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Experimental Investigation of Pressure and Blockage Effects on Combustion Limits in H₂-Air-Steam Mixtures

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**EXPERIMENTAL INVESTIGATION OF PRESSURE AND BLOCKAGE
EFFECTS ON COMBUSTION LIMITS IN H₂-AIR-STEAM MIXTURES**

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ABSTRACT

Experiments with hydrogen-air-steam mixtures were conducted in the Heated Detonation Tube (43 cm diameter and 12 m long) to determine the region of benign combustion; i.e., the region between the flammability limits and the deflagration-to-detonation transition limits. Obstacles were used to accelerate the flame; these include 30% blockage ratio annular rings, and alternate rings and disks of 60% blockage ratio. The initial conditions were 110°C and one or three atmospheres pressure. A benign burning region exists for rich mixtures, but is generally smaller than for lean mixtures. Effects of the different obstacles and of the different pressures are discussed.

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EXECUTIVE SUMMARY

Combustion in hydrogen-air-steam mixtures can be very complex; the peak pressures and impulses can vary significantly depending on mixture composition, initial pressure and temperature, interaction region geometry, and the characteristics of obstacles that may be present. Some structures can survive the pressures generated by "benign" combustion (ordinary deflagrations), but may be threatened by more severe forms of combustion such as accelerating flames and detonations.

We conducted two major series of experiments. The primary purpose of these experiments was to determine the existence and magnitude of a region of "benign burning," defined by combustion pressures sufficiently low to prevent structural damage. The first series of tests employed a set of equally spaced "washer-" or ring-shaped obstacles that obscured 30% of the cross-sectional area of the Heated Detonation Tube (HDT). The second series employed an obstacle arrangement using alternate ring- and disk-shaped obstacles that blocked 60% of the cross-sectional area. These two obstacle configurations (connoted 30% BR (blockage ratio) and 60% BR) were intended to conservatively bracket the range of obstacles that could actually be encountered.

Seventeen tests were conducted in the first series, and 20 in the second. A temperature of 110°C (230 °F) was used for all tests; initial pressures were one and three atmospheres. For tests with steam, the primary hydrogen-air equivalence ratios tested were 2.38 and 5, although a few tests were also performed for $ER = 0.5$ and 1. The equivalence ratio is the ratio of fuel to oxygen in a mixture divided by the ratio of fuel to oxygen for a corresponding stoichiometric mixture. Hence for hydrogen-air-steam mixtures the equivalence ratio is the hydrogen mole fraction divided by twice the oxygen mole fraction. Mixtures with equivalence ratios more than one are called rich; mixtures with equivalence ratios less than one are called lean. Steam concentrations ranged from 0 to 55%. In addition, dry hydrogen-air tests were conducted for rich mixtures.

The conclusions from this work are summarized in Section 5. In addition to the quantitative results, several important qualitative conclusions can be inferred from this work.

1. A benign burning region exists for rich mixtures, but is generally smaller than for lean mixtures.

2. The combustion characteristics and limits depend on both the obstacle configuration and the initial pressure. Because of the limited data, it was not always possible to distinguish which of these two conditions more strongly affected the results. However, the data indicate that the combined effects of initial pressure and obstacle configuration were very important.

a. For rich dry mixtures, the triggering limit appeared to move slightly to mixtures containing less oxygen and more hydrogen with increasing blockage ratio, that is to less sensitive mixtures, but the data are inadequate to confirm this. A sensitive mixture is defined as one chemically reactive enough to support a detonation or high speed deflagration. Increasing pressure tended to move the triggering limit towards more sensitive mixtures, but the effect may also be small. However, increasing blockage ratio and decreasing initial pressure both appeared to move the flame acceleration limits to less sensitive mixtures; these two effects appeared to be independent and additive. The benign burning regions ranged from as little as 1% hydrogen to possibly as much as 5%.

b. For $ER = 5$, no significant reduction in triggering limit could be ascribed to obstacle effects, while decreasing initial pressure again resulted in a shifting of the triggering limit. No data are available for flame acceleration limits at 3 atmospheres; however, a pressure effect is noticeable by inference from the triggering limit. The combined effects of pressure and obstacle configuration were very evident; the flame acceleration limit changed approximately 13%. However, the separate influence of pressure and obstacles cannot be distinguished with existing data. The combined effects resulted in a reduction of the benign burning region from about 11% steam (3 atmospheres, 30% BR) to about 2% steam (1 atmosphere, 60% BR).

c. For $ER = 2.38$, the data implied that the combined effects of pressure and obstacles increased the flame acceleration limit from 30.5% steam (3 atmospheres, 30% BR) to a region of 37 - 40% steam (1 atmosphere, 60% BR).

d. For $ER = 1$, no effect of obstacle configuration was noticeable within the accuracy of the data.

3. For several compositional regimes, flame acceleration and DDT were not observed because the testing was not extended into sufficiently reactive compositions. It is expected that DDT would have been observed if more reactive mixtures had been tested.

There is no theory available to predict the various limits required to determine the benign burning region. Hence, the only way to determine these limits is to conduct tests.

1.0 INTRODUCTION

The purpose of this report is to present the results of flame acceleration tests of hydrogen-air-steam mixtures in the Heated Detonation Tube. In particular, the tests were conducted to determine the extent of the region of "benign burning" where the mixture would burn without significant flame acceleration or transition to detonation. Some of the tests were conducted with a 30% blockage ratio annular ring obstacle array, and some of the tests were conducted with a 60% blockage ratio ring/disk obstacle array. The emphasis of the tests was on rich mixtures where the benign burning region was expected to be narrow. However, some of the tests were conducted with stoichiometric mixtures (i.e., equivalence ratio (ER) = 1) and some with lean mixtures (ER < 1). The equivalence ratio is defined as the ratio of fuel to oxygen in a mixture divided by the ratio of fuel to oxygen in a corresponding stoichiometric mixture. In hydrogen-air-steam mixtures it is the hydrogen mole fraction divided by twice the oxygen mole fraction. Mixtures with equivalence ratios larger than one are called rich; mixtures with equivalence ratios below one are called lean.

