RI 7457

Bureau of Mines Report of Investigations/December 1970

Hydrogen Flare Stack Diffusion Flames: Low and High Flow Instabilities, Burning Rates, Dilution Limits, Temperatures, and Wind Effects

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 7457

Hydrogen Flare Stack Diffusion Flames: Low and High Flow Instabilities, Burning Rates, Dilution Limits, Temperatures, and Wind Effects

By J. Grumer, A. Strasser, J. M. Singer, Patricia M. Gussey, and Valeria R. Rowe

UNITED STATES DEPARTMENT OF THE INTERIOR
Walter J. Hickel, Secretary

BUREAU OF MINES
Elburt F. Osborn, Director

The work upon which this report is based was done by the Bureau of Mines, U.S. Department of the Interior, under a working fund agreement with the Space Nuclear Propulsion Office, Cleveland, Ohio.

CONTENTS

ILLUSTRATIONS

TABLES

TABLES--Continued

HYDROGEN FLARE STACK DIFFUSION FLAMES: LOW AND HIGH FLOW INSTABILITIES, BURNING RATES, DILUTION LIMITS, TEMPERATURES, AND WIND EFFECTS

by

J. Grumer,[1] A. Strasser,[2] J. M. Singer,[3] Patricia M. Gussey,[4] and Valeria R. Rowe[3]

ABSTRACT

The Bureau of Mines, under the sponsorship of the Space Nuclear Propulsion Office, conducted a laboratory-scale hydrogen safety study which determined several combustion characteristics of hydrogen diffusion flames.

Experiments show that ambient air may enter the top of a hydrogen flare stack when the hydrogen flow is low. A new concept, supported by photographic evidence, predicts that diffusion flames burning in air on a wide, upright pipe (stack) and fed with slow, upward flows of buoyant gas will induce a downward flow of air along the walls of the pipe that can support combustion within the pipe. Predicted flamedip limits agree roughly with experimental values determined on 6-, 12-, and 18-inch-diameter stacks and increase with increasing stack diameter.

Measurements were made of the limiting flow at which a hydrogen diffusion flame blows out in still air. By means of an empirical application of the critical boundary velocity gradient concept, these data lead to a blowout limit of about 10^8 reciprocal seconds for a hydrogen diffusion flame. Burning rates of large hydrogen diffusion flames ranging from about 0.03 to 1 ft/sec were used to predict approximate flame heights on flare stacks.

Temperatures of larger hydrogen diffusion flames up to about 3,600° F were observed, but the most representative value appears to be about 2,600° F.

It was found that crosswinds do not strip significant amounts of unburned hydrogen from its diffusion flame and that water-cooled flare stacks are not likely to be damaged when flame is blown back into them by opposing winds.

[1] Acting project coordinator and supervisory research chemist.
[2] Research physicist.
[3] Research chemist.
[4] Chemist.
All authors are with the Safety Research Center, Bureau of Mines, Pittsburgh, Pa.

INTRODUCTION

Although there have been accidents, industrial flare stack operations have a good safety record. Usually gases being flared have low heating values and are slow burning. Flow rates are rather steady and within design limits. Most frequently, diffusion flames are employed, that is, no air is knowingly mixed with the combustible stream within the piping or in the flare stack (burner). All air for combustion comes from the open atmosphere surrounding the flame, downstream of the flare stack exit. This paper considers only diffusion flames.

Flare stack operations required in the research and development of space vehicles have also enjoyed a good safety record. In these operations, fast-burning hydrogen is flared. Malfunctions of hydrogen flare stacks have generally occurred at low flows. Flows vary from the small flows due to boiloff from storage vessels to flows of about 300 lb/sec for about a half hour. Thus it may be necessary to flare more than 200 tons of hydrogen quickly and safely. Although no blowout of a neat hydrogen diffusion flame has been reported yet, the possibility of such blowout at high flows of hydrogen must be considered. The problem of flame height on flare stacks, which is related to the burning rate, and the problem of maintaining a hydrogen flame heavily diluted with inerts such as helium, nitrogen, or steam have recently interjected themselves into the planning of space test stands; concern has arisen over wind effects and other factors.

LOW FLOW INSTABILITY LIMIT

At present when hydrogen is dumped at a test stand, it is either vented unburned, burned as a diffusion flame on a flare stack (<u>12</u>),[5] or vented over a burn pond (<u>22</u>). In burn ponds, the hydrogen is dispersed through a pipe manifold submerged in water and bubbled into the atmosphere where it is ignited and burned; this method is not considered here. Industry, particularly the petrochemical industry, has realized the hazard of flame receding into a line and of flow reversal during flaring of waste gas. It recognizes the advisability of using a "continuous purge in flare systems where the average flow is too low to support stable combustion" (<u>2</u>). Such maleffects have been attributed to air initially present in a flare system or entering through openings in the lines. The present paper proposes a new mechanism explaining malfunctions due to low flow.

Most previous investigators (<u>2</u>, <u>9</u>, <u>12</u>, <u>15</u>) have treated the problem of low flow instability as one involving premixed flames, that is, hydrogen and air are assumed to mix inside the flare stack prior to burning. In fact, the problem is more likely to be one of diffusional burning; air and fuel mix at the flame surface as burning progresses. For example, Hajek and Ludwig (<u>9</u>) recognized that all flare stacks which burn combustible mixtures have a stable operating velocity range outside of which they do not operate safely. They also recognized that below the low velocity limit all or part of the flame may

---

[5] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

drop into the stack. They assumed that the flashback theory for premixed flames on gas burners (7, 8, 13, 24) was relevant to the low flow instability limit of hydrogen diffusion flames on flare stacks. Their treatment of such flame instability was based on information by Lewis and Von Elbe (13) and Von Elbe and Mentser (24), which treat the problems of flashback and flame tilt of premixed flames. When flashback occurs the premixed flame moves upstream into the burner until it is quenched or stabilized by a change in channel geometry or local fuel-air composition. When flame tilt occurs, the premixed flame partially enters the port; the plane of the flame base is at some angle to the plane of the port. Flame tilt can degenerate into flashback as the walls are warmed by the tilted flame. Both of these flame phenomena were treated by considering the balancing of counter current velocities; namely, the burning velocity close to the wall and the stream velocity close to the wall. Instability due to flame tilt (24), which is likely on large diameter burners, was not considered by Hajek and Ludwig, nor was the information in reference 8 which indicates that classical flashback and tilted flame theories are inadequate for predicting the low flow instability limit for wide burners. Moreover, Hajek and Ludwig make two assumptions that are not reasonable. First, they assume that at a Reynolds number of 2100 the flashback velocity is the same for laminar and turbulent flow. Secondly, they derive an equation for a Reynolds number of 2100 but apply it generally. An empirical coefficient is also employed.

In applying either the classical or the empirical flashback equations to flashback limits of flare stacks, the percentage of hydrogen in the flare stack gases must be given. The composition selected may correspond to the rich flammability limit of hydrogen (74 percent hydrogen in air), or more conservatively, to the peak flashback limit (36 percent hydrogen in air) (8). Mass flows at the flashback limits of these two hydrogen-air mixtures have been calculated for three flare stacks. The limit flows are given in table 1 and compared with the flows at which fire or no fire inside the stack has been reported. Only the Hajek and Ludwig equation (calculated for 74 percent hydrogen in air) fits a field observation; it fits the observation made with the 8-inch twin-flare stack (fig. 1) but not with the 18- and 42-inch single stacks. Thus, neither the Hajek-Ludwig nor the classical equation is relevant to the hydrogen flare-stack low flow problem.

TABLE 1. - Field experienced limits and predicted limits of fires in hydrogen flare stacks

Flare stack diameter, in.	Actual hydrogen flows, lb/sec		Predicted hydrogen flows, lb/sec				
			Classical flashback equation		Hajek and Ludwig equation (9)		This study
	Fire in stack	No fire in stack	36% H_2 in air	74% H_2 in air	36% H_2 in air	74% H_2 in air	
Twin 8........	0.10 to 0.35	0.4	0.11	0.028	4.8	0.28	0.26
18............	7.5×10^{-5}	[1] 9.1×10^{-4}	.32	.08	27	1.6	1.1×10^{-2}
42............	-	[1] 4.9×10^{-3}	>.32	>.08	>27	>1.6	.12

[1]Manufacturer's specified minimum flow.

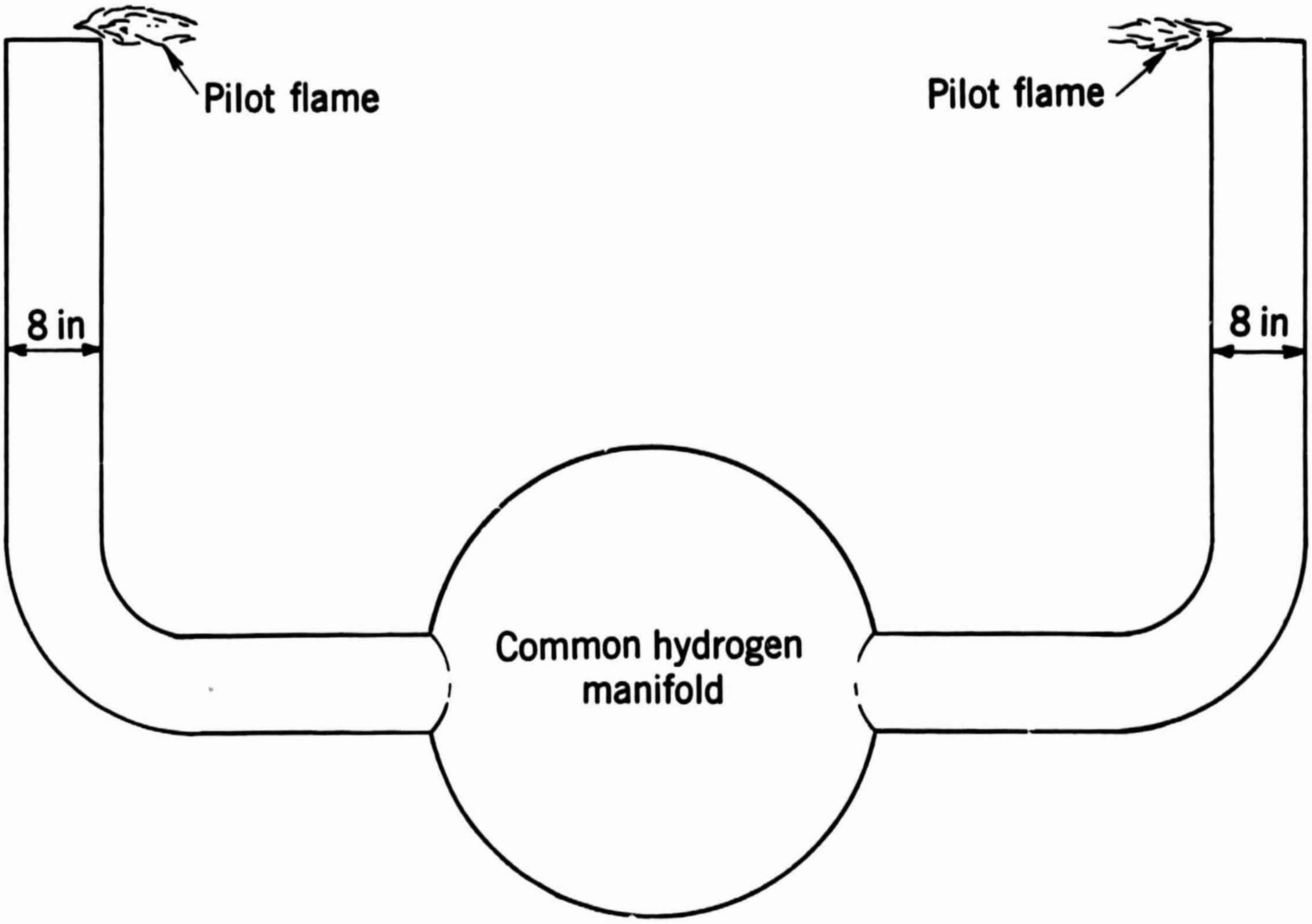

FIGURE 1. - Twin 8-Inch-ID Flare Stack.

Consider the flare stack in table 1 in which hydrogen was being flared through two 8-inch-id twin stacks connected (as shown in fig. 1) to a common manifold. For a flow of 0.10 to 0.35 lb/sec of hydrogen, flame formed inside one of the flare stacks near the manifold and oscillated between the two stacks. Both flare stacks operated satisfactorily when the total flow into the manifold was 0.4 lb/sec. Experiments showed that air can be inducted through one of the stacks while buoyant gases flow up the other. When helium flowed into the system, Pitot tube readings at the top of the flare stacks were negative for one stack and positive for the other.

A mechanism may be advanced to explain flame instability at low flows of hydrogen, employing the twin flare stack arrangement in figure 1 as an example. It may be assumed that flow of air down one flare stack is due to the buoyancy head of a column of hydrogen flowing in the other stack. The resistance to the downward air flow is due to friction with the stack walls. (Frictional pressure due to hydrogen flow is neglected because it is balanced by the pressure head causing hydrogen to flow.) The frictional head for turbulent flow ΔP_α, ft (23), is given by the following equation:

$$(\Delta P_\alpha)_{air} = \left[16L\,\rho_{air}\,V^2_{air} \middle/ \pi^2 D^5_{air}\right]\left[0.0036 + 0.24(2/Re)^{.35}_{air}\right] \qquad (1)$$

The buoyancy head ΔP (23) is given by the following equation:

$$(\Delta P_{\gamma})_{H_2} = gL\ \rho_{air}\ (1-d_{H_2}) \quad (2)$$

Equating 1 and 2 we get 3 which gives V_{air}, ft^3 per sec, the maximum flow of air which can be inducted by this system is as follows:

$$V_{air} = \frac{\pi\left[g\ (1-d_{H_2})\right]^{1/2}\ D_{air}^{2.5}}{4\left[0.0036 + 0.24\ (2/Re)_{air}^{.35}\right]^{1/2}} \quad (3)$$

L the length, ft; g, the gravitational constant, ft/sec^2; d, the specific gravity, compared with air at 1 atm; ρ, the density, lb/ft^3; D, the burner diameter, ft; and Re, the Reynolds number.

