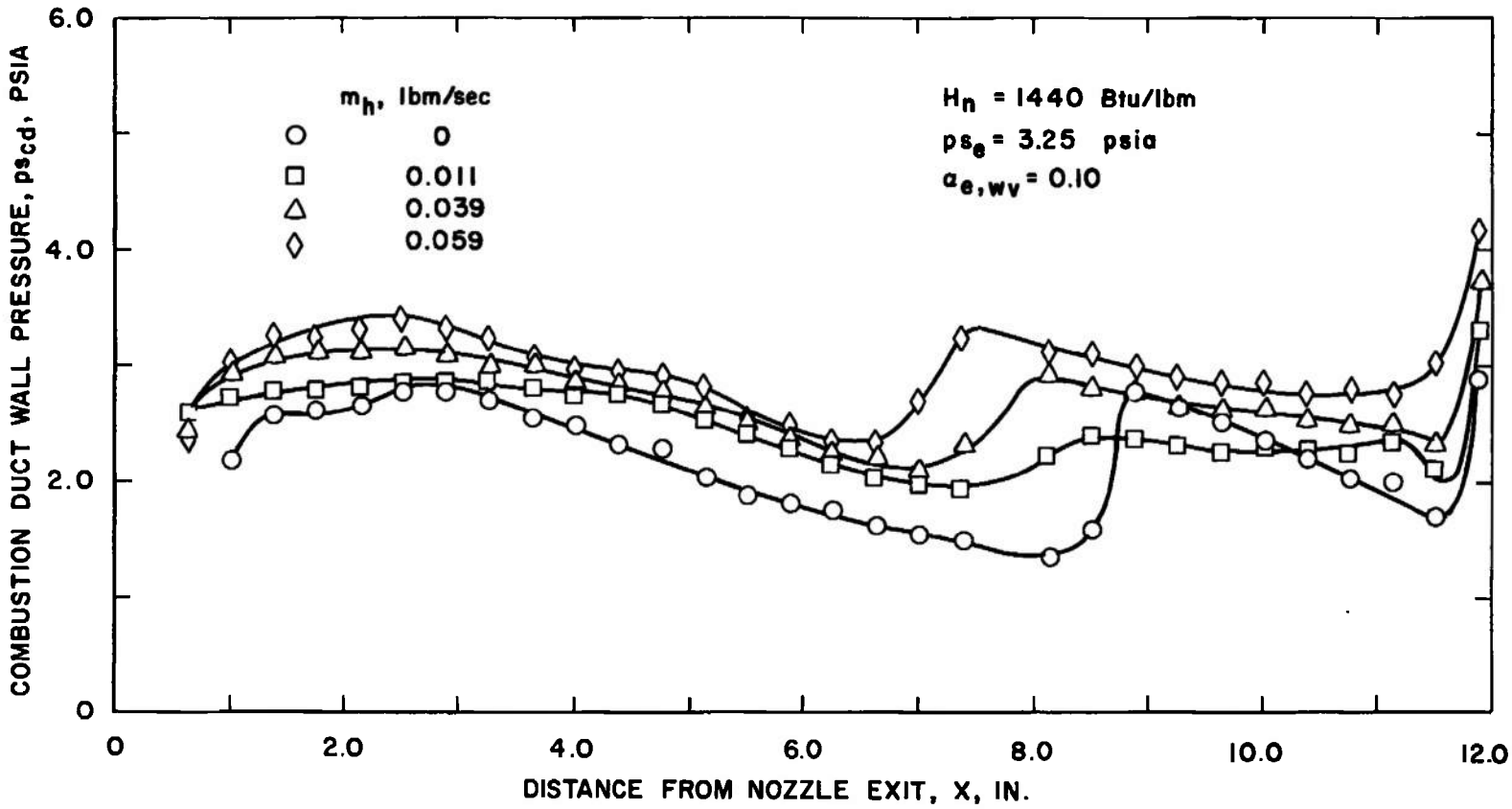

Fig. 10 Combustion Duct Wall Pressure Distribution as a Function of Hydrogen Mass Flow Rate