Figure 1 shows the flammability limits for hydrogen-air-steam mixtures taken from Marshall [1] at initial temperatures of approximately 110°C (230 °F). The initial pressures for these tests varied from approximately 1 atmosphere for lean tests to 3.7 atmospheres for rich tests. Also shown are estimates of the deflagration-to-detonation transition (DDT) limit for a large (10 m) duct [2] and for a 0.36 m (14 inch) duct typical of the inner diameter of the obstacles in the Heated Detonation Tube calculated by S. Slezak. The DDT limit occurs approximately when the detonation cell size, λ , is equal to the duct diameter, or the inner diameter of obstacles in a tube with obstacles. The location of the DDT limit and the limit for significant flame acceleration are of importance because flame acceleration and detonation can lead to instantaneous peak pressures above the adiabatic isochoric complete combustion (AICC) pressure. The AICC pressure is sometimes called the constant volume explosion pressure. The region between the flame acceleration limit and the flammability limit is a region of "benign burning." There was concern that such a benign-burning region might not exist or be very narrow for rich hydrogen-air-steam mixtures, while a reasonably wide benign-burning region has been shown to exist for lean and stoichiometric hydrogen-air-steam mixtures.

With the 30% blockage ratio ring obstacles shown in Figure 2, Slezak in work carried out at Sandia National Laboratories, investigated the flame acceleration behavior of hydrogen-air-steam mixtures at equivalence ratios of 1.0 (stoichiometric) and 0.5 (lean) at one atmosphere initial pressure and 110°C in the Heated Detonation Tube (HDT). In addition, Slezak performed tests of hydrogen-air mixtures near the lean flammability limit at one atmosphere initial pressure and 110°C and 25°C. Sherman used the same apparatus to perform tests of hydrogen-air-steam mixtures on the rich side at three atmospheres initial pressure and 110°C at equivalence ratios 2.38 and 5.0, and with 0% steam

(the limit for rich hydrogen-air mixtures). Hence, comparisons between the work of the two researchers were limited because they studied different mixtures and operated at different initial pressures. In carrying out tests with the 60% blockage ratio ring/disk obstacles, Sherman investigated rich and lean compositions at one and three atmospheres initial pressure.

2.0 EXPERIMENTAL APPARATUS

The Heated Detonation Tube (HDT) [3] is composed of three stainless steel tubes bolted together. At the ignition end there is a short 91.4 cm (3 ft) tube of 40.6 cm (16 inch) internal diameter and 45.7 cm (18 inch) external diameter. The other two tubes are each 6.10 m (20 ft) long and of 43.2 cm (17 inch) internal diameter and 45.7 cm (18 inch) outer diameter. Hence the total length of the HDT is 13.1 m (43 ft). The mixtures were ignited with a Tayco ignition coil using 110-125 VDC obtained from a NiCad battery pack.

The 30% blockage ratio ring obstacles used in the first series of tests is shown in Figure 2; the 60% blockage ratio ring/disk obstacles are shown in Figures 3 and 4. The axial positions of the leading edge of the obstacles are shown in Table 1. The obstacles were placed in the longer tubes. Hence the short 0.914 m long tube was empty except for the igniter. The first obstacle was always placed in the larger internal diameter tube, with its leading edge against the shoulder formed by the smaller inner diameter of the short tube. Hence, the first obstacle was 0.914 m (3 ft) from the ignition end. The relative axial position of the obstacles was maintained by nuts and washers mounted on the eight 3/4" (19 mm) diameter threaded rods that passed through the eight holes in the obstacles. The threaded rods ran the entire length of the obstacle array. The rear end of the threaded rods butted against the HDT back plate, preventing axial motion of the obstacle array.

For strength, with the second set of obstacles, the first ring obstacle consisted of two rings in contact with one another. Therefore the axial positions of the other obstacles was shifted 1.27 cm (1/2 inch) away from the ignition end. For both obstacle sets, the obstacles were uniformly spaced one tube diameter apart, 0.432 m (17 inches). The first obstacle in the ring-disk set was a ring, as were obstacles 3,5,.....,27,29. The disks were placed between the rings and hence were obstacles 2,4,....,26,28. With the large cross sectional area of these obstacles there was no unobstructed line-of-sight path through the tube. This means the flame had to follow a tortuous path rather than a straight line down the center of the tube as in the 30% blockage ratio obstacle array. It was hypothesized that the increased turbulence so generated might increase the flame acceleration compared to an obstacle array of 60% blockage ratio rings.

The obstacles which had thermocouples mounted to measure combustion front time-of-arrival are also shown in Table 1. The time-of-arrival was determined by observing the time at which the measured temperature began to rise sharply. For the 60% blockage T

Table 1
Axial Location of the Thermocouples on Obstacles

Obst. Axial Position*			30% BR Rings	60% BR Ring/Disks	
No.	Inches	Meters	Thermocouples	Obst.	Thermocouples
1	36	0.914	Y	R	Y
2	53	1.346	Y	D	Y
3	70	1.778	N	R	YF
4	87	2.210	Y	D	N
5	104	2.642	N	R	YF
6	121	3.073	Y	D	N
7	138	3.505	N	R	Y
8	155	3.937	Y	D	N
9	172	4.369	N	R	Y
10	189	4.801	Y	D	N
11	206	5.232	Y	R	Y
12	223	5.664	N	D	N
13	240	6.096	N	R	Y
14	257	6.528	Y	D	N
15	274	6.960	N	R	YF
16	291	7.391	Y	D	YF
17	308	7.823	Y	R	Y
18	325	8.255	N	D	N
19	342	8.687	N	R	YF
20	359	9.119	N	D	N
21	376	9.550	Y	R	YF
22	393	9.982	N	D	N
23	410	10.414	Y	R	Y
24	427	10.846	Y	D	Y
25	444	11.278	N	R	YF
26	461	11.709	N	D	N
27	478	12.141	N	R	Y
28	495	12.573	Y	D	N
29	512	13.005	Y	R	Y

