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PRELIMINARY STUDY OF GASEOUS NITROGEN-LIQUID OXYGEN MIXING AND SELF-CLEANING

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INTRODUCTION

The modified NASA Langley 8 Foot High Temperature Tunnel (8'HTT) will utilize pressurized gaseous nitrogen (GN_2) to transfer liquid oxygen (LOX) from a run tank to the tunnel combustor. Since the contamination of the LOX by the pressurizing GN_2 may prove to be an important operational constraint, it is desirable to have reliable data concerning the penetration of GN_2 into LOX during pressurization and the subsequent self-cleaning after "blowdown," i.e. venting to atmospheric pressure. Such data, unfortunately, are scanty or non-existent. The purpose of this study is to gather preliminary data to establish some coarse engineering guidelines, until facilities become available to conduct a more comprehensive experiment.

EXPERIMENTAL PROCEDURE

The experimental procedure is illustrated in figure 1. The experiment was conducted in a 45-gal dewar (Linde GP-45), which is capable of sustaining a static pressure in excess of 150 psi. For each test the dewar was filled with LOX to a specified level. The test procedure consisted of three steps: (1) Pressurization - the dewar was pressurized with GN_2 for a specified holding time; (2) Blowdown - the pressure was vented slowly to 0 psig; and (3) Analysis - the evaporating liquid was analyzed in a Teledyne Percent Nitrogen Analyzer. A continuous record of the vapor analysis was kept on a strip chart recorder. The two adjustable paramenters--the initial volume of LOX in the dewar and the "holding time" of the pressurizing GN_2 are summarized for three tests in table 1. Because of an unexpectedly low blowdown time however, LN_2 remained at the LOX surface for a time much longer than the holding time. In fact, N_2 remained liquid during blowdown as long as the pressure exceeded 52 psi, the condensation pressure of N_2 at the LOX temperature; thus the effective holding time was much longer than the specified 5 or 10 min. The "blowdown time" for which $P > 52$ psi is also indicated in table 1. The LOX was delivered from the Linde LR-25 storage tank with a purity of 99.9% and the GN_2 from a "T" size cyliner with a purity of 99.9%. The N_2 content of the evaporating liquid versus time is shown as a wavy line in figures 2a, b, and c for tests #1, 2, and 3.

Also shown in table 1 are the conditions for a test conducted in the 7-Inch High Temperature Tunnel (pilot tunnel for the 8'HTT), hereafter called the "7-Inch Test" and described briefly later in this memorandum.

ANALYSIS

The interpretation of the experimental results is based on the following physical model. During pressurization N_2 penetrates into the LOX by simple molecular diffusion. The depth of penetration depends upon the GN_2 pressure, which determines the surface concentration, and the holding time. After blowdown the liquid evaporates. At any given time the composition of the evaporating liquid reflects the concentration profile established in the liquid by diffusion.

Several assumptions are introduced to simplify the analysis:

(1) Evaporation of the liquid proceeds at a constant rate.

(2) The flow of vapor from the dewar to the N_2 analyzer is steady and thus equal to the evaporation rate.

(3) Over the course of a test the ullage volume (above the liquid) remains constant. This implies that the number of moles of vapor in the ullage volume remains constant and that only a small volume of liquid evaporates. Coarse measurements of the liquid level by a float confirmed the validity of this assumption.

(4) To simplify the mathematics, the N_2 profile in the LOX is represented as an exponential function of distance, instead of the appropriate complementary error function, and after blowdown is considered frozen in time.

The first step in the analysis is to derive a continuity equation for the number of moles of N_2 vapor in the ullage volume. Let $n_N(t)$ be the number of moles of N_2 at time t. Then the number of moles at a time increment dt later can be written

$$n_N(t + dt) = n_N(t) + dn_{NL} - dn_N, \tag{1}$$

where dn_{NL} is the gain due to evaporation of the liquid and dn_N is the loss due to outflow to the analyzer. Now according to assumption (1)

$$dn_{NL} = Rx_{NL}dt, \tag{2}$$

where x_{NL} is the instantaneous mole fraction of N_2 in the liquid and R the evaporation rate in mole/sec. Similarly, according to assumption (2)