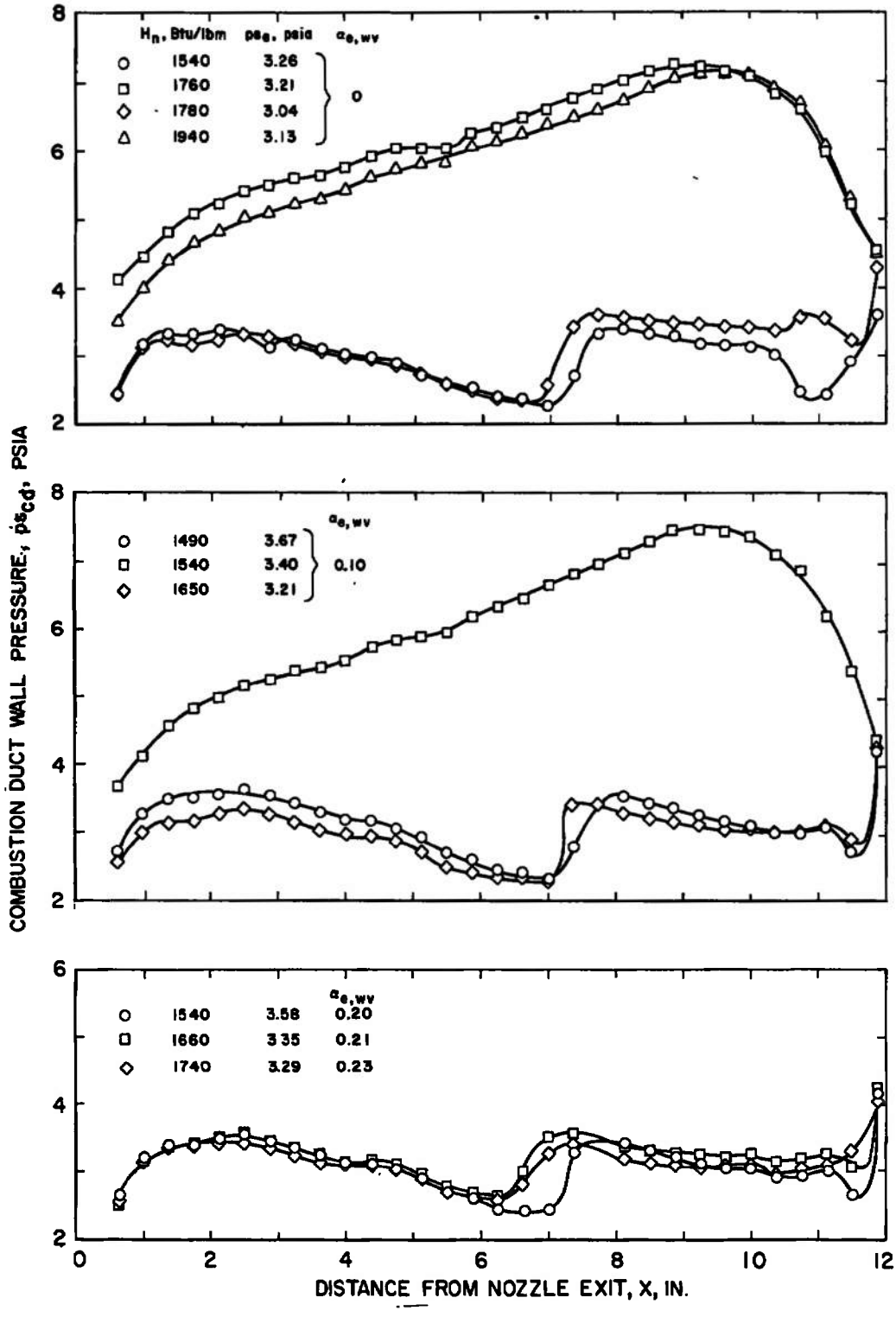

Fig. 11 Combustion Duct Wall Pressure Distribution for a Variation of Vitiation Level