If air and hydrogen mix in the flare stack carrying the hydrogen, and if the resulting mixture contains 74 percent hydrogen, it is flammable. Pilot flames on top of flare stacks can ignite the mixture, and flame may propagate into the flare stack. After flame propagates down one stack, air induction down the other depends on the buoyancy of the combustion products flowing up the first. Extensive flame propagation into the flare stack is impossible at higher flows of hydrogen because the local concentrations of hydrogen are likely to exceed the rich limit of flammability. A sharp limit between flame dip and no flame dip is unlikely, because here and there a pocket of flammable mixture may form. As the hydrogen flow is increased, even this fragmentary flame dip becomes unlikely. Thus the proposed mechanism provides a basis for calculating the minimum flow of hydrogen above which flame is not expected to penetrate into the flare stack. Equation 4 yields the minimum flow of hydrogen,

$$V_{H_2} = (0.74/0.26)\ V_{air}. \quad (4)$$

The proposed concept yields results that are not in conflict with field experience available to the authors. As shown in table 1, the predicted limit for flame stability on the 8-inch twin-flare stack is 0.26 lb/sec. Experience shows the limit to be less than 0.4 lb/sec, more than 0.10 lb/sec, and perhaps more than 0.35 lb/sec. Fire in an 18-inch-id single-flare stack has been observed while hydrogen was flowing at about 7.5×10^{-5} lb/sec. The minimum flow stated in the manufacturer's operating instructions for this flare stack is about 1×10^{-3} lb/sec. The concept proposed in this study leads to a minimum hydrogen flow of about 1.1×10^{-2} lb/sec.

When a single stack is used, additional assumptions are necessary in order to assign values to D_{air} and Re_{air} in equation 3. In the twin-flare-stack example, one flare stack carries the downflow of air, and the other stack carries the upflow of hydrogen. In the single-stack case, one stack has to carry both flows. Accordingly, two additional assumptions were made. First, 74 percent of the cross-sectional area of the stack was assigned to the hydrogen flow and the remaining annulus of 26 percent to the countercurrent air flow. This matches the earlier assumption that the hydrogen-air combination of interest when mixed contains 74 percent hydrogen. Second, the frictional pressure head due to the downward flow of air in the pipe was taken to be equivalent to the frictional pressure head for a circular pipe whose radius is the equivalent hydraulic radius of the annulus assumed to carry the downward airflow.

The experimental points observed in this laboratory with the 6-, 12-, and 18-inch stacks at which flame was observed to begin to enter each flare stack are presented in figure 2 as flamedip limits. No sharp limits could be obtained, as would be expected. The observed limits agree roughly with the predicted limits for the same diameter stacks. Equation 3 was modified for the prediction of the value for the 6-inch stack by assuming laminar flow. Turbulent flow was assumed for the 12- and 18-inch stacks because the Reynolds numbers were near 2000, and the stack lengths were four pipe diameters. It is unlikely that laminar flow will exist in the field when large-diameter flare stacks are employed. Table 2 gives other characteristics about these experiments and also about flameback limits, which are the flows at which the flame had moved into the stack so that most of it was inside the pipe.

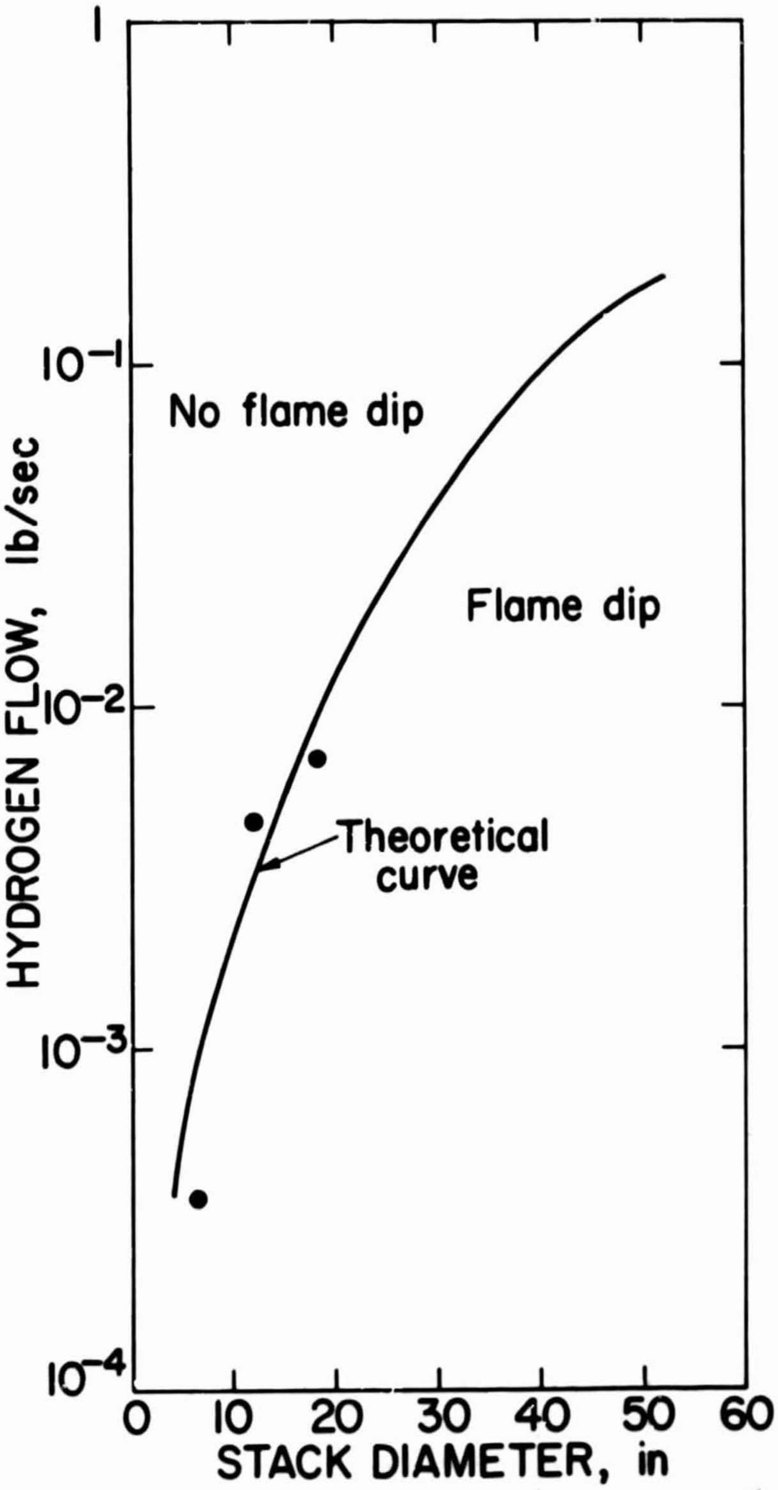

FIGURE 2. - Dip Limits of Hydrogen Diffusion Flames Into Stack.

Further evidence that air can flow downward from the open atmosphere into a stack was obtained by experiments using helium in place of hydrogen (table 3). Samples were taken inside of the 18-inch-id stack through which helium was flowing at the rate of 0.5 cfs. The experimental arrangement is shown in figure 3A. With a loosely fitting cover on the stack, helium percentages were about 90 to 100. With the cover removed and the same flow maintained, percentages of air were 85 to 70 1 inch inside stack and <70 about 2 feet inside of the stack. (See table 3, part A.) The experiments with helium clearly indicate that had low flows of hydrogen been used, air would have flowed into the stack. If the hydrogen had been ignited, it could have burned inside of the stack, although no air was sent into the system upstream of the stack.

TABLE 2. - Flamedip and flameback limits for hydrogen diffusion flames in open air

Stack diameter, inches	Flamedip limits				Flameback limit experimental, lb/sec
	Predicted, lb/sec	Experimental, lb/sec	Velocity, ft/sec	Reynolds No.	
6.............	1.3×10^{-3}	3.5×10^{-4}	[1]0.36	[1]170	5.3×10^{-5}
12.............	2.9×10^{-3}	4.7×10^{-3}	[1]1.20	[1]1,100	6.3×10^{-4}
18.............	1.1×10^{-2}	6.9×10^{-3}	[1].78	[1]1,100	7.0×10^{-4}
42.............	.12	-	2.4	7,900	-
52.............	.18	-	2.5	10,000	-

[1] Experimental flamedip values, based on hydrogen flow through entire cross section. Others predicted.

TABLE 3. - Percentages of air inside of an 18-inch-id stack with upward helium flow of 0.5 or 0.8 cfs

Flare stack	Sampling position coordinates, inches		Air, percent
	From top	From wall	
WITH LOOSE COVER ON STACK			
Apparatus 3A...	8	1	12
	8	9	0
	8	9	10
Apparatus 3B...	[1]36	9	[2]9
	[1]36	9	5
WITH STACK OPEN TO ATMOSPHERE			
Apparatus 3A...	1	1	85
	1	5	69
	1	9	69
	4	1	79
	4	5	80
	8	1	75
	8	1	74
	8	9	69
	12	1	68
	12	9	68
	18	1	70
	18	9	65
	24	9	66
Apparatus 3B...	[3]61	6	[2]70
	[3]61	6	59
	[4]36	9	[2]71
	[4]36	9	66

[1] Sampling point A.
[2] 0.8 cfs.
[3] Sampling point B.
[4] Sampling point C.

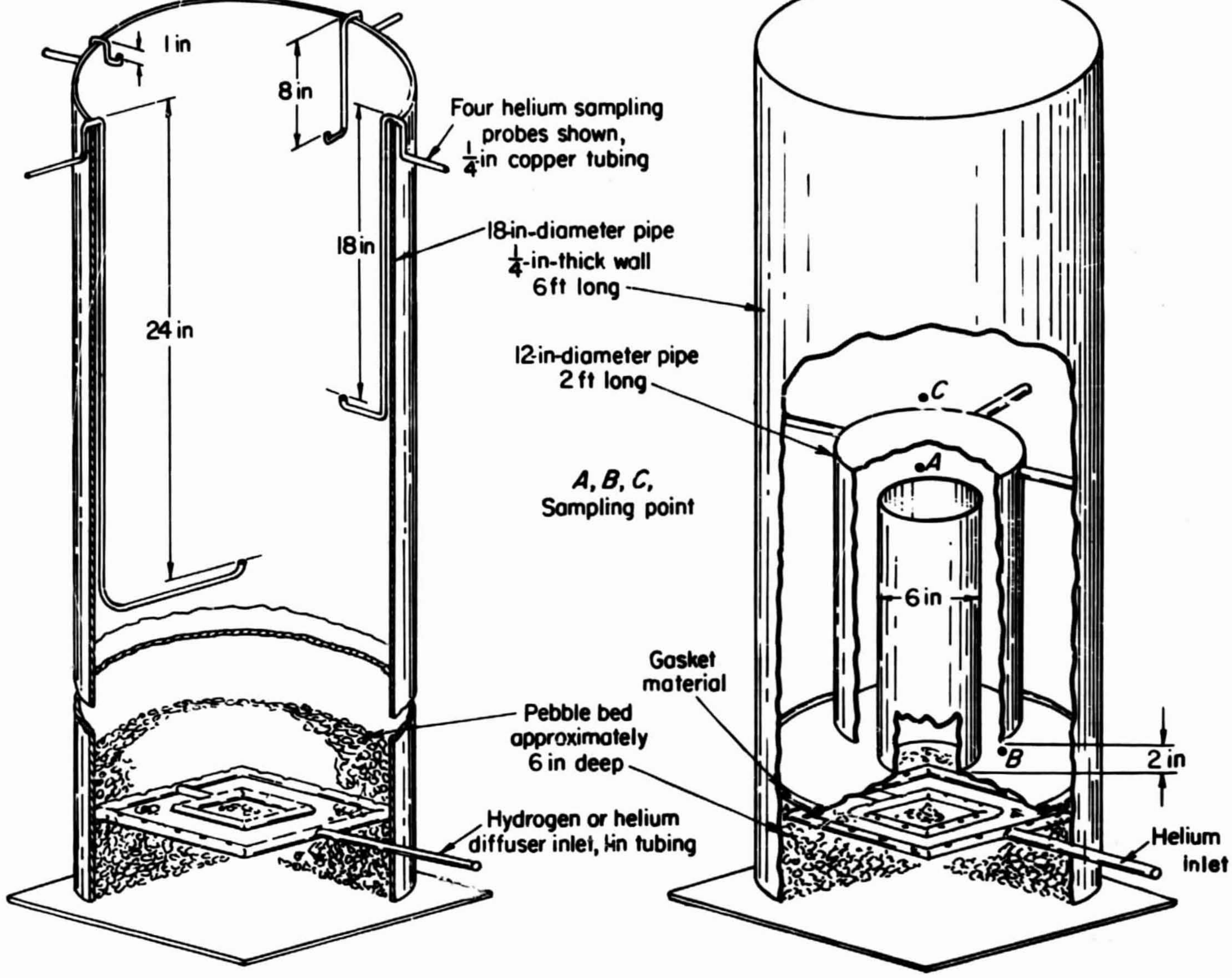

FIGURE 3. - Experimental Flare Stacks Showing Sampling Points.