$$dn_N = Rx_N dt, \tag{3}$$

where x_N is the mole fraction of N_2 in the vapor. Upon inserting (2) and (3) into (1) one obtains:

$$\frac{dn_N}{dt} = Rx_{NL} - Rx_N \tag{4}$$

By definition

$$n_N = n_T x_N,$$

where n_T is the total number of moles of vapor. It follows from assumption (3) that

$$\frac{dn_N}{dt} = n_T \frac{dx_N}{dt} \tag{5}$$

According to assumption (4) x_{NL} has the following profile:

$$x_{NL} = \exp(-z/h), \tag{6}$$

where z is the vapor-liquid interface location at time t relative to the original interface and h a characteristic distance, which will be called the "penetration depth." Because evaporation takes place at a constant rate [assumption (1)], it follows that z is linear in time:

$$z = Rv_L t/A \tag{7}$$

where v_L is the molar volume of the liquid and A the cross sectional area of the dewar. Substituting (5)-(7) into (4) yields the final form of the continuity equation:

$$n_T \frac{dx_N}{dt} + Rx_N = R \exp(-Rv_L t/Ah) \tag{8}$$

The solution to equation (8), together with the initial condition $x_N = x_{NO}$ at $t = 0$, is

$$x_N = \frac{[x_{NO}\,\tau_1 + (1 - x_{NO})\tau_2]\ e^{-t/\tau_1} - \tau_2 e^{-t/\tau_2}}{\tau_1 - \tau_2} \tag{9}$$

where

$$\tau_1 = n_T/R, \tag{10}$$

$$\tau_2 = Ah/Rv_L \tag{11}$$

Time $t = 0$ is taken to be the time when the pressure at blowdown reaches 1 atm. The value of x_{NO} at this time is read from the strip chart recorder.

Values for evaporation "time constants" τ_1 and τ_2 were determined for each test through a best-fit of equation (9) to the data taken from the strip chart.

Plots of equation (9) using the best-fitted values of τ_1 and τ_2 are shown as solid lines in figures 2a, b, and c. Once τ_1 and τ_2 were established, then the evaporation rate R and penetration depth h were determined from equations (10) and (11). The results are shown in table 2. In the present experiment the parameter values are $A = 254 \text{ in}^2$, $v_L = 0.00827$ gal/mole (mean of LN_2 and LOX at -195.8°C), and n_T (in moles) is computed from the ideal gas law

$$n_T = PV_u/RT = 0.51V_u, \tag{12}$$

where V_u is the ullage volume, in gallons, listed in table 2.

COMPARISON WITH THE 7-INCH TEST

A previous test conducted in the 7-inch tunnel differs from the Linde tests in three respects. First, the higher pressurization level, shown in table 1, was sufficient to bring both components to the critical state. Secondly, because the insulation on the 7-inch run tank is not of dewar quality, the liquids evaporated at a much higher rate. Finally, the composition of the mixture was monitored by draining the liquid at a specified level into a sound velocity measuring cell below the run tank. The contamination profile, which is the result of monitoring the liquid at four different levels, is shown in figure 3. The evaluated evaporation rate and penetration depth are listed in table 2.

CONCLUSIONS

The Linde tests indicate that under a pressurization level of 150 psi the penetration of N_2 into LOX is extremely small. The results of tests #1 and #2 show the dependence of the penetration depth upon ullage volume. The smaller penetration depth of test #2 is possibly attributable to the warmer temperature and thus reduced N_2 condensation near the top of the dewar. Tests #1 and #3, on the other hand, were conducted under nearly identical conditions; the difference in penetration depth must either be considered to fall within the bounds of experimental error or must be attributed to the variation of some unidentified test parameter.

The measured evaporation rates appear reasonable. In the Linde tests this amounts to about a gal/day, which is typical for a 45-gal dewar. In the 7-inch test the measured rate indicates that the liquid in the 4-gal run tank completely evaporates in 4 × (1/5) h or 48 min, which agrees with experience.

The large penetration depth under 1500 psi in the 7-inch test, on the other hand, raises significant concerns and may impose a constraint on 8'HTT operations. A test, combining high pressurization and slow evaporation, is being planned and should yield more reliable data. This will allow closer simulation of the actual penetration and three to four hour self-cleaning time, which will actually exist in the 8'HTT operation.