BR = blockage ratio

R = ring obstacle, D = disk obstacle,

N = no thermocouples mounted

Y = thermocouples mounted

YF = thermocouples mounted but never operated

* = axial position of ring/disk obstacles after the first one shifted 0.0127 m (1/2 inch) away from ignition end

ratio ring/disk obstacles, two thermocouples were placed on all the rings and on three of the disks. On the instrumented ring obstacles, one thermocouple was placed at the geometric center of the tube mounted on a cross bar; the other thermocouple was placed at the intersection of the cross bar and the annular ring near the top of the tube. Unfortunately, only about half of the thermocouples functioned after the obstacles had been placed in the HDT. The difficulties in working with the fine thermocouple wires in the cold of winter led to many of these failures. Because detonations were avoided in testing the ring/disk obstacles, few additional thermocouples failed until late in the test period. With the 30% blockage ratio ring obstacles, far

fewer thermocouples failed at the beginning of that test period, but additional ones failed throughout the test period. Several of the tests with the 30% BR ring obstacles generated severe pressure pulses which presumably caused the failure of thermocouples. By the end of both series of tests, a sufficient number of thermocouples had failed such that there was concern that too few of them functioned to accurately determine the combustion front speed of propagation down the tube.

The data acquisition system was triggered from a signal obtained from the thermocouple at the center of the first obstacle. When its signal indicated a rise of approximately 100°C, the data acquisition system was triggered using a LeCroy TG8610B trigger generator. The trigger signal was sent to the LeCroy 6810 digitizers which recorded the data, and to the LeCroy 8501 programmable clocks used to send timing signals to the digitizers. If the data acquisition system was not triggered, the test was noted as "no burn." The only data recorded for the no-burn tests were the initial conditions in the HDT and the fact that it was a no-burn test. Although there may have been some combustion in the "no-burn" tests, the flame was not vigorous enough to heat the center thermocouple on the first obstacle.

Flammability-limit tests are normally carried out in vessels without obstacles. Either the propagation of the flame front is tracked or the pressure rise after the igniter is activated is measured. A mixture is considered flammable if the flame front propagates the length of the vessel (usually upwardly or downwardly), or the pressure rise is above some arbitrary minimum. Marshall [1] defined the mixture as flammable if there was a minimum pressure rise of 6 kPa; Kumar [4] assumed the mixture was flammable if he saw flame propagation even part way through his test vessel, as measured by thermocouple temperature rise. A further cause of possible difficulty in comparing the flammability limits of different researchers may have been their use of different initial temperatures and pressures. Marshall [1] used an initial air partial pressure of 82 kPa (hence a total initial pressures of approximately 1 atmosphere for lean tests up to approximately 3.7 atmospheres for rich tests) and a range of initial temperatures, approximately 110°C; Kumar [4] tested at 100°C and 200°C at initial pressures from 20 to 51 kPa. Because of the differences in the experimental setup of flammability-limit tests and our flame acceleration tests, the HDT triggering limit may not be the same as the flammability limit but should be close to it.

In all tests in which the data acquisition system was triggered, the behavior of the system prior to triggering was recorded by using "pretrigger" mode. In pretrigger mode, data from the time just prior to triggering (typically 1/8th the total sample points) are retained, and data from after the trigger are appended. This permitted us to retain data on the early buildup of pressure. Our data acquisition system further permitted the use of up to three sampling speeds, one for the pretrigger

period, one for a "near" posttrigger period, and one for a "far" posttrigger period.

Three quartz piezoelectric pressure transducers were placed flush on the tube wall at the locations shown in Table 2. Note that the locations were not the same for both sets of obstacles. These transducers have the advantage of fast response, 500 kHz resonant frequency, and of being rugged. They have the disadvantage of not being able to measure steady-state pressure, or slow pressure changes below a frequency of approximately 3 Hz. Transducers P1 and P3 were PCB brand model 113A, and gauge P2 was a Kistler brand model 211B3. In all tests with the ring-disk obstacles and most tests with the 30% blockage ratio ring obstacles, the changes were rapid enough to avoid the low frequency loss of response. In tests with burn times of more than approximately one half a second, corresponding to flame propagation speeds of less than about 25 m/s, there may have been some loss of pressure transducer response due to the slow changes in pressure. It was found when the transducers were removed for calibration after the 60% blockage ratio ring/disk obstacle array tests, that transducer P2 had been placed coincident in axial location with one of the ring obstacles which was not the case with the 30% blockage ratio ring obstacles. The axial position of the obstacles in the second set was slightly different than in the first set as explained in Section 2.0. Hence its anomalously high readings in the second set of tests may indicate the effects of flow into corners.

Table 2
Pressure Transducer Locations

<u>Transducer</u>	<u>Axial Location, m</u>	
	<u>30% BR Rings</u>	<u>60% BR Ring-Disks</u>
P1	5.96	1.69
P2	8.73	8.73
P3	12.08	12.08

The pressure transducers were calibrated prior to the tests, between the first and second set of obstacle tests, and after the second obstacle tests. These are called pretest, intermediate, and post test in Table 3. The three transducers were nearly linear in response. Hence the measured pressure response of the transducers is given by the voltage output multiplied by the transducer sensitivity plus a zero offset. Only their sensitivity (voltage output/pressure input) is of concern. Any change in zero offset is accounted for by assuming the mean voltage output of the first 125 sample points represents the initial pressure as given just prior to the tests by an accurate static pressure gauge. The results of the transducer calibrations shown in Table 3 indicate only minor changes in transducer sensitivity. All calibrations were carried out at room temperature by Sandia personnel in the Secondary Standards and Instrument Repair Division. We do not have the capability to test piezoelectric pressure transducers at elevated temperatures.

However, in the PCB catalog for the model 113A, the specification (presumably the maximum) of the temperature coefficient is given as 0.01%/°F. For a temperature difference of $(230 - 70) = 160^{\circ}\text{F}$, this corresponds to less than 2% change in sensitivity.