An assembly consisting of an inverted cap over an upright pipe located deep within a flare stack is called a molecular seal (18). It is often used to prevent air from entering from the top of the flare stack. According to Reed (18) "a commercially available molecular seal installed immediately below the flare at the top of the riser will establish perfect safety from entry of air to the flare system when the purge volume admitted is capable of a line velocity of from 0.10 to 0.15 foot per second..." The top of the riser, that is the top of the inverted cap, may be many feet below the top of the flare stack. For example, Lapin (12) in his tests of hydrogen flare stacks used a commercially available molecular seal, which was about 12 feet below the top of the flare stack. These inverted cap systems are placed far enough inside of the flare stack to keep them away from the high temperatures at the top of the flare section (12).

It does not appear reasonable in view of the foregoing discussion that a trap of this sort would prevent all ingress of air into a flare stack system against a slow flow of buoyant gas. Air should be able to fall to the downstream exit of the trap, as demonstrated by the following experiments: A simulated molecular seal was constructed to fit the 18-inch-diameter stack (fig. 3B). With a loose cover on the stack, helium at a rate of about 0.8 cfs was used to flush air out of the stack and the seal. This flow corresponds to a linear velocity of 0.43 ft/sec in the 18-inch-diameter section and 0.78 ft/sec in the annulus formed by the 1-foot-diameter seal. In two minutes all the air was flushed out of the stack. The cover was removed with the helium continuing to flow. After 1 minute, samples were taken at points A, B, and C in figure 3B. Sampling time was approximately 1 minute. Point A is located inside the seal just below its top, point B is at the bottom of the seal at its downstream end, and point C is immediately above the seal on the axis of the stack. A second run was made sampling at the same points but with the flow reduced to about 0.5 cfs, which corresponds to 0.30 ft/sec in the stack and 0.55 ft/sec in the annulus. Helium flow was continued for 3 minutes with the cover on. Sampling was started 1 minute after the cover was removed with the flow continuing. As shown by the data in part B of table 3, air entered the stack when the cover was removed. At point B the percentage of air was 70 in the first run and 59 in the second. Thus the seal was not affective here. Point C, where the air concentration was 66 percent, was 36 inches down the stack. At point A within the seal the observed air percentages were 9 and 5, respectively. Clearly ingress of air into the stack was not arrested; only the ingress of air into the seal was arrested.

Motion pictures were taken of flames on the 12-inch stack at the flamedip limit and at lower flow rates, dropping progressively almost to the flameback limit. Flames on the 18-inch stack at about the flamedip limit were also filmed. A frame-by-frame analysis of these films showed that the flame heights fluctuated considerably, at a frequency of about 2 to 3 fluctuations per second for the 12-inch stack and about 2 fluctuations per second for the 18-inch stack. An example of the extremes observed in flame shape and height is given in figure 4 which shows two 0.04-sec views of a 0.66 cfs (3.3×10^{-3} lb/sec) hydrogen flame on the 12-inch stack. This flow (0.66 cfs) is below the experimental flamedip limit but above the experimental flameback limit. The flame in the right hand frame is almost twice the height of the other. More significantly, large voids exist at the base and within the body of the flames. These voids moved around and are attributed to flame quenching by the combustion products accumulated in the immediate vicinity. As these pockets of burned gas are dissipated by diffusion and slow convection, air comes in and "heals" the flame void. In the meantime, a pocket resulting in flame extinguishment grows elsewhere. At higher flow rates, burned gases are removed and air is entrained much faster, so that burning becomes continuous up to extremely high rates of flow which may again disrupt the turbulent flame (4, 11). In connection with the occurrence of holes in diffusion flames, it may be noted that surprisingly high concentrations of nitrogen have been observed underneath hydrocarbon diffusion flames (6, 20-21), indicating that considerable convective transport occurs across diffusion flame surfaces or through gaps in flame as shown in figure 4.

The exposure time of the motion pictures was about 0.0167 sec/frame. Stills of methane diffusion flames taken at the same speed also showed voids

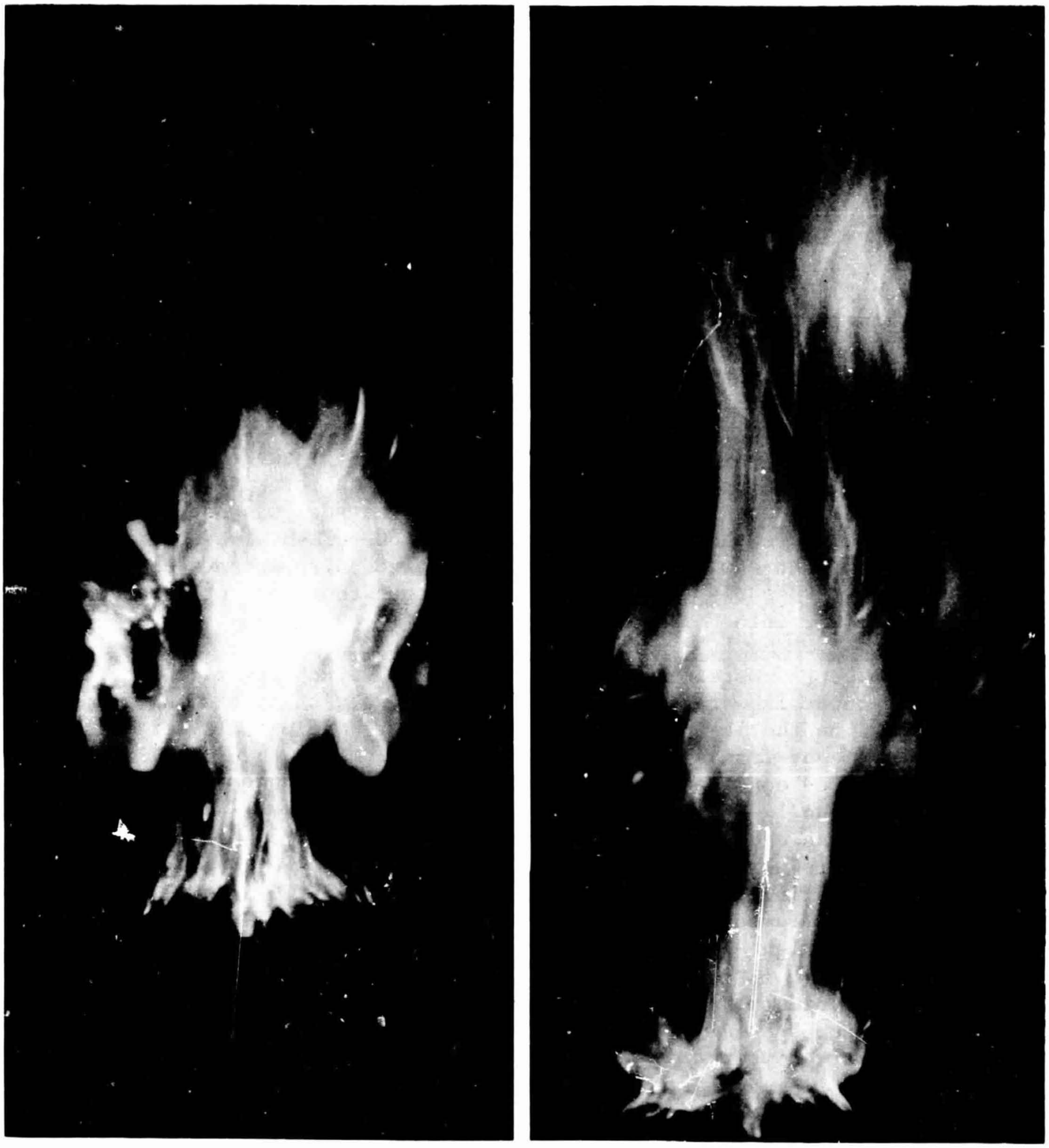

FIGURE 4. - Two Views of a Hydrogen Diffusion Flame on a 12-Inch Stack, Flow Rate = 0.66 cfs.

in the flame, indicating that such voids are not limited to hydrogen nor probably to wide stacks.

Experiments were also conducted with low-flow-hydrogen flames on the 12-inch stack to determine whether small pilot flames could heal the voids observed in unpiloted flames. The hydrogen flows were 0.66 cfs and 0.25 cfs (1.25×10^{-3} lb/sec); the methane flow for two pilot flames at the base of the main flame was 0.0012 cfs from ¼-inch-od tubing. The greater hydrogen flow is below the flamedip limit, and both flows are above the flameback limit. In motion pictures taken with and without the pilot flames, gaps appeared frequently in the flame, and the flame varied in shape although the flow was constant. This indicates that in this present case pilot flames do not contribute appreciably to the healing of holes in turbulent flames, as they do with turbulent premixed flames in free air (4, 11).

The cycling of flame shape appears to be of the order reported for smaller flames of other fuels. Barr (1) observed that butane diffusion flames fluctuate with a frequency of about 10 to 15 hertz. Maklakov (14) also reports 10 to 15 hertz and finds that the frequency is independent of the identity of the gas, and that the frequency decreases somewhat with the increase in burner diameter. For example, fluctuations of a carbon monoxide flame change from 15 hertz on a 0.5-cm burner to 12 hertz on a 1.2-cm burner.

HIGH FLOW INSTABILITY LIMIT

The high flow instability limit of a diffusion flame, that is, the flow rate at which the flame completely leaves the burner port and ceases to exist, is referred to as the diffusion-flame blowout limit. It parallels the blowoff limit of premixed flames. No blowout limits have been reported previously for pure hydrogen diffusion flames in still air. Recently Vranos, Taback, and Shipman (25) reported limits for small hydrogen jets burning in concentric high-velocity air streams. They found regions of stable burning over a large range of hydrogen and air velocities, including sonic flows of hydrogen. Blowout in wind was reported for a 0.1658-inch-id burner.

Blowout is far more complex than blowoff. In earlier work (3), the critical boundary velocity gradient concept was used successfully to correlate blowoff limits of premixed laminar and turbulent propane-air flames with the blowout of turbulent diffusion flames of propane. With this as a precedent, the concept has been used here to extrapolate from experiments with very small laboratory burners to very large diameter-flare stacks. Because of insufficent flow capacity, the blowout of hydrogen diffusion flames from large diameter stacks could not be measured directly in this laboratory. Thus very small diameter burners had to be used, and even under these conditions blowout of a neat hydrogen flame was attained only on the smallest orifice used (table 4). Most of the measurements were for blowout limits of neat mixtures of hydrogen with nitrogen; these data were extrapolated to obtain a blowout limit for hydrogen diffusion flames.

Theory for correlating blowoff limits of premixed flames, using the concept of the critical boundary velocity gradient is reviewed in a previous report (8). Blowoff supposedly occurs when the local stream velocity everywhere over the stream cross section exceeds the local burning velocity. Generally, a flame stabilizes at the stream boundary where the local flow velocity and burning velocity are equal. Elsewhere the flame surface assumes an angle to the local flow direction such that the component of the flow velocity normal to the flame surface equals the burning velocity. This does not describe diffusional flame burning because a diffusion flame, particularly a turbulent one, does not consist of a sharply defined thin boundary separating the unburned mixture of fuel and air from its burned products. It may be that this situation is roughly approximated at the base of the diffusion flame over the burner port and accordingly its blowoff and blowout characteristics can be correlated by the critical boundary velocity gradient concept.

TABLE 4. - Blowout and lift-off limits of diffusion flames of hydrogen-nitrogen mixtures

Burner diameter, inch	Blowout velocity, ft/sec	Lift-off velocity, ft/sec	Reynolds No.	Boundary velocity gradient	
				Sec^{-1}	Average for blowout, sec^{-1}
COMPOSITION, PERCENT BY VOLUME: 62.9 H_2, 36.1 N_2, 1.0 O_2					
0.077	781	-	17,800	7.49×10^6	6.09×10^6
.179	815	-	42,700	6.36×10^6	
.233	743	-	51,000	5.13×10^6	
.306	-	778	69,900	5.15×10^6	
.306	797	-	71,600	5.38×10^6	
COMPOSITION, PERCENT BY VOLUME: 70.2 H_2, 28.7 N_2, 1.1 O_2					
0.077	853	-	17,200	7.98×10^6	8.57×10^6
.179	925	-	42,900	7.24×10^6	
.233	1080	-	65,400	8.97×10^6	
.233	-	872	53,000	6.23×10^6	
.306	-	957	76,200	6.77×10^6	
.306	[1]1200	-	95,700	10.1×10^6	
COMPOSITION, PERCENT BY VOLUME: 76.8 H_2, 21.7 N_2, 1.5 O_2					
0.077	820	-	14,400	6.67×10^6	10.8×10^6
.179	-	772	31,300	4.81×10^6	
.179	1480	-	60,000	1.50×10^7	
COMPOSITION, PERCENT BY VOLUME: 87.8 H_2, 10.9 N_2, 1.3 O_2					
0.077	-	1200	14,900	9.99×10^6	43.5×10^6
.077	2760	-	34,300	4.31×10^7	
.179	-	1010	29,100	5.95×10^6	
.179	[1]3170	-	91,200	4.39×10^7	
COMPOSITION, PERCENT BY VOLUME: 100 H_2					
0.037	-	3880	11,200	5.50×10^7	
.037	6730	-	19,400	1.43×10^8	
.043	-	3540	12,000	4.40×10^7	
.043	[1]8920	-	30,200	2.25×10^8	

[1]Maximum velocity, blowout not attained.