ACKNOWLEDGMENT

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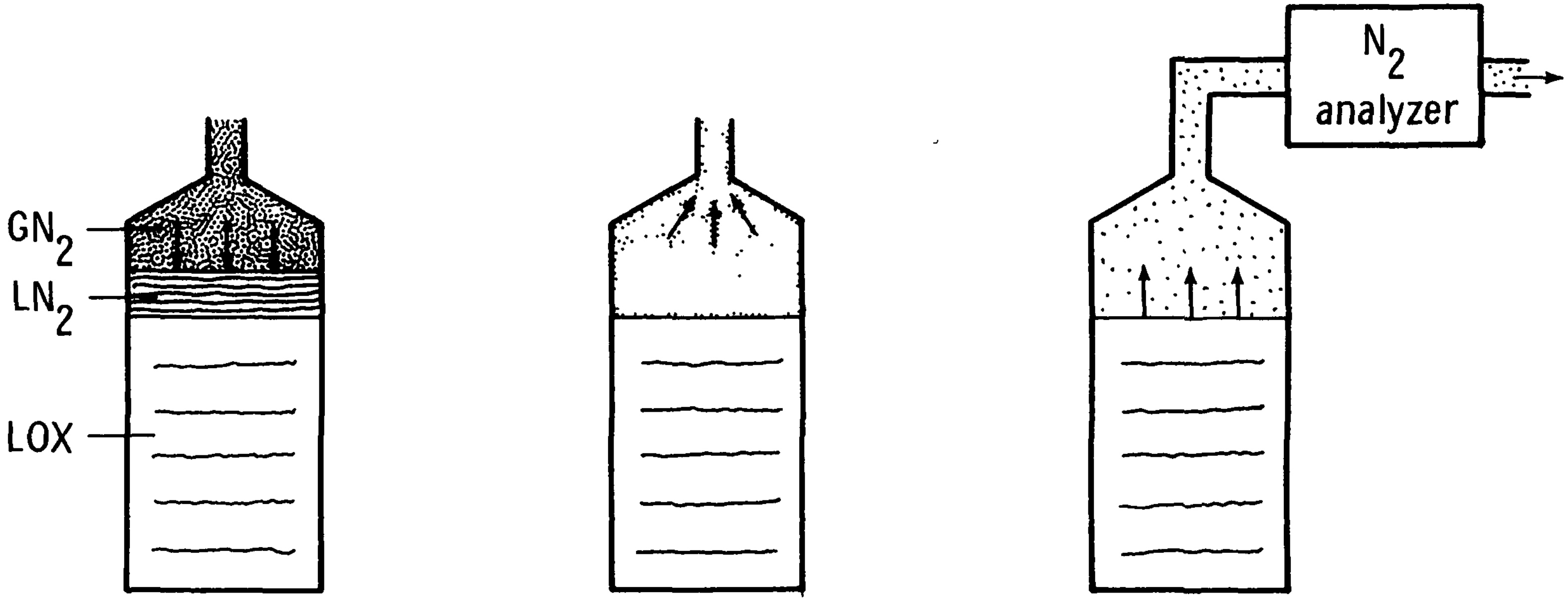
TABLE 1.- SUMMARY OF TEST CONDITIONS

Test Condition	Test #1	Test #2	Test #3	7-inch Test
Holding pressure, psi	150	150	150	1500
Holding time, min	15	15	5	5
Blowdown time, hr ($P > 52$ psi)	1.36	0.77	1.44	-----
Liquid level, % of maximum	35	85	45	100
Ullage volume, gal	29.0	6.7	24.5	0
No. moles in ullage volume	14.8	3.4	12.5	0

TABLE 2.- SUMMARY OF TEST RESULTS

Quantity	Test #1	Test #2	Test #3	7-inch Test
Time constant τ_1, hr	2.6	0.85	1.6	-----
Time constant τ_2, hr	0.41	0.08	0.05	-----
Evaporation rate R, gal/h	0.047	0.033	0.065	5.046
Penetration depth h, in.	0.018	0.0024	0.0030	22.17



(1) Pressurization (2) Blowdown (3) Analysis

Figure 1. Illustration of the Test Procedure.