Table 3
Pressure Transducer Sensitivity

<u>Trans.</u>	<u>Sensitivity in millivolt/psi</u>				<u>STD Dev./Mean</u>
	<u>Pretest</u>	<u>Intermediate</u>	<u>Post test</u>	<u>Mean</u>	
P1	7.805	7.737	7.783	7.775	0.0045
P2	9.527	9.327	9.593	9.482	0.0146
P3	7.974	7.826	7.870	7.890	0.0096

3.0 COMBUSTION BACKGROUND

In a brief study of the literature on the effect of obstacles on flame acceleration and DDT, Sherman, the first author, found two effects which seemed to be generic, at least in small-scale tests. The effect of obstacles on flame acceleration, from low speed burning to moderately fast flame propagation speeds, increases monotonically with increasing blockage ratio, at least up to large blockage ratios (over 90%). However, large blockage ratio obstacles can inhibit DDT. In this report, we consider the "flame acceleration limit" as the gas mixture composition at which the peak pressure exceeds the AICC pressure. If the results found in the study by Sherman for small-scale tests apply to the HDT tests, the flame acceleration limits should move outward to less reactive mixtures as the blockage ratio is increased, but the DDT limits should move inward to more reactive mixtures. However, because of the small number of tests and little or no DDT data, this hypothesis could not be confirmed.

We define the benign burn region as the compositional region between the triggering limit and the flame acceleration limit. In this region, the peak combustion pressure will not exceed the AICC pressure. Since the triggering limit is near the flammability limit, it is important to understand the behavior of the flammability limit with pressure. Our colleague, K. W. Boyack, reviewed the literature on the effect of elevated pressure on hydrogen-air flammability limits. Figure 5 is his update of the figure given in Coward and Jones [5] for hydrogen-air mixtures. Coward and Jones plot the results of References 6-8. References 9-11 are newer work. There is scatter in the value of the rich flammability limit of hydrogen-air mixtures at one atmosphere, and scatter in the effect of elevated pressure on the flammability limit. Three references [6,7,9], using initially room temperature, indicate that the effect of elevated pressure up to about ten atmospheres is to cause the flammability limit to move to lower values of hydrogen mole fraction; two studies [8,11] show the opposite effect; the work by Ale et al. [10] also shows the opposite effect, but the two reported data

points are so far apart in pressure that they may provide no information in the region of interest, i.e., 1-3 atmospheres. Three of four studies show that the lean downward flammability limit increases slightly with increasing pressure. Hence, the existing data are sufficiently contradictory to preclude drawing conclusions without further testing.

4.0 EXPERIMENTAL RESULTS

The experimental results with the 30% blockage ratios ring obstacle array are shown in Table 4; the results with the 60% blockage ratio ring/disk obstacle array are shown in Table 5. Shown in the tables are the experimentally determined values of maximum pressure for the three pressure transducers, the maximum impulse (the time integral of pressure), and the maximum speed of propagation of the combustion front down the tube determined from the thermocouple signals. Also shown are theoretically computed values of the adiabatic isochoric complete combustion (AICC) pressure, the Chapman-Jouguet (CJ) detonation pressure, the normally reflected CJ pressure, and the CJ detonation speed.

The pressure signals with the 60% blockage ratio ring/disks are more complex than those from the 30% blockage ratio rings. This is not surprising in view of the complex nature of the flow path and the expectation of the generation of complex shock wave patterns. The peak pressures observed are sometimes found in narrow peaks of duration less than one millisecond. We were concerned therefore that peak pressure alone might not be a good measure of potential structural damage. Hence we have carried out a computation of the impulse (per unit area). Our impulse calculations were carried out with a moving time window. The window selected was 5 milliseconds. A crude method of estimating the structural effect of a detonation load is to find the maximum impulse in a quarter of a natural period, the Sewell-Kinney criterion. Without better knowledge of the natural period of the steel structure of interest, we selected a period of 20 ms; i.e., a quarter-period window of 5 ms. If another value of the window used in calculating the impulse were deemed more suitable, the calculations of the impulse could be redone. The pressure data are stored digitally on magnetic tape and are available for future use. Because the initial pressure differs in different tests, we have defined the impulse as the time integral of the absolute pressure rather than the overpressure (pressure - initial pressure). We define

$$I(t) = \int_{t-\Delta t/2}^{t+\Delta t/2} P(t) dt \quad \Delta t = 5\text{ms.}$$

If the time integral of overpressure is negligible in the time window Δt , the above definition of impulse causes it to approach the value $P_0\Delta t$ rather than zero, where P_0 is the initial

pressure and Δt is the time window used in the integration, here 5 ms. In the figures used in this report, the maximum value of the impulse is shown. It was suggested that an "effective" or "mean" pressure be defined as the impulse divided by the period of the window. Although presentation of the data in this form has several potential advantages, we used impulse. In dynamic load analyses the load due to pressure spikes is often presented in terms of impulse.

4.1 Igniter Performance

The time period between the initiation of power to the Tayco igniter and the triggering of the data acquisition system was in the range 25-45 seconds. This time period then includes not only the warmup time for the igniter until ignition but some time for the flame to traverse the distance to the first obstacle. The igniter was able to function repeatedly. Sandia modified the plug that connected to the igniter in order to operate the plug at high temperature.

4.2 Definitions Associated With the Burn Region

The triggering limit is defined for this report as the limiting gas mixture which, after the igniter is turned on, the combustion triggered the data acquisition system. The data acquisition system was triggered when the thermocouple at the center of the first obstacle measured a temperature rise of approximately 100°C. Tests in which there was no triggering are indicated as "no-burn" tests, although there was presumably some minor combustion. We expected the triggering limit to be approximately equal to the corresponding flammability limit defined in the next paragraph.