For laminar flow, the gradient g_B is as follows:

$$g_B = 8\,\overline{U}/D, \tag{5}$$

where $\overline{U}$ is the linear velocity in ft/sec, and D is the diameter in feet. For turbulent flow, it is as follows:

$$g_B = 0.0395\ \bar{U}\ Re^{.75}/D, \qquad (6)$$

where Re is the Reynolds number.

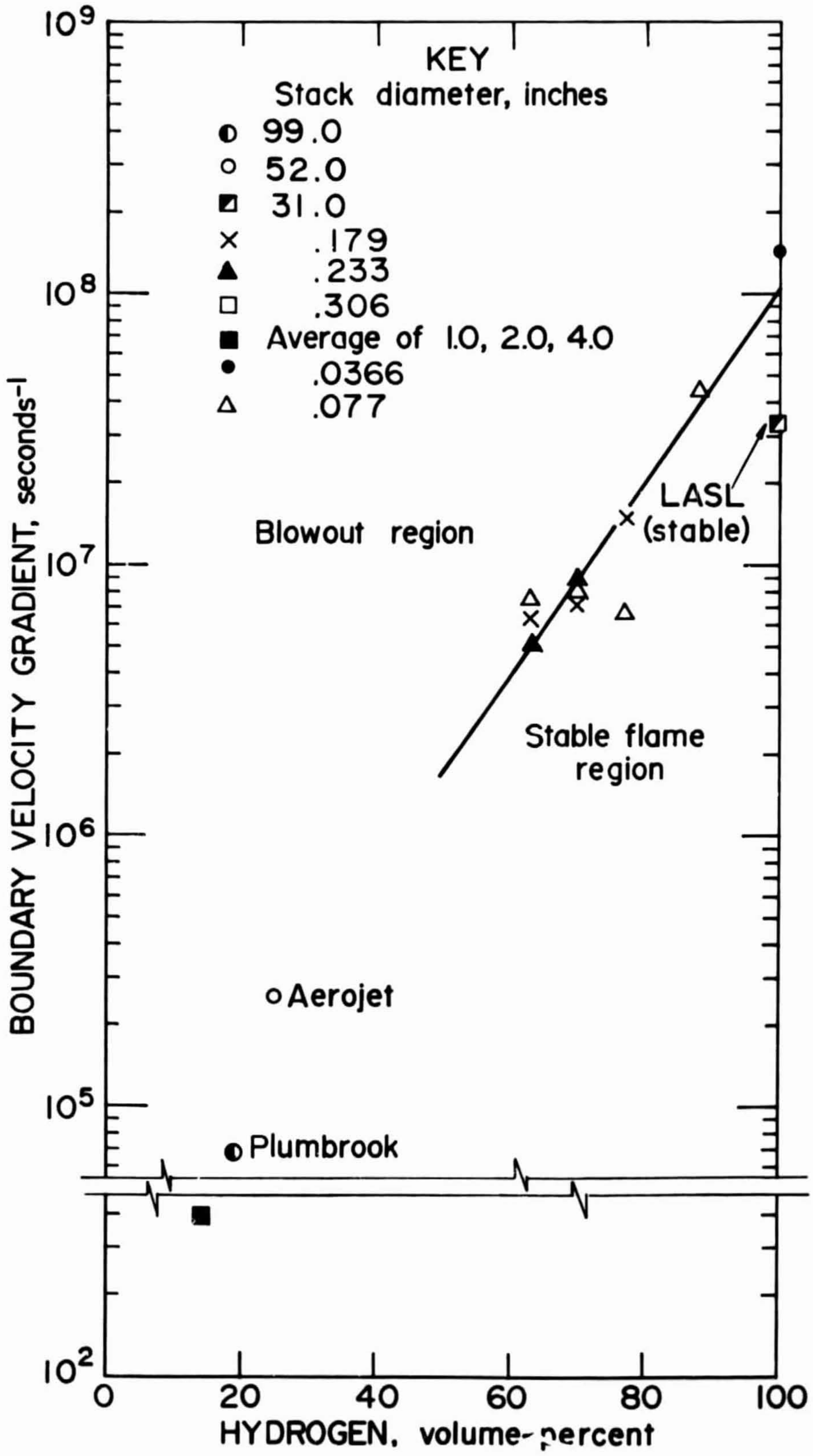

FIGURE 5. - Blowout Limits and Stable Flame Point of Diffusion Flames in Air of Mixtures of Hydrogen Plus Inert Gases.

One direct measurement was made of the blowout velocity of hydrogen (table 4). It was achieved on the 0.037-inch burner and indicates that the critical boundary velocity gradient for blowout of a hydrogen diffusion flame is about 10^8 reciprocal seconds. Confirmation of this measurement by means of hydrogen-nitrogen mixtures involved burners with inside diameters up to 0.306 inch. Table 4 summarizes all data obtained with hydrogen-nitrogen mixtures that contain over 60 percent hydrogen.

In figure 5, extrapolation of the least-squares lines fitting the critical boundary velocity gradients of table 4 indicates that the gradient for blowout of a pure hydrogen flame is about 10^8 sec^{-1}. The least-squares line intercepts by extrapolation a blowout point computed on the basis of an observation by the Aerojet-General Corp., Sacramento, Calif., and nearly intercepts another point observed by the NASA-Lewis Research Center, Plumbrook Station, Cleveland, Ohio. The line exceeds as it should the stable flame point computed on the basis of an observation by LASL. The data leading to these three points based on field experience are in table 5. Finally, figure 5 shows a limit obtained with hydrogen-nitrogen mixtures containing about 15 percent hydrogen. Data for this point will be presented later in discussions of dilution limits for hydrogen. This lowest point lies below an extrapolation of the least-squares line, which is to be expected since the blowout curve for the hydrogen-nitrogen system should intercept the abscissa at some hydrogen concentration above 4 percent.

TABLE 5. - Blowout limits and stable flame data for diffusion flames on flare stacks in air of mixtures of hydrogen plus inert gases

Stack diameter, inches	Hydrogen, percent	Flow, ft^3/sec			Reynolds No.	Blowout gradient, sec^{-1}
		Hydrogen	Nitrogen	Steam		
[1] 99..............	19.4	2,370	-	9,830	2.43×10^6	6.7×10^4
[2] 52..............	25.6	2,330	2,150	4,780	1.60×10^6	2.6×10^5
[3] 31..............	100	58,400	-	-	2.43×10^7	3.3×10^7

[1] Observation by NASA-Lewis Research Center, Plumbrook Station.
[2] Observation by Aerojet-General Corporation, Sacramento.
[3] Stable flame. Observation by Los Alamos Scientific Laboratory (LASL).

The blowout limit derived in this manner for a hydrogen diffusion flame should be considered as an order of magnitude evaluation. The laboratory burners are much smaller than the flare stacks used in the field and one cannot as yet scale with certainty. That the field experiences are consistent with laboratory data is reassuring but not necessarily corroborative. Other reservations about this extrapolation stem from the results reported in a previous investigation (7).

Examination of figure 5 shows that mixtures which can blow out from flare stacks because the velocity gradient is too much for the particular stack diameter and the particular hydrogen inert gas composition could conceivably be stablized at a lower flow rate or on a larger diameter stack. In other words, mixtures that do not burn under particular conditions could perhaps burn under other conditions. Thus, it is a matter of concern whether a hydrogen-inert gas mixture that is not capable of stabilizing on a particular flare stack could become hazardous as the flow drifts or is blown elsewhere.

The study of blowout limits also led to a limited study of flamelift. This is the condition where the flame lifts off the burner and is stabilized about 1 to 2 inches above it (fig. 6). Liftoff limits are included in table 4, but no correlation is offered. Lifted flames could be blown out by crosswinds with velocities about 60 to 80 percent of the wind velocities required for flames that were fully seated on the burner. As shown in table 6, only negligible quantities of hydrogen were detected below the flame base, except when the probe was placed into the stream flowing towards the flame base (table 6, distance from burner axis <0.25 inch).

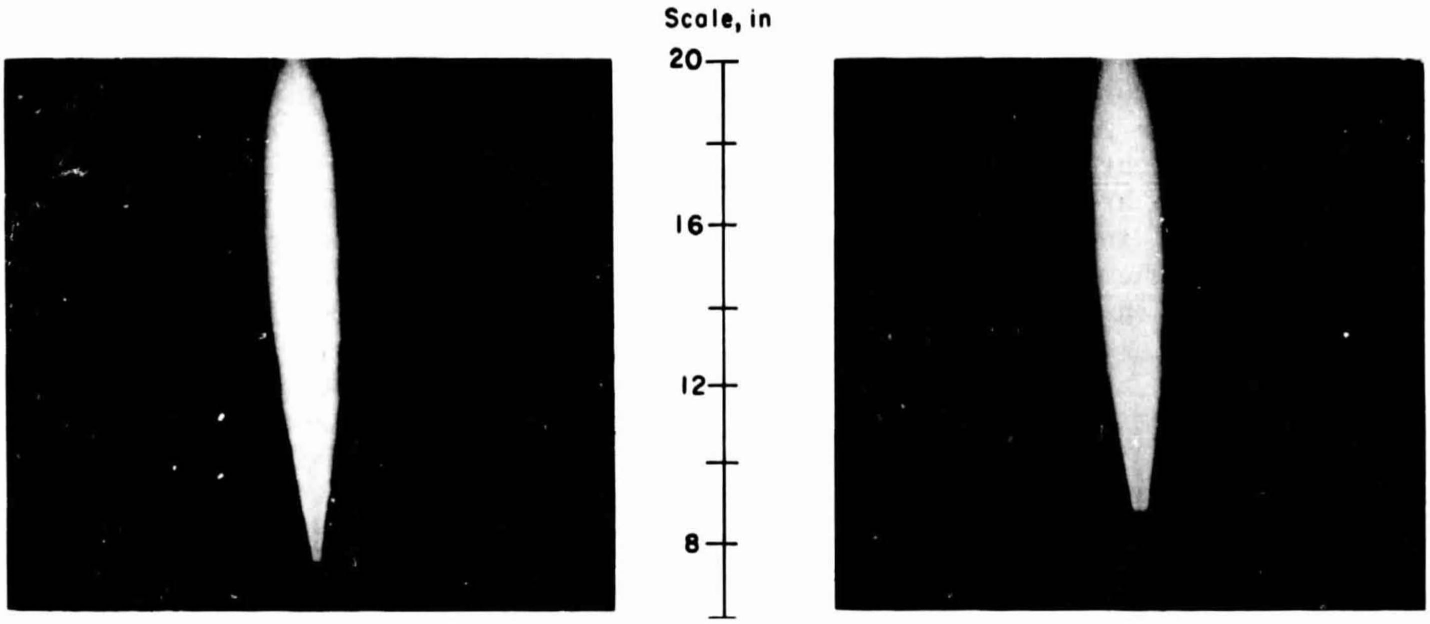

FIGURE 6. - Lift-Off of a Hydrogen Diffusion Flame From a 0.77-Inch-Diameter Burner.

TABLE 6. - Composition of gases near lifted diffusion flames of hydrogen-nitrogen mixtures. Burner diameter = 0.179 inch. Flame base = about 0.5 inch diameter.

Height above burner, inches	Distance from burner axis, inch	Velocity, ft/sec	Observed composition of products, percent		
			Hydrogen	Nitrogen	Oxygen
COMPOSITION, PERCENT BY VOLUME: 76.8 HYDROGEN, 21.7 NITROGEN, 1.5 OXYGEN					
1.0................	0.19	814	9.7	74.7	15.6
1.0................	.38	814	.06	79.3	20.6
1.5................	.50	814	Trace	79.4	20.5
COMPOSITION, PERCENT BY VOLUME: 87.8 HYDROGEN, 10.9 NITROGEN, 1.3 OXYGEN					
1.0................	0.19	2,400	12.0	70.2	17.8
1.0................	.38	1,940	Trace	79.5	20.5

DILUTION LIMITS OR BLOWOUT LIMITS OF HIGHLY DILUTED DIFFUSION FLAMES OF HYDROGEN-INERT GAS MIXTURES

For various reasons, steady flows of inert gas (nitrogen, helium, or steam) may be maintained during flare stack operation while hydrogen flows are varied. This is particularly likely to occur during startup or shutdown of a run. Conceivably, hydrogen will not be burned when the proportion of hydrogen to inert gas is too low for diffusion flame burning, and unburned hydrogen will be discharged from the flare stack. The problem is not one of traditional flammability limits of premixed static mixtures (5); the blowout limit of a diffusion flame is involved. Since blowout is brought about by heavy dilution with inerts, this limit is termed a dilution limit to differentiate it from blowout caused by high flow rate of fuel. Theory for correlating blowoff limits of premixed flames is discussed in the section on the high flow instability limit and is used here to correlate dilution limits.

Blowout gradients for hydrogen-nitrogen diffusion flames on 1-inch, 2-inch, and 4-inch-id burners are presented in table 7; the average values constitute the coordinates of the lowest point plotted in figure 5. These are averages of a range of fuel composition ranging from 10.8 percent hydrogen to 17.9 percent, and blowout gradients ranging from about 10 to 1700, variations which are small in the context of figure 5. In comparison, the first two points in table 5 were obtained with full-scale flare stacks flaring during startup when the hydrogen flow was increasing; the actual limit may be a little leaner in hydrogen because of time lag between flow readout and observation of ignition. The difference between the large-scale and laboratory runs is not attributable to the different inert gases, because steam and nitrogen have similar effects on flame stability. The difference in mixture ratios is due to the difference of the volumetric flows. (Note Reynolds numbers.) These data indicate that mixtures that blowout from flare stacks because the velocity gradient or the dilution with inerts is too much for the particular stack diameter could conceivably be stabilized at a lower flow rate or larger diameter. In other words, a hydrogen-inert gas mixture that is not capable of burning on a particular flare stack could become hazardous as the mixture drifts, or is blown elsewhere. In contrast to the data in tables 5 and 7, the minimum percent hydrogen in nitrogen among the flammability limits for the hydrogen-nitrogen-oxygen premixed static system is 4.8 (5). This percentage is not to be confused with the lean flammability limit of hydrogen in air. Incidentally, flammability limit data are available in references such as the one authored by Coward and Jones (5).