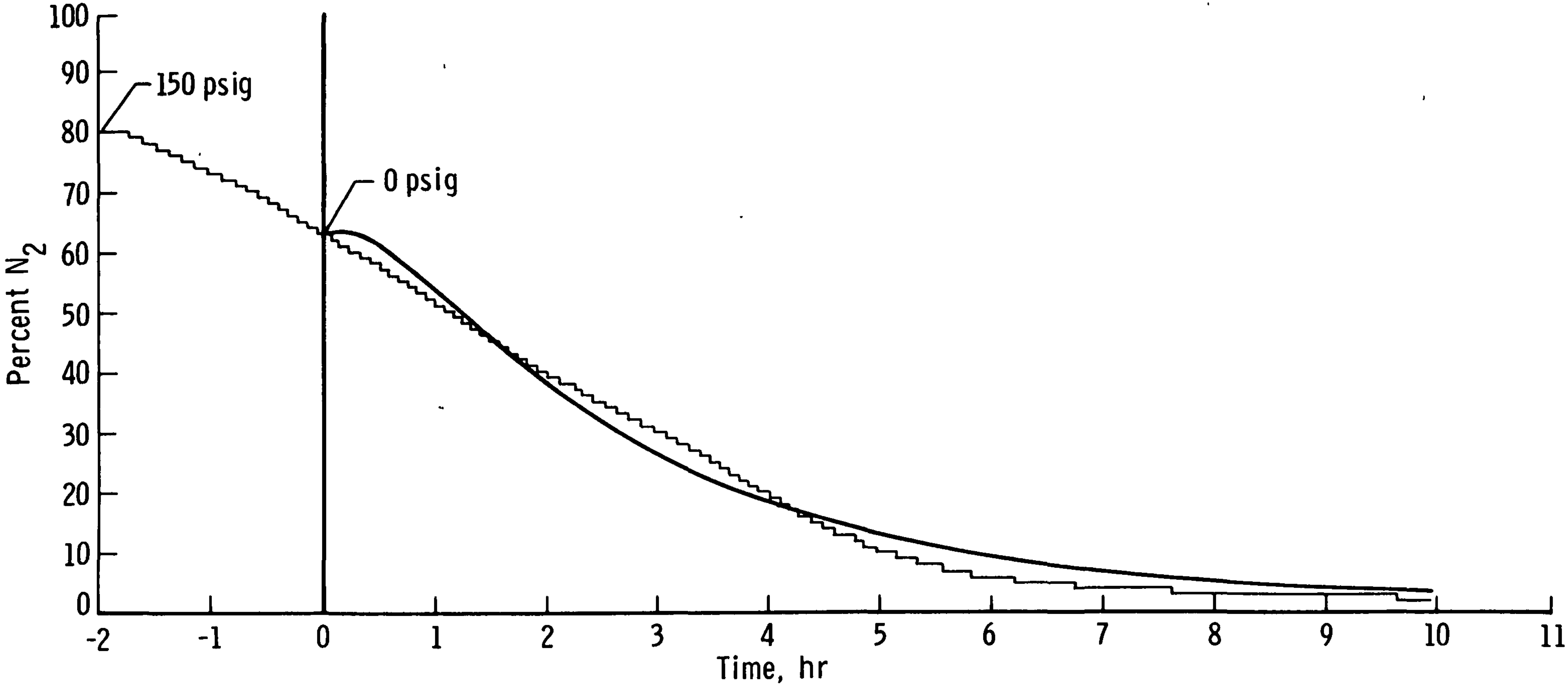


Figure 2(a). Percent N_2 in Evaporated Vapor Passing Through the N_2 Analyzer Versus Time: Test # 1. Wavy Line: Measured. Solid Line: Best Fit to Equation 9.