The flammability limit is defined as the limiting gas mixture that will propagate a deflagration indefinitely far from the ignition source. Because of buoyancy effects there may be different flammability limits for upward, downward, and horizontal propagation. For lean hydrogen-air mixtures at room temperature and pressure, the upward, horizontal, and downward flammability limits are given as 0.041, 0.060, and 0.090 mole fraction of hydrogen [5]. For rich hydrogen-air mixtures at room temperature and pressure, the flammability limit is nearly independent of the direction of propagation and is given as 0.74 mole fraction of hydrogen. This flammability limit definition has been included because it is used in several references discussed in this document.

Table 4

Test Summary of 30% Blockage Ratio Ring Obstacle Tests

Velocities in meters/second. Pressures in MPa. Impulse in kPa-s (= Mpa-ms)

Group	Initial Conditions			Test No.	Experimental Values							Theoretical Values			
	% H2	Percent	Pressure ¹		Vmax	Pressure			Impulse			Vci	Paicc	Pci	Prcl
		Xsteam				P1	P2	P3	I1	I2	I3				
0% Steam	67.72	0.00	0.311	22	2400	1.490	3.132	4.377	5.15	5.99	5.17	2310	1.359	2.575	5.876
	69.80	0.00	0.309	19	1860	1.111	1.747	3.089	4.66	5.11	6.09	2323	1.316	2.489	5.657
	71.50	0.00	0.311	18	68	0.671	0.712	0.636	3.37	3.59	3.21	2367	1.264	2.375	5.370
	73.17	0.00	0.311	17	19	0.525	0.563	0.504	2.62	2.82	2.51	2344	1.214	2.283	5.138
ER															
ER=5	4.979	3.9	0.311	16	1322	1.077	1.430	1.682	4.46	5.37	5.74	2232	1.311	2.478	4.713
	4.980	6.2	0.311	15	93	0.701	0.743	0.658	3.50	3.76	3.36	2187	1.283	2.421	5.493
	4.982	7.9	0.311	14	76	0.664	0.706	0.638	3.33	3.54	3.22	2154	1.264	2.882	5.394
	4.996	10.2	0.311	13	20	0.548	0.581	0.526	2.74	2.91	2.61	2113	1.233	2.321	5.242
	4.993	10.6	0.290	10	19	0.538	0.579	0.513	2.65	2.79	2.49	2104	1.184	2.228	5.308
	4.977	12.2	0.311	12	13	0.506	0.540	0.486	2.52	2.71	2.41	2076	1.213	2.279	5.137
	4.991	14.1	0.310	11	0	0.435	0.467	0.424	2.17	2.34	2.13	2041	1.188	2.230	5.014
	4.979	16.0	0.310	9	0	0.324	0.324	0.323	1.61	1.64	1.61	2007	1.168	2.190	4.913
ER=2.38	2.378	27.0	0.309	21	2600	2.347	2.864	4.562	5.98	5.42	7.48	1848	1.337	2.529	5.786
	2.380	28.9	0.309	20	1320	1.297	2.183	2.704	5.00	6.44	6.71	1823	1.307	2.467	5.630
	2.380	31.0	0.309	8	104	0.738	0.783	0.712	3.67	3.92	3.49	1797	1.281	2.416	5.801
	2.369	33.1	0.308	6	27	0.555	0.589	0.529	2.77	2.96	2.65	1772	1.250	2.353	4.906
	2.387	39.0	0.308	7	0	0.324	0.328	0.324	1.62	1.64	1.63	1696	1.164	2.180	4.906

(1) 3 atmospheres = .304 MPa

Table 5

Test Summary of 60% Blockage Ratio Ring/Disk Obstacle Tests

Velocities in meters/second. Pressures in MPa. Impulse in kPa-s (= Mpa-ms)

Group	Initial Conditions			Test No.	Experimental Values							Theoretical Values			
	% H2	Percent Xsteam	Pressure ¹		Vmax	Pressure			Impulse			Vci	Paicc	Pci	Prci
						P1	P2	P3	11	12	13				
0% Steam	71.52	0.00	0.102	42	682	---	1.241	0.640	---	2.94	1.78	2334	0.412	0.777	1.756
	73.26	0.00	0.103	27	840	0.271	0.738	0.597	1.35	2.00	1.82	2344	0.403	0.759	1.707
	74.65	0.00	0.102	28	690	0.254	0.480	0.477	1.24	1.85	1.79	2351	0.385	0.723	1.619
	75.84	0.00	0.102	36	111/298 ²	0.168	0.177	0.172	0.84	0.91	0.86	2258	2.358	0.373	0.698
	71.69	0.00	0.293	43	667	0.861	2.614	1.977	4.13	5.36	5.55	2335	1.185	2.233	5.048
	75.90	0.00	0.306	37	0	0.323	0.330	0.326	1.62	1.64	1.62	2358	1.119	2.096	4.673
ER															
ER=5	5.288	16.8	0.101	26	500	0.243	0.511	0.467	1.21	1.61	1.87	1979	0.363	0.706	1.582
	5.011	18.9	0.105	29	144	0.197	0.216	0.207	0.96	1.06	1.01	1956	0.371	0.693	1.543
	5.085	17.5	0.304	39		no burn									
	4.990	16.6	0.301	40		no burn									
ER=2.38	2.383	29.9	0.102	41	582	0.288	0.600	0.632	1.41	1.94	1.87	1811	0.426	0.804	1.831
	2.391	35.8	0.105	25	635	---	0.883	0.543	---	2.87	1.89	1736	0.411	0.771	1.744
	2.375	37.4	0.109	24	556	---	---	---	---	---	---	1704	0.415	0.777	1.760
	2.371	38.0	0.102	35	240	0.186	0.189	0.181	0.92	0.95	0.90	1709	0.389	0.730	1.644
	2.380	39.4	0.101	30	354	0.255	0.727	0.488	1.27	2.26	1.96	1690	0.379	0.710	1.594
	2.391	51.5	0.130	34		no burn									
	2.487	36.5	0.305	38	65	0.449	0.465	0.451	2.24	2.34	2.26	1726	1.171	2.197	4.954
ER=1	0.999	50.0	0.102	31	205	0.261	0.520	0.393	1.29	2.02	1.93	1595	0.406	0.763	1.727
	1.002	55.0	0.102	32	0	0.102	0.122	0.118	---	0.61	0.59	1541	0.381	0.712	1.601
ER=0.5	0.502	34.5	0.101	33	82	0.212	0.255	0.324	1.06	1.24	1.60	1408	0.356	0.663	1.481

--- means no signal

- (1) 1 atmosphere = 0.101 MPa
3 atmospheres = .304 MPa

- (2) A velocity of 111 m/sec was measured in the center of the tube and a velocity of 298 m/sec was measured near the tube wall. The difference is not understood.