TABLE 7. - Dilution limits of diffusion flames in air of mixtures of hydrogen and nitrogen

Hydrogen, percent	Nitrogen, ft^3/sec	Hydrogen, ($\times 10^3$)	Reynolds number	Blowout gradient, g_a
STACK DIAMETER = 1 INCH				
13.6	5.72	0.88	571	116
13.6	9.98	1.58	958	196
15.7	16.5	3.09	1,630	343
15.4	21.4	3.91	2,125	1,022
13.5	29.1	4.56	2,825	1,130
12.7	36.7	5.35	3,530	1,670
STACK DIAMETER = 2 INCHES				
12.5	4.87	0.70	244	12
13.4	10.3	1.59	513	26
16.9	15.9	3.24	814	43
STACK DIAMETER = 4 INCHES				
10.8	253	29.8	5,930	260
11.5	228	29.2	5,410	215
17.9	57.7	12.2	1,456	19
12.0	119	16.3	2,232	60
15.1	192	34.1	4,700	173
16.7	192	38.3	4,780	179
[1]14.1	-	-	-	[1]365

[1]Average.

BURNING RATES

The earlier discussion of fluctuations in flame heights is relevant to another consideration; namely, whether the reach or length of the flame on the flare stack is sufficient to impinge on the test stand or other facilities. Two theoretical approaches have been used to predict heights or lengths of flare-stack flames. The question is whether these theoretical treatments can be effectively applied to large diffusion flames. Hawthorne and others (10) studied flames with Reynolds numbers up to about 10,000 on burners up to ¼ inch in diameter. Wohl and others (26) observed that the ratio of flame height to burner diameter became constant for turbulent flames as the Reynolds number increased; the maximum tube diameter was 0.4 inch, the maximum Reynolds number was about 32,000. Observations of diffusion flames of high Reynolds numbers on large-diameter stacks show that flame length varies considerably with flow rate. Putnam's (17) study provides a semiempirical relation between flame length and flow rate. Thompson and Boncare (22) found it necessary to modify Putnam's empirical constant by a factor of almost 3 for still air in order to correct for an over-prediction of flame heights.

The approach made in this paper is entirely empirical. Burning rates have been roughly estimated from photographs of flames on burners ranging from 4 to 31 inches in diameter. The burning rate is defined as the volumetric flow rate of hydrogen divided by the surface area of the flame. Because the latter is extremely difficult to estimate, only rough determinations can be made. The results are presented in table 8. Of particular interest is the difference between apparent burning rates of hydrogen diffusion flames at low and high flow rates. The burning rates from the laboratory determinations (about 0.03 and 0.1 ft/sec) are about an order of magnitude less than those of the full-scale flames (about 1 ft/sec), which burned about 1,000 to 10,000 cfs of hydrogen on stacks about 30 inches in diameter. Turbulence levels were probably very high. Stack diameters for the two sets of data are within a factor of 3, and the flows of hydrogen are within factors of three to four orders of magnitude.

Burning rates can be used to predict flame heights if one assumes that large-scale diffusion flames have a simple geometric form, such as a frustum of an inverted cone with a half angle β. Flame height, h, is then given by,

$$\pi h^2 \tan \beta + \pi D h - V/Su\,(1-\tan^2\beta)^{1/2} = 0, \tag{7}$$

where Su is the burning velocity in ft/sec, V is the flow rate in ft^3/sec, and D is the stack diameter in feet. Table 9 shows how flame height depends on β; a burning rate of 1.0 ft/sec was assumed. A half angle of about 3° yields the best approximation. If a burning rate of 0.1 ft/sec is assumed, no reasonable value of β (up to 16°) gives as good a fit of the field data. The use of laboratory-scale data leads to overestimates of flame height.

TABLE 8. - Burning rates of hydrogen diffusion flames

Stack diameter, inches	Flow rate		Flame height, ft	Flame surface area, $ft^2 \times 10^{-3}$	Burning rate	
	Lb/sec	Ft^3/sec			Ft/sec	$(Lb/sec,ft^2) \times 10^3$
4	0.16×10^{-3} to 1.6×10^{-3}	0.031 to 0.31	1.8 to 4.4	-	≤0.03	-
12	3.3×10^{-3}	.66	3.2	0.0051	.13	0.65
12	4.6×10^{-3}	.916	6.2	.013	.07	.36
30	6.6	1,180	62 to 63	.715 to 1.22	1.0 to 1.7	5.4 to 9.2
31	70	12,500	275 to 330	8.27 to 27.1	.5 to 1.5	2.6 to 8.5

TABLE 9. - Predicted heights of hydrogen diffusion flames versus heights observed in the field

Hydrogen flow..................ft³/sec..	1,180	12,500
Stack diameter......................in..	30	31
Observed height.....................ft..	62-63	275-330
Predicted height, ft:		
0° flame spread[1].....................	150	1,500
3° flame spread[1].....................	64	254
16° flame spread[1].....................	31	108

[1]Half angle.

These burning rates are for diffusion flames, not for stationary or propagating flames of premixed hydrogen and air. A case in point illustrating propagation rates of large premixed hydrogen-air flames is reported by Reider and others (19). Hydrogen flow rates were about 120 lb/sec, and the authors estimate that a premixed hydrogen-air flame propagated downward at approximately 100 ft/sec. In normal combustion, the expansion ratio due to combustion provides about a sevenfold linear multiplication of the 9 ft/sec burning velocity. Reider's figure appears reasonable.

TEMPERATURES OF HYDROGEN DIFFUSION FLAMES

Temperature profiles at various heights above a 4-inch-diameter burner were recorded by moving an iridium versus iridium-40 percent rhodium thermocouple across a diffusion flame burning 3.5 cfm of hydrogen. The thermocouple was made of 0.0033-inch-diameter wire. The flame was about 2 feet high. Temperature fluctuations at a point of measurement ranged from a maximum of 3,590° F to a few hundred degrees Fahrenheit. Average temperatures were determined by visual estimate based on the appearance of recorder records. Axial average temperatures obtained in this way are given in table 10. Average temperatures rose from 1,970° F, 1 inch above the port to 2,590° F 13 inches above it and then declined to 1,105° F 25 inches above the port. The maximum observed temperature of 3,590° F may be compared with an adiabatic flame temperature of 3,812° F for a stoichiometric hydrogen-air flame and a computed diffusion flame temperature of 3,000° F based on radiation measurement.

Figure 7 shows the variation of calculated and measured average temperatures with distance above the flame port; agreement is generally good. Spatial and temporal temperature fluctuations make it difficult to estimate a single effective temperature for a hydrogen diffusion flame. The temperature records show that fluctuations are more frequent near the port where the average temperature is low, and become less frequent at points where the average temperature is higher. For example, 1 inch above the port the temperature fluctuates 700° F above and below the average of 1,970° F about 50 percent of the time. However, 9 inches above the port where the average temperature is 2,530° F, this temperature is exceeded by 700° F less than 25 percent of the time and does not go above 3,510° F. Temperature measurements also showed that the iridium versus iridium-40 percent rhodium thermocouple employed does not have a catalytic effect on the combustion. If a single temperature representative of a hydrogen diffusion flame must be chosen perhaps that corresponding to the peak of figure 7 (about 2,600° F) offers the best compromise, provided that it is recognized that spot instantaneous temperatures of about 3,600° F can occur.

Samples were collected at the temperature measurement points and analyzed for combustion products. Table 10 summarizes the raw water-free analysis of products together with computed water-containing products and reactants which would yield these products on combustion. In making these calculations, the total number of moles of oxygen was computed by multiplying the ratio of oxygen to nitrogen in air by the number of moles of nitrogen found. From this, the water formed was taken to be twice the difference between residual oxygen

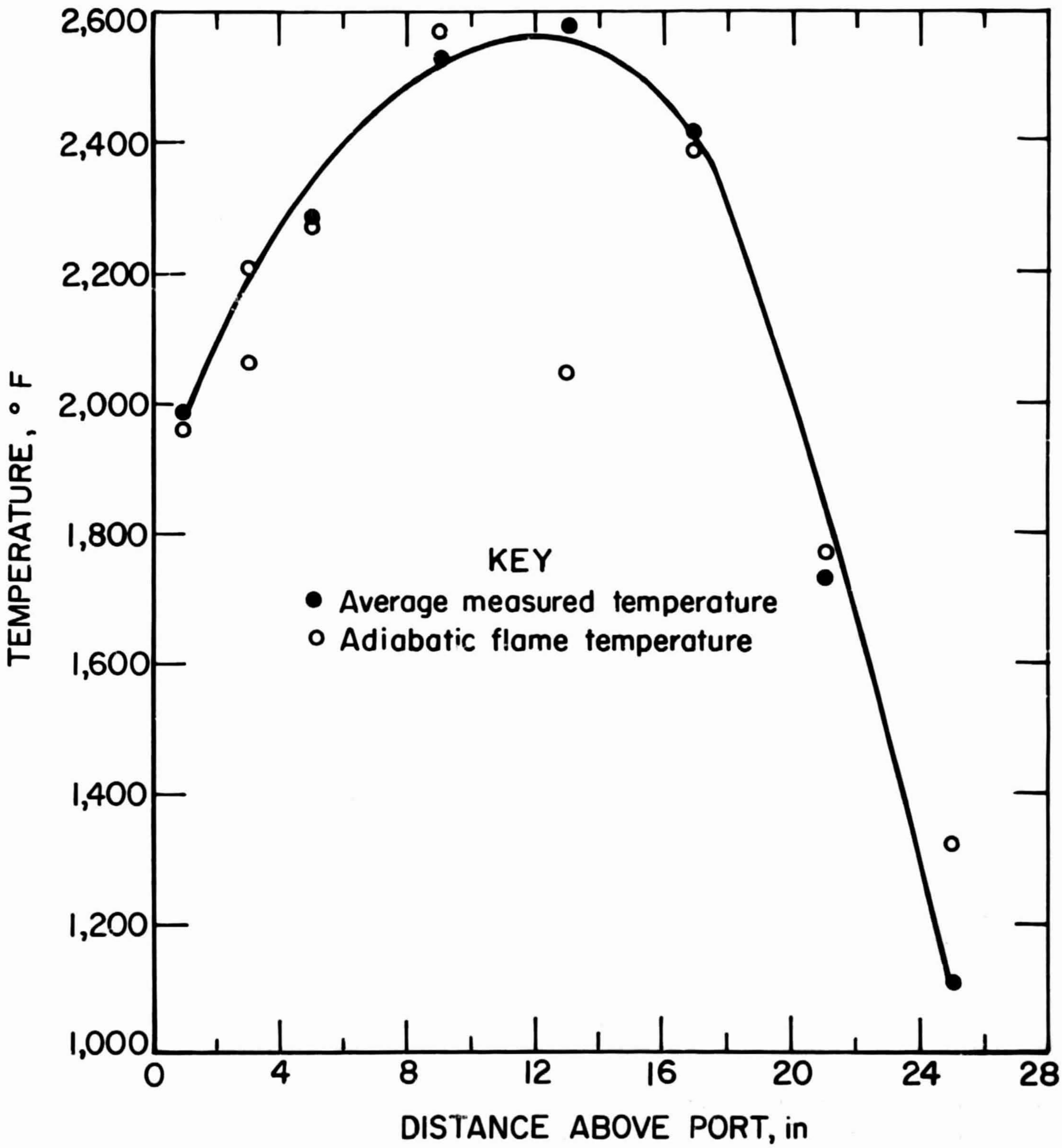

FIGURE 7. - Temperatures on the Axis of a Hydrogen Diffusion Flame. Burner diameter = 4 inches, flow rate = 3.5 cfm.

and computed oxygen. The water formed, with the hydrogen observed, gave a value of reactant hydrogen, and the nitrogen plus total oxygen equaled the reactant air. Finally, adiabatic reaction temperatures were computed based on the reactant and product compositions.