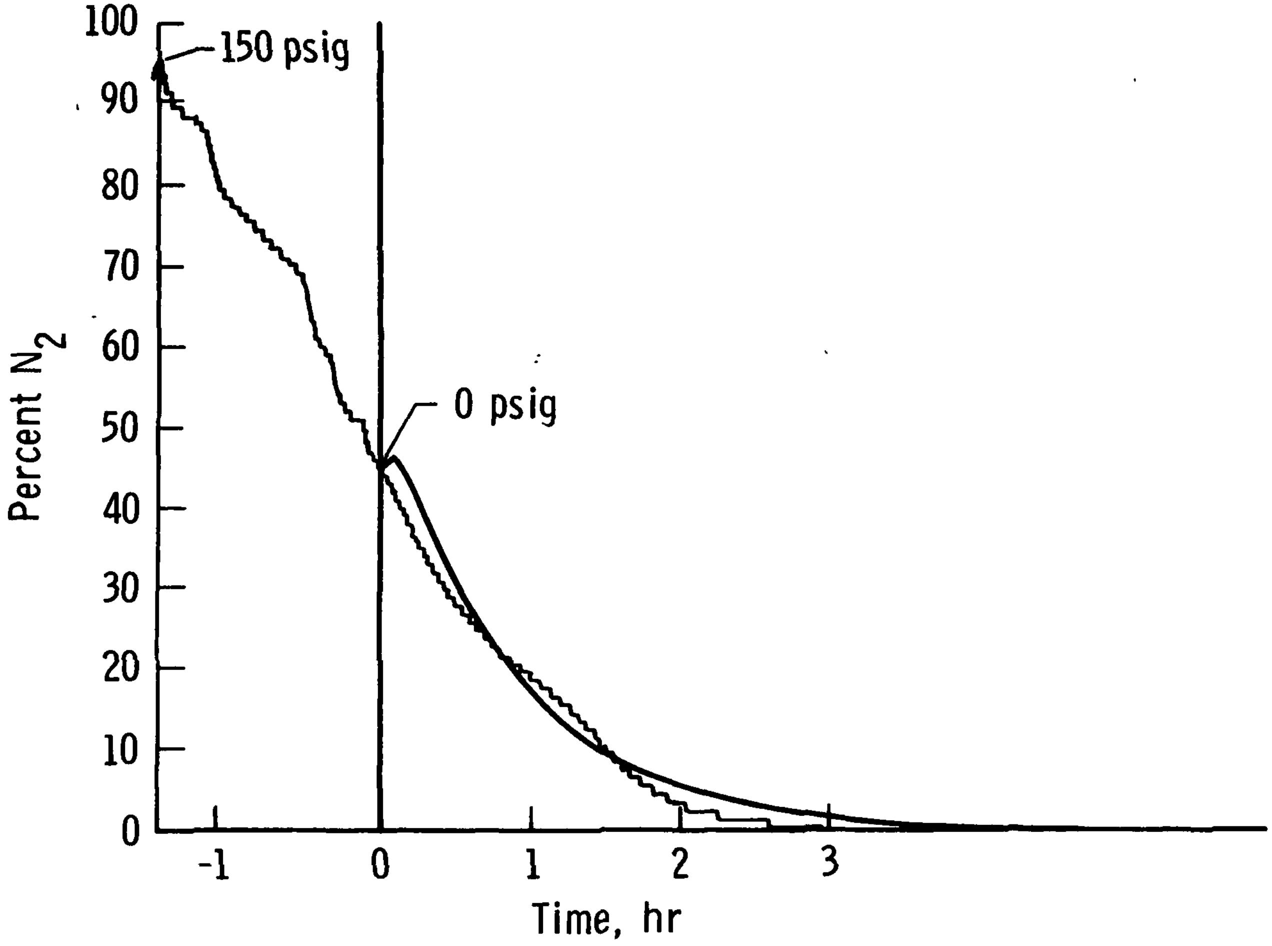


Figure 2(b). Percent N_2 in Evaporated Vapor Passing Through the N_2 Analyzer Versus Time: Test # 2. Wavy Line: Measured. Solid Line: Best Fit to Equation 9.