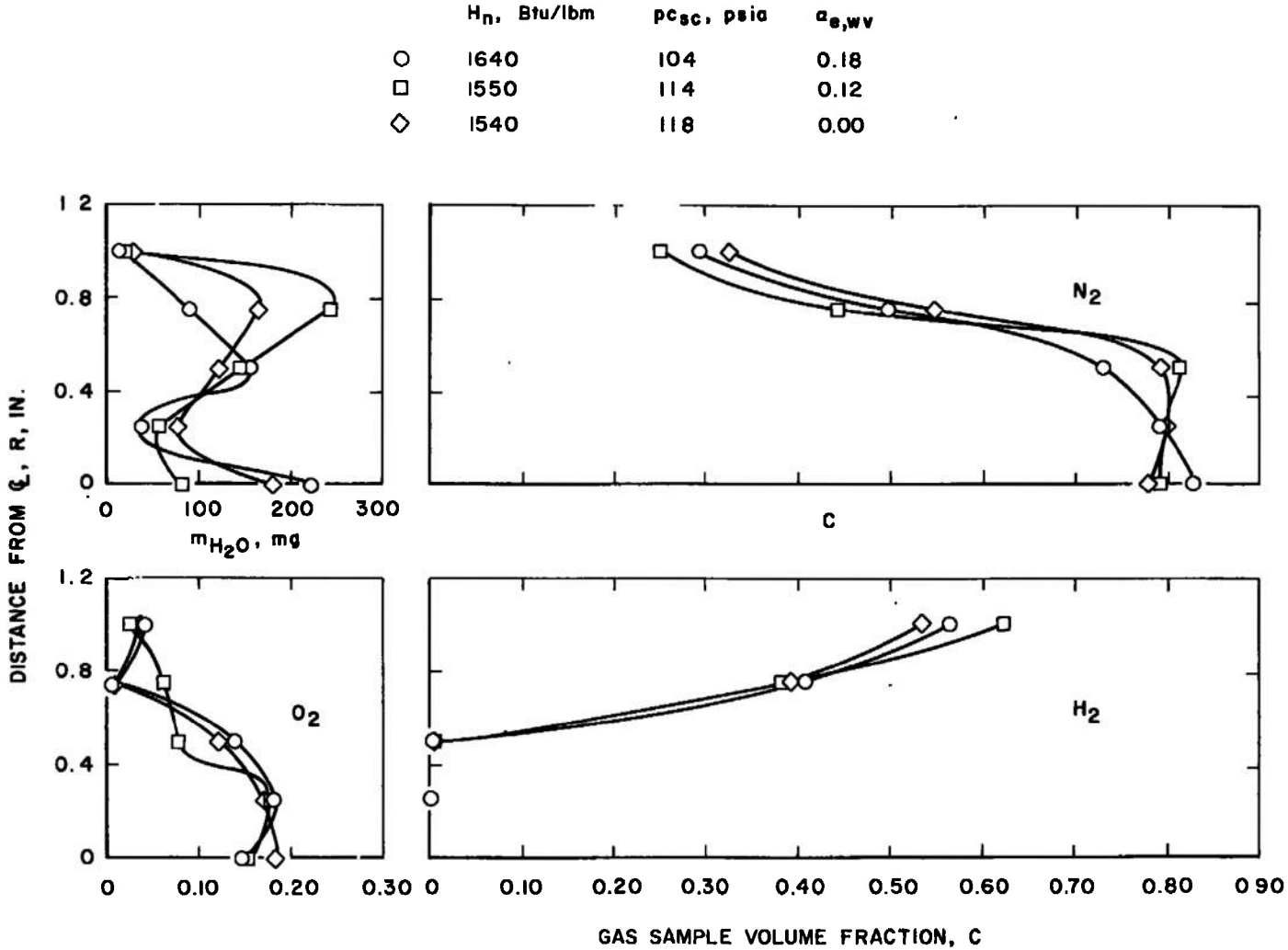

Fig. 12 Gas Composition at Exit of Combustion Duct

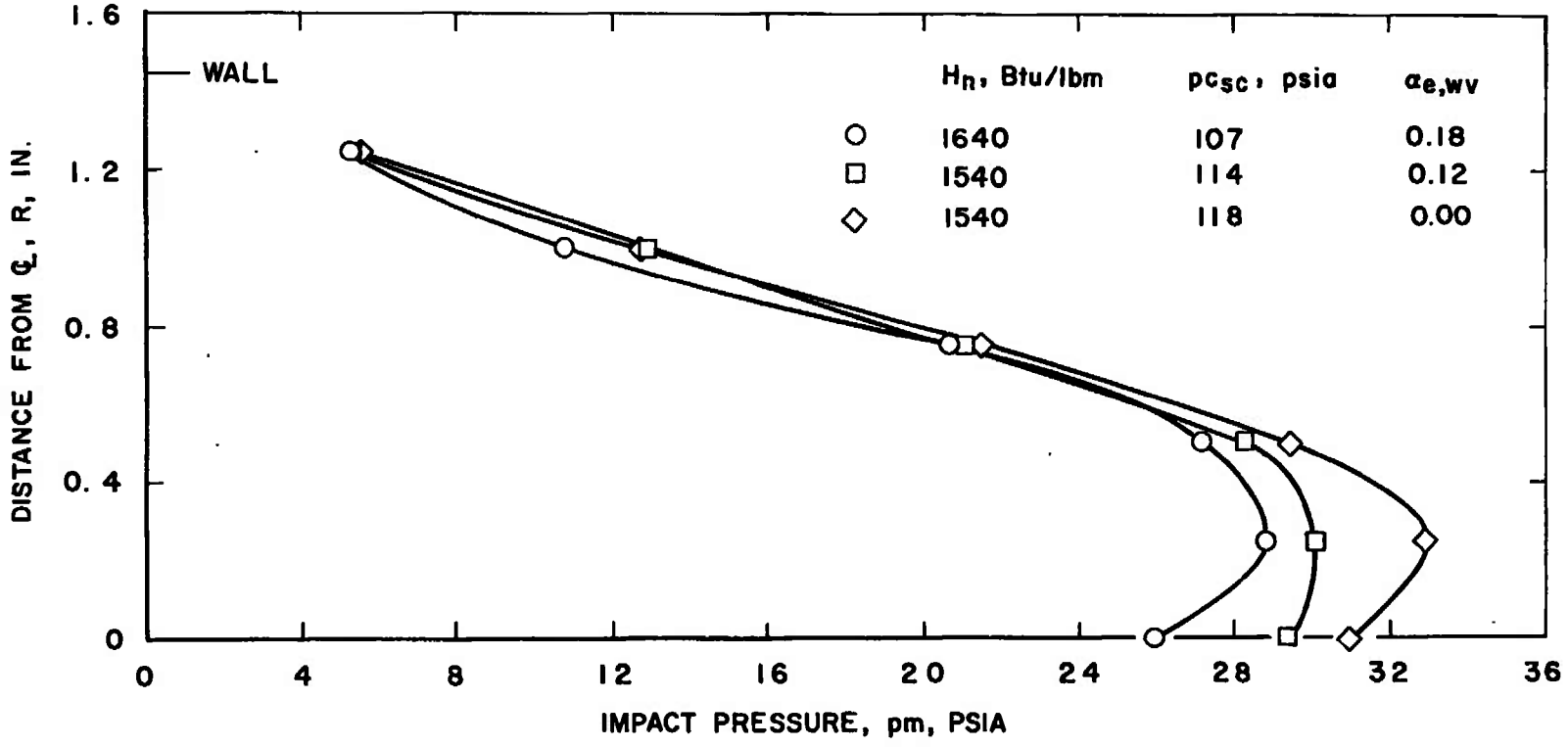

Fig. 13 Impact Pressure Distribution at Combustion Duct Exit

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13. ABSTRACT

Tests were conducted utilizing the AEDC PWT 5-MW Research Arc Heater as a high enthalpy air source to determine the effects of water vapor contamination on a hydrogen-air supersonic combustion process. A flow apparatus was constructed to permit vitiated, arc-heated airflow to mix coaxially with hydrogen in a constant area duct. The hydrogen was injected at the exit of the vitiated air nozzle which was designed for M = 2.8. Data were obtained in the form of wall pressure distributions and impact pressures and gas samples obtained from nonquenching pitot probes. The enthalpy of the mixture was varied from 1360 to 1860 Btu/lbm and the water vapor mass percent in the vitiated air was varied from 0 to 23.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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