TABLE 10. - Temperatures and analyses of gases on axis of a diffusion flame burning 3.5 cfm of hydrogen on a 4-inch-id burner

Distance above burner mouth, inches	Average temperature, ° F	Observed composition of products, mole fraction			Computed composition, mole fraction							Adiabatic reaction temperature, ° F
					Products			Reactants				
		H_2	N_2	O_2	H_2	N_2	O_2	H_2O	H_2	N_2	O_2	
1	1,970	0.404	0.530	0.061	0.349	0.459	0.053	0.139	0.457	0.429	0.114	1,960
3	2,200	.476	.520	.048	.309	.425	.039	.147	.499	.396	.105	2,065
5	2,280	.404	.530	.044	.344	.452	.038	.166	.475	.416	.109	2,280
9	2,530	.260	.688	.062	.208	.549	.049	.194	.366	.501	.133	2,580
13	2,590	.066	.814	.125	.056	.685	.105	.154	.195	.636	.169	2,100
17	2,410	.044	.841	.115	.036	.690	.094	.180	.197	.635	.168	2,390
21	1,730	.008	.841	.151	.007	.734	.132	.127	.126	.691	.183	1,780
25	1,105	.0006	.829	.170	.0005	.754	.155	.091	.088	.721	.191	1,335

Temperatures did not decrease sharply near the axis, as was to be expected if the fluid there were mainly unburned hydrogen. Instead, temperatures were somewhat higher close to the axis than elsewhere in a given cross-sectional plane of the flame. The data in table 10 offer a basis for explaining the decreasing radial temperature gradient in the upper reaches of the flame, which was observed from the axis to the edge of the flame. The hydrogen content of reconstructed reactant mixtures along the axis is low and within the range of flammability (less than 50 percent), showing that air, flame products, and fuel mix rapidly and that combustion may occur in bulk rather than at an interface between fuel and air. Moreover, cold hydrogen may be expected to diffuse outward along concentration gradients; hot water vapor and hot nitrogen will diffuse inward toward the axis. This mass exchange within the flame results in an overall transport of heat towards the axis. At more than 9 inches above the burner mouth, the reactants at the axis are fuel-lean; they are certainly leaner off the axis than at the axis. Therefore, in the upper reaches of the flame, increasing radial dilution of the mixture with distance from the axis causes a corresponding decrease of the radial temperature gradient.

FLAME CHARACTERISTICS IN WINDS

Stripping of Hydrogen From Its Diffusion Flame by Winds

The possibility was examined that winds may disrupt a hydrogen diffusion flame and transport unburned hydrogen elsewhere to form a flammable mixture. Hydrogen was burned on an upright 4-inch-id vertical stack; air at velocities up to about 40 ft per sec was directed against the hydrogen diffusion flame from an 8-inch-id horizontal stack. The experiments were conducted indoors to avoid interference from atmospheric winds. The average position and shape of the flames were recorded by 1-minute exposure photographs, and sampling probes were installed at selected distances from the flame envelope on the basis of the flame shape determined in this manner.

In a first series of experiments, four single-orifice probes were positioned around the flame envelope, 1 inch away from it. Samples were withdrawn within 1 minute and analyzed by gas chromatography with an accuracy of 0.03 percent hydrogen; no hydrogen in excess of this concentration was found in any of the samples. Table 11 gives the probe positions used to sample hydrogen flames exposed to various crosswinds. No significant quantities of free hydrogen were observed.

In a second series of experiments, multiorifice probes sampled from points spaced 0.5 inch apart around the flame (fig. 8). These integrating probes were placed at distances ranging from 6 inches outside the flame envelope to 2 inches inside of it. Hydrogen flow from the 4-inch stack was 1 cfs and the maximum crosswind velocity was 39 mph. Table 12 indicates roughly the maximum amounts of hydrogen found; accurate values could not be obtained because the detected concentrations were below the accuracy of the gas chromatograph employed. Only traces of hydrogen were observed and these just about vanished at 4 to 6 inches from the photographed envelope. These samples also show that the hazardous stripping of hydrogen from its diffusion flame by usual winds is unlikely.

TABLE 11. - Probe positions when sampling around hydrogen diffusion flames on a vertical 4-inch-id stack[1]

Height above stack port, inches	Distance downward from stack axis, inches	Height above stack port, inches	Distance downward from stack axis, inches
Hydrogen Flow: 0.082 cfs = 0.94 ft/sec; Average Air Velocity: 25 ft/sec = 18 mph		Hydrogen Flow: 0.33 cfs = 3.7 ft/sec; Average Air Velocity: 39 ft/sec = 27 mph	
2	11	[2]5	5
[2]2	3	12	10
6	2	6	14
4	[2]2	4	26
Hydrogen Flow: 1.0 cfs = 11.4 ft/sec;		2	0
Average Air Velocity: 39 ft/sec = 27 mph		11	0
13	4	6	5
[2]8	17	2	14
14	17		
2	37		

[1] No hydrogen detected within analytical accuracy of 0.03 percent hydrogen.
[2] Positions below port.

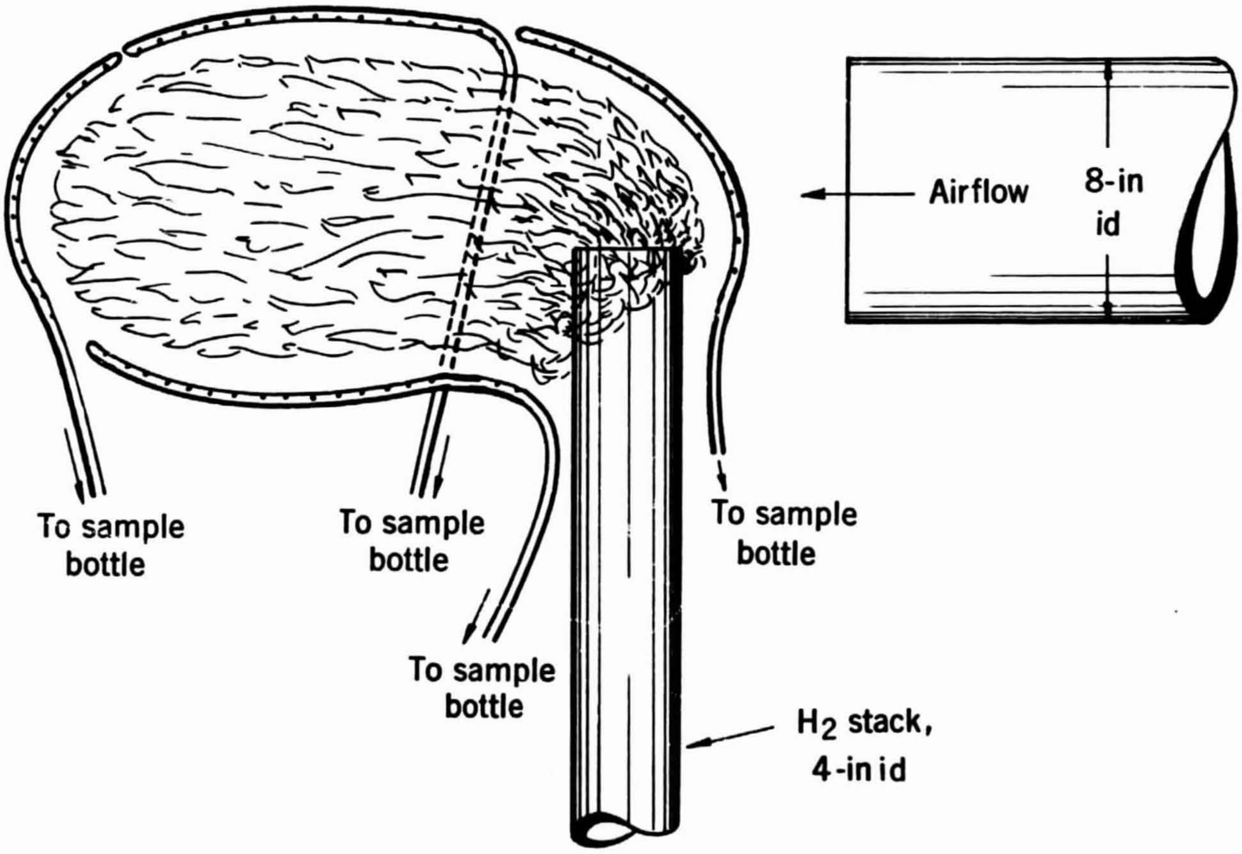

FIGURE 8. - Sampling Equipment for Hydrogen Stripping by Crosswinds.

TABLE 12. - Heights of hydrogen peaks on gas chromatographic charts. (Analyses of samples taken with integrating probes.)

Probe position, distance from flame envelope, inches	At upstream end of flame envelope, above burner, inch	Above flame envelope, inch	At downstream end of flame envelope, inch	Below flame envelope, inch
6	Zero	Zero	[1]0.06	Zero
4	Zero	0.06	.08	Zero
2	0.07	.11	.14	0.09
1	Zero	.06	.07	.08
[2]2	Zero	.08	.11	.11

[1]0.03% (accuracy of analysis) = peak height of 0.8 inch.
[2]Probe is inside flame.

Blowback of Hydrogen Diffusion Flames by Winds

The possibility of flame being blown back into a horizontal flare stack by wind and thus damaging the stack was also investigated. An array of thermocouples was placed in a horizontal 4-inch-id stack through which hydrogen flowed. This stack was faced by a horizontal 8-inch-id stack, from which an opposing stream of air flowed. The thermocouples were used to measure temperatures at a number of points under varying conditions of opposing air and hydrogen flows. Temperatures were recorded by a fast-response oscillograph. Average temperatures recorded ranged up to 1,900° F, with transient maximum temperatures about 150° F higher. Because the melting point of stainless steel is about 2,700° F there is no danger of a water-cooled stainless steel duct melting because of a hydrogen diffusion flame being blown into it by winds. Figures 9-11 show the average temperatures as a function of distance into the stack from its port. Except for the lowest hydrogen flow (fig. 9), the temperatures in the stack decrease monotonically from the port towards the base of the stack. For the lowest hydrogen flow, a local maximum temperature occurred 3 inches down the stack. For the highest air flow and the same hydrogen flow, the temperature at the 3-inch level was about the same as at the port (fig. 9). Although these temperature profiles do not clearly locate the flame position, they are significant in establishing the temperature levels that may be expected inside a hydrogen flare stack facing into an opposing wind. The possibility that the temperatures observed were affected by nonuniform wall temperatures was discounted by showing that the outside temperature of the first 6 inches of stack wall was about 1,600° F all around the tube. The temperature profiles in figures 9-11 are therefore longitudinal.

Samples taken at points where temperatures were measured were analyzed for combustion products (tables 13-14). The raw water-free analysis of the products is given, together with the computed water-containing products and the reactants that would yield these products on combustion. The reactant compositions show that when the hydrogen velocity was 12 ft/sec against an opposed wind of 45 ft/sec, the compositions were flammable to a depth of 4 inches but not at depths of 5 and 6 inches (table 13 and fig. 12). On the other hand, when a hydrogen velocity of 38 ft/sec was opposed by a wind velocity of 42 ft/sec, flammable compositions extended only as far as 2 inches,

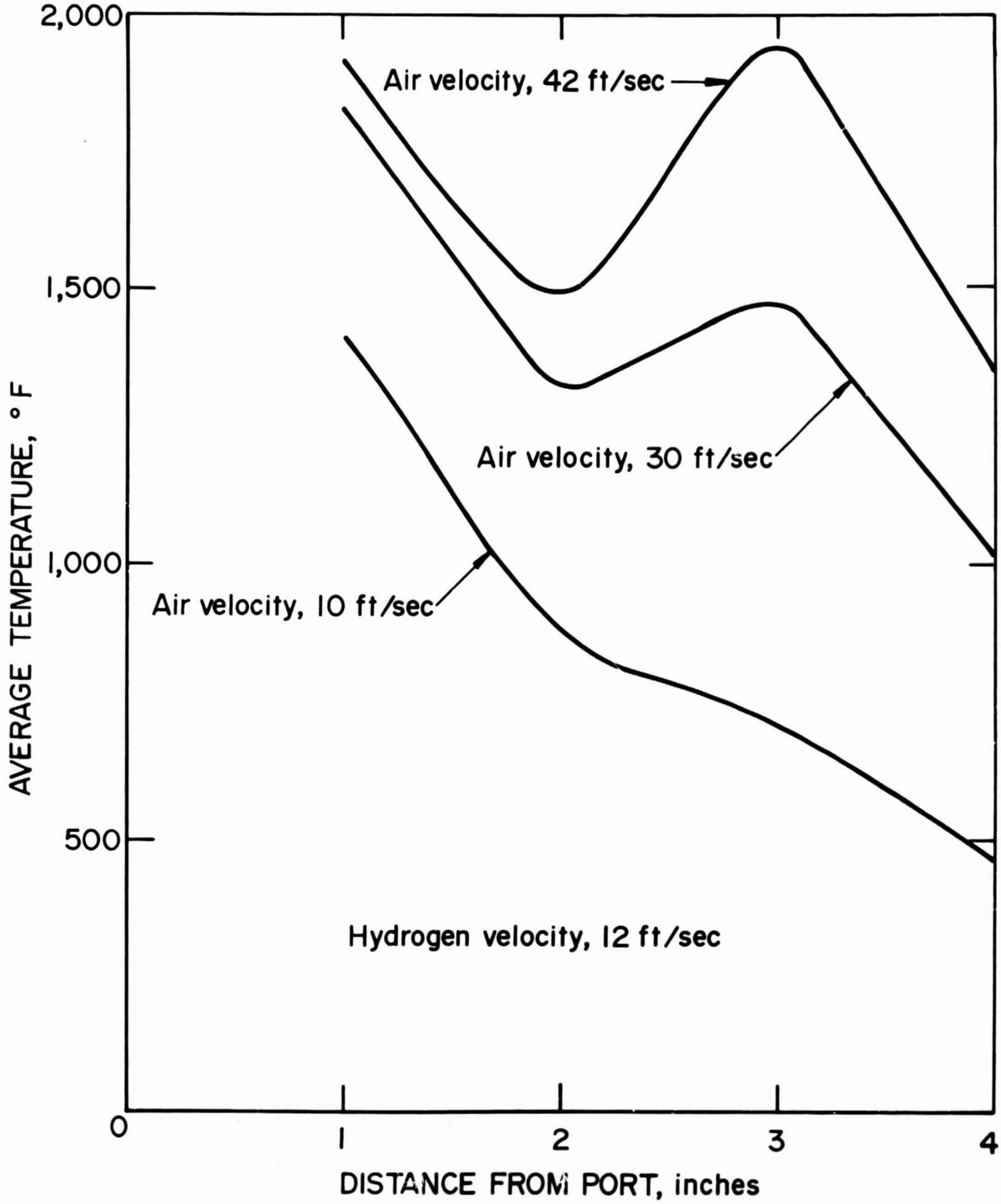

FIGURE 9. - Average Temperature Observed Inside a 4-Inch-ID Stack Burning at a 12 ft/sec Hydrogen Velocity and Facing Into Air Blast.