The full-length burn limit is defined for this report as the limiting gas mixtures that produced a deflagration that traveled the full length of the HDT.

The flame acceleration limit is defined for this report as the limiting gas mixture in which the observed peak pressure first exceeds the Adiabatic Isochoric Complete Combustion (AICC) pressure. It can be taken as the composition boundary in which violent combustion leads to significant dynamic pressure loads.

The deflagration-to-detonation (DDT) limit is the limiting mixture for the given temperature, pressure, and enclosure geometry, at which a deflagration ignited by a weak source accelerates to a detonation. The presence of a detonation is identified by the combustion front speed being approximately equal to the Chapman-Jouguet (C-J) speed, and the peak pressures being equal to or above the C-J pressure.

The benign burn region is defined in this document as the range of gas mixtures (steam and hydrogen) between the triggering limit and the flame acceleration limit. The purpose of defining a benign burn region is to quantify the range of gas mixtures where it would be possible to burn hydrogen without resulting in significant dynamic loads. On this basis the triggering limit was selected as the outer boundary of the benign burning region, as shown in Figures 16-18, because at these mixtures it is possible to initiate a burn and reduce the amount of hydrogen. The flame acceleration limit was selected as the inner boundary of the benign burning region because at these mixtures the pressure rise is still moderate. As seen in the figures, there is a separation between the flame acceleration limits and the DDT limits. In the hydrogen rich region, Figures 16 and 17, this separation can be seen by comparing the DDT limits (shaded circles) to the flame acceleration limits (shaded squares) for the 30% blockage obstacles at 3 atmospheres initial pressure. Figure 18 includes these results. In the hydrogen lean region, this separation is seen by comparing the DDT limits to the flame acceleration limits for the 30% blockage obstacles at 1 atmosphere initial pressure. This separation between the DDT and the flame acceleration limits provides a margin of safety in the application of the data presented in this document.

4.3 Rich Hydrogen-Air (No steam) Tests

The results of the tests conducted with rich hydrogen-air mixtures (no steam) are shown in Figures 6-9.

4.3.1 30% BR Ring Obstacles - 3 Atmospheres

Figures 6a-c show the results obtained with the 30% blockage ratio ring obstacle array at 3 atmospheres initial pressure. The results in Figures 6a-c indicate that the triggering limit was not reached at the richest mixture tested, which was 73% hydrogen. The results from one series of tests (Figures 10c),

indicate that the magnitude of the impulse versus the composition decreases approximately linearly to the triggering limit, although there is a great deal of fluctuation. We know of no theoretical reason why this should be true. Fitting a straight line to any pair of points in Figure 10c would result in a wide scatter of the extrapolated intercepts. Nevertheless, one estimate of the triggering limit was made by linearly extrapolating the impulse in Figure 6c. This highly uncertain procedure results in an extrapolated triggering limit of approximately 75% hydrogen. This value is above the 1 atmosphere and room temperature flammability limit of 74% hydrogen given by Coward and Jones [5], but below the elevated temperature (100°C, 0.2 to 0.5 atmosphere) limit of 77% given by Kumar [4] and the extrapolated limit value by Marshall [1] of 78% hydrogen (T = 110°C, P = 3 atmospheres). For ease of understanding, these limit values are tabulated in Table 6.

It is important to keep in mind that this extrapolation procedure has no physical basis. It was only employed as a geometric method to estimate limits, in the absence of available measurements. The extrapolation necessarily involves a high degree of uncertainty, and should be used with great caution.

The extrapolated triggering limit at 0% steam (i.e., 75% H₂), is within the expected magnitude of other measurements of flammability limits. The mixture with the highest percent hydrogen that actually burned the full length of the HDT had 73.1% hydrogen. As seen in Table 4, this was also the highest concentration of hydrogen tested. Therefore it is known that the full-length burn is greater than 73% hydrogen.

If we define the flame acceleration limit as occurring when the peak pressure is equal to the AICC pressure, then Figure 6a shows that the flame acceleration limit is at 71% hydrogen. If we take the triggering limit to be about 75% hydrogen, the benign burning region for the 30% blockage obstacles at 3 atmospheres will extend from 71 - 75% hydrogen.

Based on Figure 6b, the corresponding DDT limit appears to be between 68 and 69% hydrogen.

For reference purposes, all the values for the triggering limits, full length burns, the flame acceleration limits and the DDT limits are presented in Table 7. Included in Table 7 are the results of Slezak taken in the HDT with the 30% BR ring obstacles. Where values are uncertain, ranges are given that may bracket or exceed the ranges determined experimentally or by subjective extrapolation; e.g., although the preceding discussion estimated the 3 atmosphere - 30% BR triggering limit as ~75% hydrogen, the entry in Table 7 is ~74-76%, which more accurately represents the associated uncertainty. All safety calculations should be based on this table, using conservative values where appropriate.