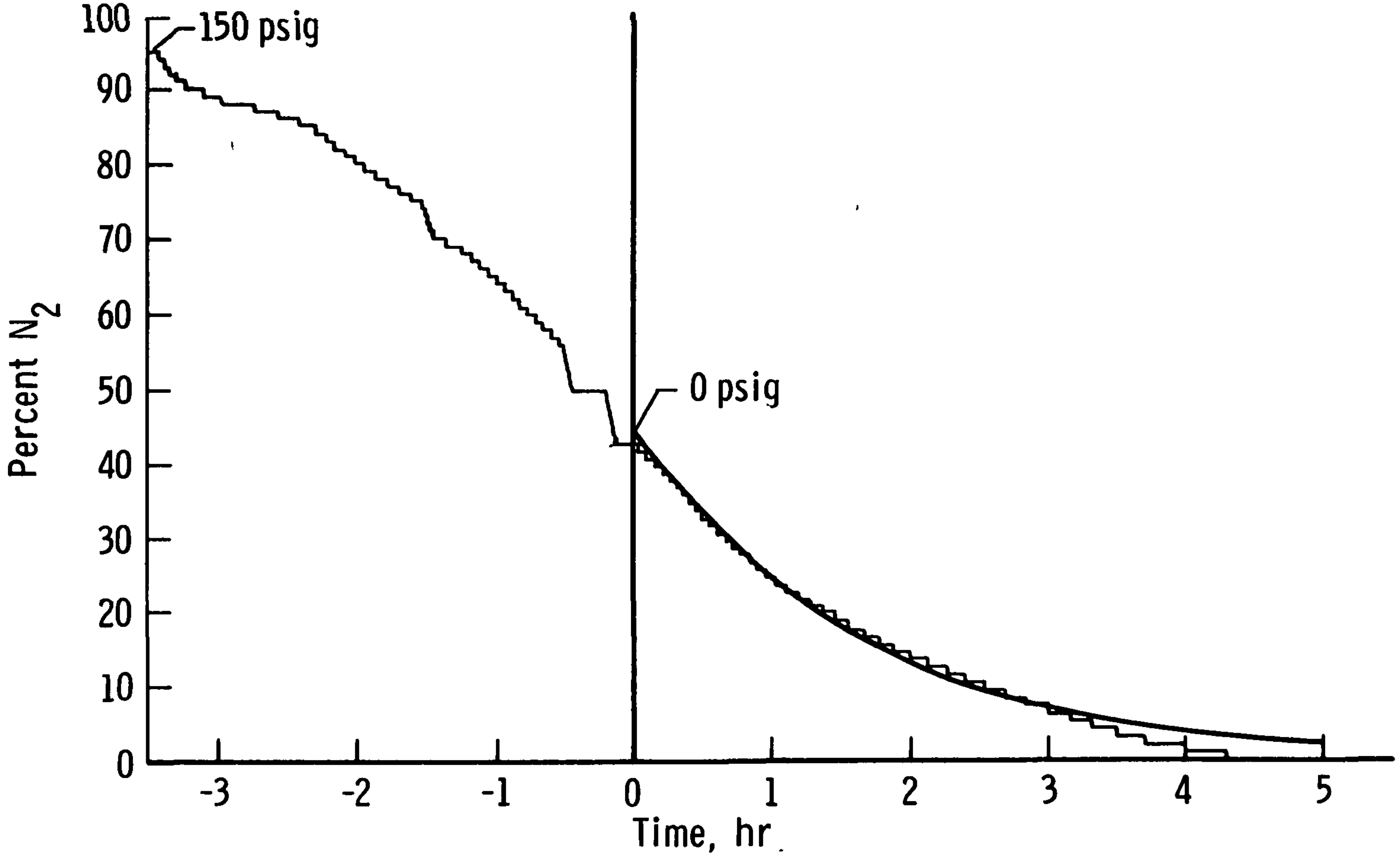


Figure 2(c). Percent N_2 in Evaporated Vapor Passing Through the N_2 Analyzer Versus Time: Test # 3. Wavy Line: Measured. Solid Line: Best Fit to Equation 9.