with compositions at the 3- and 4-inch levels being in the nonflammable range (table 14 and fig. 12). Visual observation indicated that the flame was blown

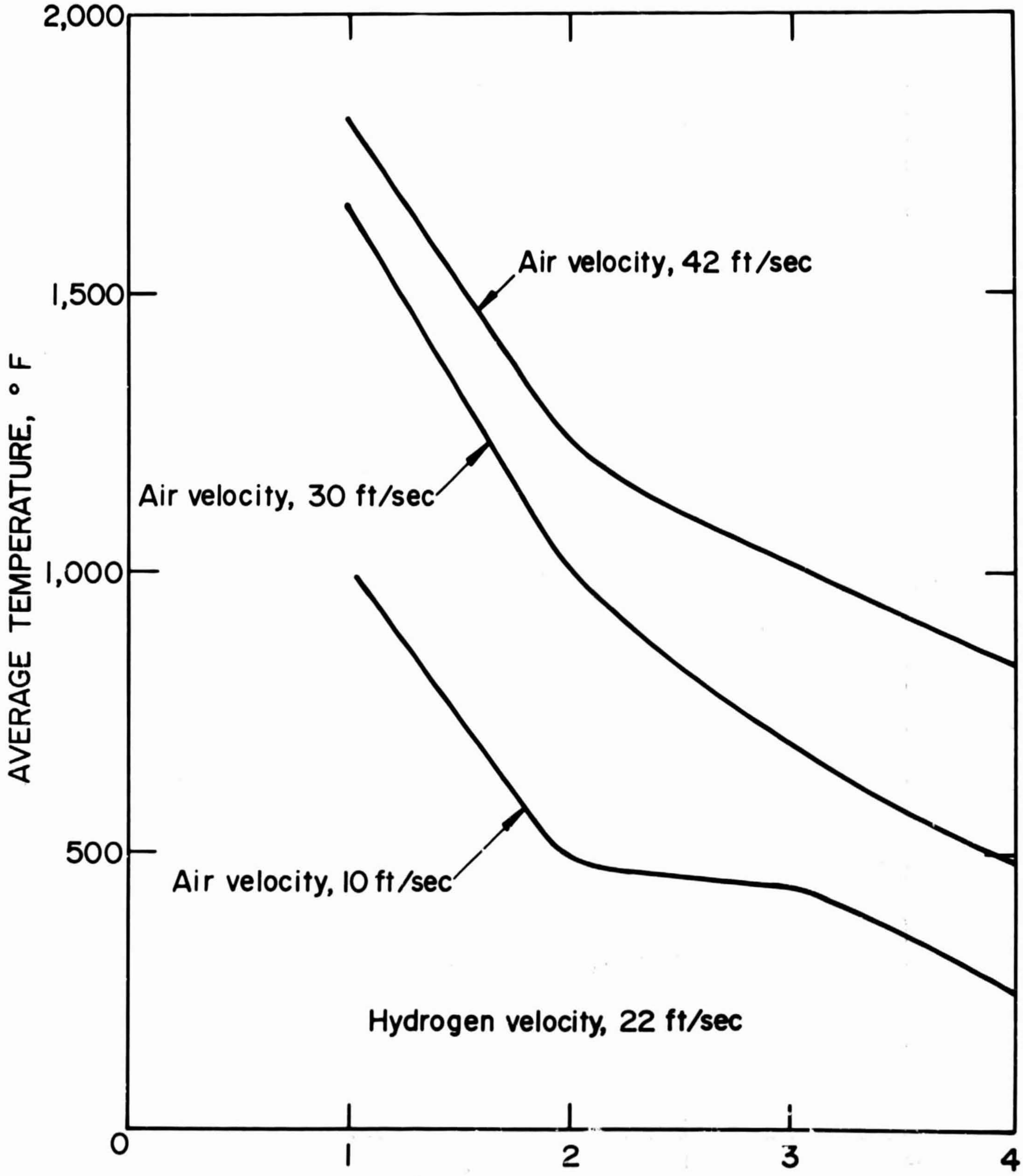

FIGURE 10. - Average Temperature Observed Inside a 4-Inch-ID Stack Burning at ~ 22 ft/sec Hydrogen Velocity and Facing Into Air Blast.

into the stack about 4 to 6 inches, for a hydrogen flow of 12 ft/sec and about 3 inches for a flow of 38 ft/sec.

TABLE 13. - Temperatures and analyses of gases inside of a horizontal 4-inch-id diffusion flame burner, facing into an opposing wind. Hydrogen velocity, 12 ft/sec; axial air velocity, 45 ft/sec.

Distance from burner mouth, inches	Observed[1] average temperature, ° F	Observed composition of products, mole			Computed composition of products, mole fraction				Reactants, mole			Computed adiabatic reaction temperature, ° F
		H_2	N_2	O_2	H_2	N_2	O_2	H_2O	H_2	N_2	O_2	
2	1,485	0.198	0.700	0.054	0.163	0.576	0.045	0.216	0.379	0.576	0.153	2,800
3	1,945	.598	.382	.005	.508	.325	.004	.163	.671	.325	.086	2,270
4	1,330	.594	.362	.014	.524	.319	.012	.145	.669	.219	.085	2,040
4	1,330	.632	.318	.029	.580	.292	.027	.101	.681	.292	.078	1,500
5	-	.804	.180	.010	.752	.168	.009	.071	.823	.168	.045	1,090
6	-	.864	.110	.008	.843	.108	.008	.041	.884	.108	.029	690

[1] Separate run.

TABLE 14. - Temperatures and analyses of gases inside of a horizontal 4-inch-id diffusion flame burner, facing into an opposing wind. Hydrogen velocity, 38 ft/sec; axial air velocity, 42 ft/sec.

Distance from burner mouth, inches	Observed average temperature, ° F	Observed composition of products, mole			Computed composition of products, mole fraction				Reactants, mole			Computed adiabatic reaction temperature, ° F
		H_2	N_2	O_2	H_2	N_2	O_2	H_2O	H_2	N_2	O_2	
1	1,440	0.180	0.652	0.090	0.166	0.600	0.083	0.151	0.344	0.652	0.172	2,080
2	815	.584	.356	.017	.525	.321	.015	.139	.664	.321	.085	1,970
3	-	.820	.148	.012	.793	.143	.012	.052	.845	.143	.038	836
3	-	.802	.182	.011	.751	.170	.010	.069	.820	.170	.045	1,080
4	35	.878	.102	.013	.860	.100	.013	.027	.888	.100	.027	330

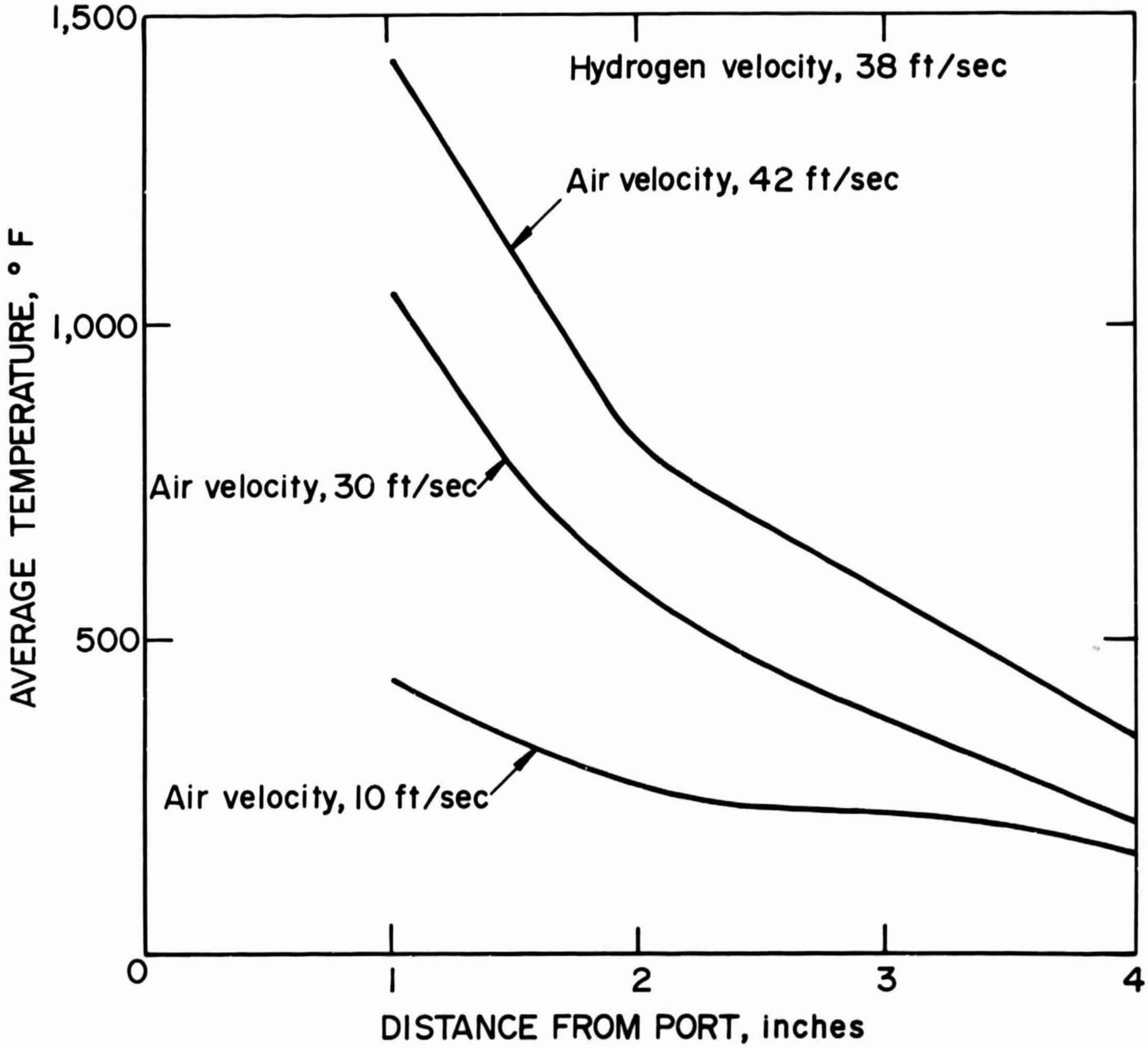

FIGURE 11. - Average Temperature Observed Inside a 4-Inch-ID Stack Burning at a 38 ft/sec Hydrogen Velocity and Facing Into Air Blast.

The reactant and product compositions were used to compute adiabatic reaction temperatures. Calculated adiabatic flame temperatures were considerably higher than the experimental temperatures. This is to be expected because the calculations assume that there is no heat loss to the walls. As such, they may be considered to set an upper limit to the temperatures produced by hydrogen diffusion flames blown into a duct. Only at the 2-inch sampling point with low flows of hydrogen was the computed temperature high enough to damage an uncooled stainless steel flare stack. Apparently blowback of flames under conditions comparable to these will not endanger water-cooled flare stacks.

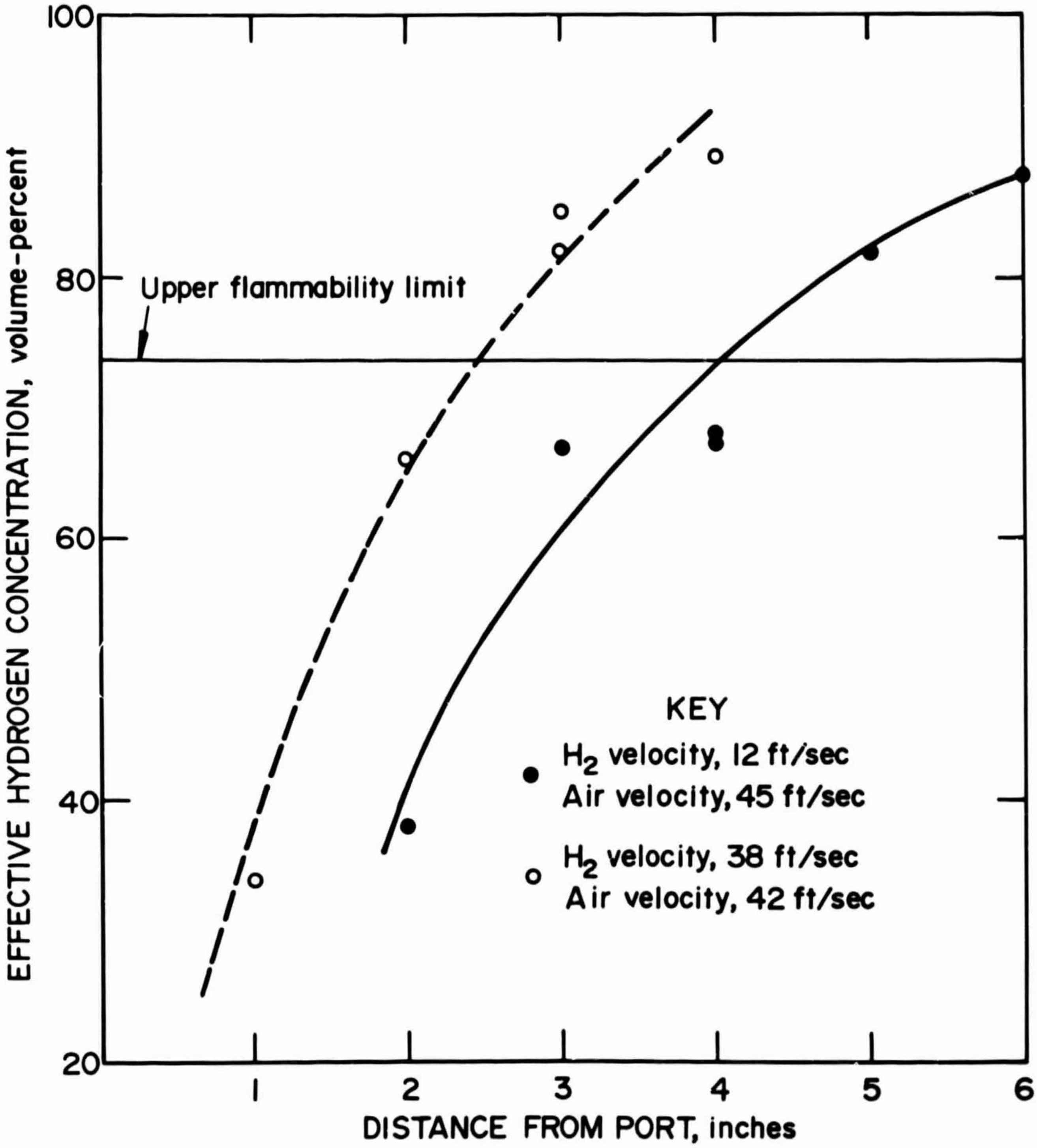

FIGURE 12. - Effective Hydrogen Concentration in 4-Inch-ID Stack With Diffusion Flame Burning Against Opposed Wind.