Table 6
Hydrogen-Air Rich Flammability/Triggering Limits

<u>Researcher/ Apparatus</u>	<u>Sherman HDT</u>	<u>Marshall FITS</u>	<u>Kumar</u>	<u>Coward & Jones</u>
% Hydrogen	~75*	78**	77	74
Temperature, °C	110	~110	100	21
Pressure, Atm.	3	~1-3.7	0.2-0.5	1
Orientation	Horizontal	Vertical	Vertical	Vertical
Configuration	30 BR obst.	no obst.	no obst.	no obst.
Diameter, m (in)	0.43 (17)	1.52 (60)	0.05 (1.97)	0.05 (1.97)
Length, m (in)	13.1 (516)	3.4 (134)	1.8 (71)	1.5 (59)
Detector	TC-trigger	Pressure	TC	Visual

TC-trigger = thermocouple trigger

TC = response of any of several thermocouples

* extrapolated value triggering limit

** extrapolated value flammability limit

4.3.2 60% BR Ring/Disk Obstacles - 1 Atmosphere

The results of the tests with the 60% blockage ratio ring/disk obstacles at 1 atmosphere pressure are shown in Figures 7a-c. The triggering limit was beyond 75.9% hydrogen which was the richest mixture tested. Application of the highly uncertain technique of linear extrapolation of the impulse values (I₁), shown in Figure 7c, gives a triggering limit of approximately 76.5% hydrogen. The entry in Table 7 is approximately equal to or greater than 76% hydrogen.

As seen in Figure 7a, the peak pressure is equal to the AICC pressure at 75% hydrogen and therefore, the flame acceleration limit was selected as 75% hydrogen. Hence the region of benign burning is approximately the range 75% to greater than 76% hydrogen. These values are shown in Table 7. Hence, the combined effects of reducing the pressure and changing the obstacle configuration has reduced the benign burning region from about 4% hydrogen to about 1% hydrogen; this was due primarily to the increase in flame acceleration limit to less sensitive mixtures. The relative importance of increasing pressure versus increasing obstacle blockage ratio could not be distinguished from the data.

No tests resulted in DDT, since more sensitive mixtures were not tested.

Table 7
Summary of Results

STEAM (HYDROGEN³) MOLE FRACTIONS, PERCENT

<u>ER</u>	<u>LIMIT</u>	<u>30% BR RINGS</u>		<u>60% BR RING/DISK</u>	
		<u>1 Atm.</u>	<u>3 Atm.</u>	<u>1 Atm.</u>	<u>3 Atm.</u>
0% ³ Steam (rich)	Triggering	-	~74-76 ¹	>76 ²	76
	Full length burn	-	>73	-	-
	Flame acceleration	-	71	75	~72-75
	DDT	-	68-69	-	-
5.0	Triggering	-	16	≥20 ²	<16.6
	Full length burn	-	12	-	-
	Flame Acceleration	-	5	17.7	(<16.6) ⁴
	DDT	-	0-2	-	-
2.38	Triggering	-	39	-	-
	Full length burn	-	>33	-	-
	Flame Acceleration	-	30.5	37-40	-
	DDT	-	27	<30	-
1.0	Triggering	55-60	-	~55	-
	Full length burn	55	-	-	-
	Flame Acceleration	50	-	~50	-
	DDT	25	-	-	-
0.5	Triggering	45-50	-	-	-
	Full length burn	45	-	-	-
	Flame Acceleration	31	-	-	-
	DDT	8-9	-	-	-
0% ³ Steam (lean)	Triggering	~6	-	-	-
	Full length burn	7	-	-	-
	Flame acceleration	9	-	-	-
	DDT	13	-	-	-

¹ Extrapolated from benign burn region data.

² Extrapolated from the flame acceleration region.

³ The values for 0% steam are given as percent hydrogen; all other entries are percent steam.

⁴ By inference from the triggering limit.

4.3.3 60% BR Ring/Disk Obstacles - 3 Atmospheres

Only two tests were conducted with the 60% blockage-ratio obstacles at 3 atmospheres initial pressure. This was not sufficient to accurately determine the limits behavior with the 60% BR ring/disk obstacles but the following paragraphs describe the information learned from these tests.

Figures 8a-c show the effect of different obstacle configurations for measurements with an initial pressure of 3 atmospheres with rich hydrogen-air mixtures and no steam. At 71.5% hydrogen the maximum pressure, maximum flame propagation speed, and maximum impulse are above the AICC values with the 60% blockage ratio ring-disk obstacles and below the AICC values with the 30% blockage ratio rings. This indicates that flame acceleration will occur at a higher hydrogen concentration with the 60% blockage obstacles than with the 30% blockage obstacles.

For the 60% BR ring/disk obstacles at 76% hydrogen, the pressure rise was very small. Hence this mixture must be near the triggering limit. The extrapolated estimate of the triggering limit for the 30% BR ring obstacles was $\approx 75\%$ hydrogen in section 4.3.1., although it could have been higher (Table 7 uses 74-76%); hence, the triggering limits could have been the same for the two obstacle configurations, within experimental error and the sparse data base. Consequently, even with the limited data, it appears that for the 60% BR ring/disk obstacles the benign burn region is probably smaller than the 30% BR ring obstacles at 3 atmospheres.

Figures 9a, b show the effect of initial pressure (1 vs 3 atmospheres) with the 60% blockage obstacles. For the same flame speeds and completeness of combustion, the peak combustion pressures should be proportional to the initial pressure (ignoring minor effects such as suppression of dissociation at the higher pressure). Therefore, we have divided by three the peak combustion pressures for the tests with initial pressure equal to 3 atmospheres. Hence the maximum pressures for the tests with one and three atmospheres initial pressure in Figure 9a, b are directly comparable. As seen in Figure 9b at 76% hydrogen the 1 atmosphere test had a burn velocity of 300 m/s while the 3 atmosphere test did not burn the full length of the tube. The plot of the burn pressure (Figure 9a) shows the same effect. This pair of tests implies that the triggering limit moves to less reactive mixtures as the pressure increases from one to three atmospheres.

4.4 Tests at ER = 5.0 (with Steam)

The results of the tests conducted at ER = 5 are shown in Figures 10-12.

4.4.1 30% BR Ring Obstacles - 3 Atmospheres

The results of the tests with the 30% blockage obstacles at 3 atmospheres initial pressure are presented in Figures 10a-c. As indicated by the labels "incomplete burn" in Figure 10b, the combustion front traveled only part way down the tube at 14.1% and 16.0% steam (58% and 57% hydrogen). As seen in Table 4 at an ER = 5 and 16% steam, the pressure rise was detectable but very small. Therefore 16% steam is taken as the triggering limit for an ER = 5 at 3 atmospheres with 30% blockage.