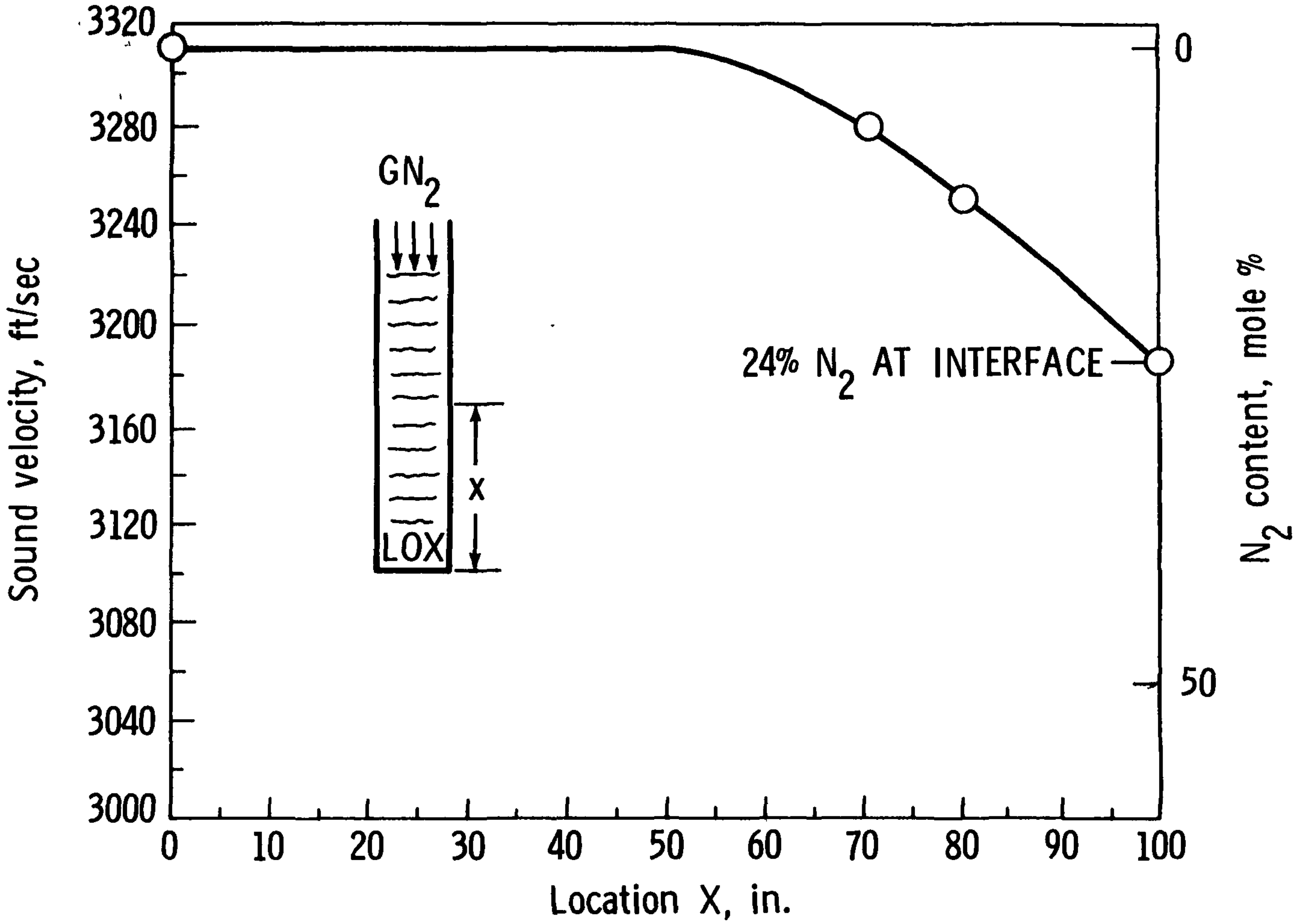


Figure 3. Contamination Profile Resulting From N_2 Pressurization of LOX at 1500 psi for 5 Min, in the 7-Inch Run Tank.

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16. Abstract

The penetration of gaseous nitrogen into liquid oxygen at a pressure of 150 psi was determined by monitoring the composition of the evaporating liquid in a nitrogen analyzer. For pressurization times of about 1 hr the penetration depth varied between 0.0024 and 0.018 in. at an evaporation rate of about 1 gal/day. These are small compared to the penetration depth of 22.2 in. measured in the 7-inch high temperature tunnel at a pressure of 1500 psi, pressurization time of 5 min, and evaporation rate of 121 gal/day.

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