Experiments were performed to determine the position of the stagnation point of the wind blowing into the cavity formed by the stack, which was effectively closed at the opposite end. Static and total pressure heads were measured by Pitot tube at various points inside and outside of the 4-inch-id stack closed at the far end; there was no hydrogen flow, and wind was blowing against the stack with an average velocity of 58 ft/sec (table 15). Readings are time averages taken over a period of about 1 minute. Slow-response slope gages were used to measure the pressure heads. The readings provide no information about instantaneous velocities or directional changes of the flow. Only the rough coincidence of flame position and the location of the stagnation point of the wind blown into the stack are considered significant.

TABLE 15. - Total and static pressures and corresponding air velocities produced by a wind from an 8-inch-id duct blowing against a coaxial 4-inch-diameter horizontal stack

Distance inside 4-inch stack, in.	Radial distance from top edge of 4-inch stack, in.	Total pressure, inches of water	Static pressure, inches of water	Calculated air velocity, ft/sec
[1]5	0.25	1.2	[1]0.3	77
	1.25	1.4	[1].3	84
	2.25	1.5	[1].3	86
	3.25	1.6	[1].3	89
[1]3	.25	1.1	[1].1	71
	1.25	1.5	0	77
	2.25	1.9	.1	86
	3.25	1.9	0	89
0	.25	1.2	.8	41
	1.25	1.7	1.6	21
	2.25	2.0	1.6	41
	3.25	1.8	1.6	29
2	.25	2.5	2.4	21
	1.25	2.3	2.2	21
	2.25	2.6	2.2	41
	3.25	2.6	2.1	46
4	.25	2.6	2.6	0
	1.25	2.5	2.5	0
	2.25	2.6	2.4	29
	3.25	2.6	2.6	0
6	.25	2.6	2.8	[1]29
	1.25	2.7	2.8	[1]21
	2.25	2.6	2.8	[1]29
	3.25	2.7	2.8	[1]21
8	.25	2.7	2.8	[1]21
	1.25	2.7	2.5	29
	2.25	2.5	2.8	[1]35
	3.25	2.7	2.8	[1]21

[1]Distance outside 4-inch stack. Distance between 8-inch duct and 4-inch stack = 12 inches. Average air velocity from 8-inch duct = 39 mph = 58 ft/sec.

Though no hydrogen flow was used in these experiments, the location of the stagnation point is probably the same as with a low hydrogen flow; the velocity pressure heads due to low flows of hydrogen are much less than the velocity pressure head of the wind in these experiments. The peak velocities reported in table 15 agree roughly with velocities expected from flowmeter readings; the latter correspond to an average velocity of 58 ft/sec from the 8-inch duct. Assuming that the flow profile was about that for turbulent pipe flow (16), the velocity in the axial core of the stream would be about 70 ft/sec. The agreement was good between velocities based on the two types of measurements, suggested that the stagnation distance was located correctly. Thus the flame tends to position itself at about the stagnation point of the wind blowing into the stack.

Another conceivable interpretation is that the distance that the flame is blown back into the stack by wind is determined by the compression of the oncoming hydrogen and that the maximum flame penetration can be predicted from the perfect gas law for a supposed stagnant column of hydrogen. According to this concept, the depth of the penetration would depend on the length of the stack and not on its diameter. However, this concept was shown to be invalid by experiments with 2-inch- and 4-inch-id stacks, 3 feet long. Flame penetrated deeper into the 4-inch stack than into the 2-inch stack when air velocities were the same for both sets of experiments, and the hydrogen flow was 40 ft/sec through the 4-inch stack and 23 ft/sec through the 2-inch stack; the flame penetrations were 3 inches and ½ inch, respectively. Computations based on velocity heads and friction with the stack walls did not correlate with actual flame positions.

Blowout Limits of Hydrogen-Nitrogen Diffusion Flames in Crosswinds

An earlier section of this paper dealt with blowout limits in still air of flames of hydrogen and nitrogen mixtures heavily diluted with nitrogen; ratios of hydrogen to nitrogen at blowout were determined at various flows of nitrogen. Since flows with high concentrations of inerts are often encountered in the operation of flare stacks it was reasonable to examine the increase due to a crosswind in the hydrogen-inert gas ratio required for stable burning. Experiments were performed in which winds of various velocities impinged laterally on a diffusion flame from an upright 4-inch stack (table 16). Within the experimental uncertainty, the blowout ratios of flames of these mixtures burning in winds of up to 50 ft/sec are not significantly different from those in still air. It was observed, however, that the winds drove flames into the stack as much as a foot from the port.

These three studies of hydrogen diffusion flame characteristics show that winds do not create an additional hazard in flare stack operation attributable to stripping of hydrogen from the flame, blowing of flame into the stack, or excessive instability of hydrogen-inert gas flames.

TABLE 16. - Effect of crosswind on blowout limits of hydrogen-nitrogen diffusion flames on a 4-inch-diameter stack

Average wind velocity, ft/sec	Hydrogen, percent	Stack flow, ft^3/sec		Reynolds No.	Velocity, ft/sec
		Nitrogen	Hydrogen		
[1] 0	8.7	0.174	0.0267	4100	2.29
12.7	18.0	.117	.0258	2900	1.64
15.3	15.3	.147	.0267	3530	1.99
20.5	15.3	.152	.0266	3680	2.04
22.5	14.5	.159	.0272	386[illegible]	2.13
30.8	15.3	.146	.0260	3550	1.97
32.3	15.3	.148	.0267	3590	2.00
41.6	18.0	.117	.0259	2900	1.64
45.1	16.7	.130	.0262	3190	1.79
48.5	16.7	.132	.0260	3230	1.81
54.5	16.0	.142	.0263	3440	1.92

[1] Averages include data previously reported in table 7.

SUMMARY

The safe operation of flare stacks raises problems of flame instability due to (1) low and high flows of hydrogen; (2) dilution of hydrogen with inerts; (3) heating hazards related to the temperature of the flame and to its length which in turn is related to its burning rate; and (4) the effect of winds upon flame shape, flame position, and the conceivable stripping of unburned hydrogen. Laboratory experiments supplemented with some field experience provide data that can be used to anticipate the existence and degree of these hazards. For example, considering a 52-inch-diameter flare stack the minimum flow required to avoid flamedip is predicted to be about 0.18 lbs/sec of hydrogen. The minimum flow at which blowout would occur from an 18-inch stack is predicted to be about 140 lbs/sec of hydrogen. Temperatures across large hydrogen diffusion flames may approach about 3,600° F, but a more typical value is about 2,600° F. Other specifics such as flame height can be computed when operational parameters, such as flow, are known.

REFERENCES

1. Barr, John. Diffusion Flames. Paper in 4th Symposium (International) on Combustion. Williams and Wilkins Co., Baltimore, Md., 1953, pp. 765-771.

2. Bluhm, W. C. How To Operate a Flare System Safely. Oil and Gas J., Aug. 28, 1961, pp. 73-77.

3. Bollinger, L. M., and D. T. Williams. Experiments on Stability of Bunsen Burner Flames for Turbulent Flow. Nat. Advisory Comm. Aeronaut. Tech. Note 1234, June 1947, 18 pp.

4. Burgess, D. Structure and Propagation of Turbulent Bunsen Flames. BuMines Bull. 604, 1962, 42 pp.

5. Coward, H. F., and G. W. Jones. Limits of Flammability of Gases and Vapors. BuMines Bull. 503, 1952, 155 pp.

6. Gordon, A. S., S. R. Smith, and J. R. McNesby. Study of the Chemistry of Diffusion Flames. Paper in 7th Symposium (International) on Combustion, Butterworths, London, 1959, p. 317.

7. Grumer, J. Flashback and Blowoff Limits of Unpiloted Turbulent Flames. Jet Propulsion, v. 28, November 1958, pp. 756-758.

8. Grumer, J., M. E. Harris, and V. R. Rowe. Fundamental Flashback, Blowoff and Yellow-Tip Limits of Fuel-Gas-Air Mixtures. BuMines Rept. of Inv. 5225, 1956, 199 pp.

9. Hajek, J. D., and E. E. Ludwig. How To Design Safe Flare Stacks. Petrol. Chem. Eng., v. 32, June 1960, pp. C31-C38; July 1960, pp. C44-C51.

10. Hawthorne, W. R., D. S. Weddell, and H. C. Hottel. Mixing and Combustion in Turbulent Gas Jets. 3d Symposium on Combustion, Flame and Explosion Phenomena. Williams and Wilkins Co., Baltimore, Md., 1949, pp. 266-288.

11. Karlovitz, B., D. W. Dennison, Jr., D. H. Knapschaefer, and F. E. Wells. Studies on Turbulent Flames. Paper in 4th Symposium (International) on Combustion, Williams and Wilkins Co., Baltimore, Md., 1953, pp. 613-620.

12. Lapin, A. Hydrogen Vent Flare Stack Performance. Ch. in Advances in Cryogenic Engineering, Vol. 21. Plenum Press, New York, 1967, pp. 188-206.

13. Lewis, B., and G. Von Elbe. Stability and Structure of Burner Flames. J. Chem. Phys., v. 11, 1943, pp. 75-97.

14. Maklakov, A. I. Oscillation of Diffusion Flames Appearing When There Is a Laminar Flow of the Ignitable Medium. Zh. Fiz Khim., v. 30, 1956, p. 708.

15. Peterson, P. Explosions in Flare Stacks. Chem. Eng. Prog., v. 63, No. 8, 1967, pp. 67-70.

16. Prandtl, L., and O. G. Tietjens. Applied Hydro- and Aeromechanics. Dover Publications, Inc., New York, 1957, pp. 48-49.

17. Putnam, A. A., and C. F. Speich. A Model Study of the Interaction of Multiple Turbulent Diffusion Flames. Paper in 9th Symposium (International) on Combustion. Academic Press, New York, 1963, pp. 867-877.

18. Reed, R. D. Factors for Safe Design of Operation of Flares and Flare Systems. Pres. at the Symposium on Explosion Effects and Flare Stacks. 63d Nat. Meet. AIChE, Feb. 18-21, 1968. American Institute of Chemical Engineers, New York, 1968, pp. 1-15.

19. Reider, R., H. J. Otway, and H. T. Knight. An Unconfined Large-Volume Hydrogen/Air Explosion. Pyrodynamics, v. 2, 1965, pp. 249-261.

20. Singer, J. M., and J. Grumer. Carbon Formation in Very Rich Hydrocarbon-Air Flames. BuMines Rept. of Inv. 6007, 1962, 80 pp.

21. Smith, S. R., and A. S. Gordon. Studies of Diffusion Flames. I. The Methane Diffusion Flame, J. Phys. Chem., v. 60, 1956, p. 759.

22. Thompson, W. R., and C. S. Boncare. Design and Development of a Test Facility for the Disposal of Hydrogen at High Flow Rates. Paper Q-6, Cryogenic Engineering Conf., June 13-15, 1966, Boulder, Colo., 12 pp.

23. Von Elbe, G., and J. Grumer. Air Entrainment in Gas Burners. Ind. and Eng. Chem., v. 40, No. 6, June 1948, pp. 1123-1129.

24. Von Elbe, G., and M. Mentser. Further Studies on the Structure and Stability of Burner Flames. J. Chem. Phys., v. 13, 1945, pp. 89-100.

25. Vranos, A., E. D. Taback, and C. W. Shipman. An Experimental Study of the Stability of Hydrogen-Air Diffusion Flames. Combustion and Flame, v. 12, June 1968, pp. 253-260.

26. Wohl, K., C. Gazley, and N. Kapp. Diffusion Flames. Third Symposium on Combustion, Flame, and Explosion Phenomena. Williams and Wilkins Co., Baltimore, Md., 1949, pp. 288-300.

INT.-BU.OF MINES,PGH.,PA. 15584