As seen in Table 4, at 12.2% steam the flame propagated down the entire length of the tube at a maximum speed of 13 m/s. Because of the low flame speed, 12% steam is taken as the full length burn limit. As seen in Figure 10a the peak pressure was equal to the AICC pressure at 5% steam. Therefore, the limit of significant flame acceleration was approximately 5% steam (64% hydrogen). The DDT limit (Figure 10b) was between 0% and 2% steam (67% hydrogen). These values are summarized in Table 7.

At ER = 5, the region of benign burning for the 30% blockage ratio ring obstacles at 3 atmospheres initial pressure is approximately 5% to 16% steam.

4.4.2 60% BR Ring/Disk Obstacles - 1 Atmosphere

The results of two tests with the 60% BR ring/disk obstacles at ER = 5 and one atmosphere initial pressure are shown in Figures 11a-c. Figure 11a indicates the peak burn pressure was equal to the AICC pressure at approximately 17.7% steam. Therefore, the flame acceleration limit is approximately 17.7% steam (56% hydrogen). No tests were performed in mixtures with the potential for DDT.

Linear extrapolation of the impulse in Figure 11c would again provide a highly uncertain estimate of the triggering limit; this value is greater than 20% steam (54% hydrogen), although it could be significantly higher.

More tests are needed with the 60% BR ring/disk obstacles at ER = 5.0 and one atmosphere initial pressure to have confidence in the tentative result just stated. In particular, the triggering limit is highly uncertain.

4.4.3 60% BR Ring/Disk Obstacles - 3 Atmospheres

The results of the two tests conducted with the 60% BR ring/disk obstacles at 3 atmospheres initial pressure are shown in Figures 12a, b together with those of the 30% BR ring obstacles at 3 atmospheres initial pressure. Both of these two 60% BR ring/disk obstacle tests were outside the triggering limit. As discussed in section 4.4.1, these mixtures would also be outside the triggering limit for the 30% BR ring obstacles at

the same initial pressure, 3 atmospheres. Therefore, the results imply that the triggering limit may be independent of the obstacle array used.

Comparison of the results of Figures 11a-c for tests with the 60% BR ring/disk obstacles at an initial pressure of 1 atmosphere, with the results shown in Figures 12a,b for the same obstacle array at an initial pressure of 3 atmospheres, shows a shift in the triggering limit. At the same mixture compositions that did not burn at 3 atmospheres initial pressure (16.6% and 17.5% steam), we had accelerated flames when the initial pressure was one atmosphere.

Since neither of the two tests with the 60% BR ring/disk obstacles at 3 atmospheres initial pressure triggered the system, we have no data on the corresponding flame acceleration or DDT limits. However, it is clear that the flame acceleration limit must be less than the triggering limit, which in turn is less than 16.6% steam. This shows that increasing the pressure moves the flame acceleration limit to more sensitive mixtures for the same obstacle configuration.

4.5 Tests at ER = 2.38

The results of tests at ER = 2.38 are shown in Figures 13-15.

4.5.1 30% BR Ring Obstacles - 3 Atmospheres

Figures 13a-c show the results of tests with the 30% BR ring obstacles conducted at 3 atmospheres initial pressure. As seen in Table 4 there was only a small pressure rise for an ER = 2.38 at 1 atmosphere initial pressure at 39% steam (test number 7). This says that the triggering limit is at approximately 39% steam (30.5% hydrogen).

As seen Figure 13a, the flame acceleration limit, the limiting composition at which the maximum pressure exceeds the AICC pressure, is at approximately 30.5% steam (35% hydrogen). Hence the benign burning region for the 30% BR ring obstacles at 3 atmosphere initial pressure is approximately between 30.5% and 39% steam. These values are tabulated in Table 7.

Based on Figures 13a,b, the DDT limit is at approximately 27% steam (36.5% hydrogen).

4.5.2 60% BR Ring/Disk Obstacles - 1 Atmosphere

The results for tests with the 60% BR ring/disk obstacles at 1 atmosphere initial pressure are summarized in Figures 14a-c. The maximum pressure, flame propagation speed, and maximum impulse values fail to follow a consistent trend. The indication is that there was an error in conducting test 35 or 30 (i.e., 38.0 or 39.4% steam, respectively).

These $ER = 2.38$ measurements were taken in mixtures with a steam mole fraction between 30 and 39%. The solid line connecting squares in Figure 17 gives a general indication of the flame acceleration limit for 60% blockage at 1 atmosphere pressure. This assumed limit line crosses the $ER = 2.38$ line at approximately 37% steam. This indicates that the error would be in test number 30. However, for both pressure and flame speeds, results from test 35 seem incongruous with respect to neighboring tests. Neglecting test 35, the pressures measured for test 30 (39.4% steam) would imply that the flame acceleration limit is higher than 39.4% steam, rather than the interpolated value of 37% steam estimated above. Table 7 shows this limit as between 37 - 40%, to include the uncertainty in the tests. However, if test 30 is correct, the actual value would exceed 39.4%. Additional data are required to clarify this situation.

4.5.3 60% BR Ring/Disk Obstacles - 3 Atmospheres

Only a single test was conducted at $ER = 2.38$ with the 60% BR ring/disk obstacles at an initial pressure of 3 atmospheres. The results are shown in Figure 15a, b in which they are compared to results from the 30% BR ring obstacles also at 3 atmospheres. The maximum flame propagation speed down the tube with the 60% BR ring/disk obstacles appears higher than that expected for the 30% BR ring obstacles, but their burn pressures are comparable.

4.6 Tests at $ER = 1.0$

4.6.1 60% BR Ring/Disk Obstacles - 1 Atmosphere

Tests 31 and 32 were performed with an $ER = 1.0$ using the 60% BR ring/disk obstacles at 1 atmosphere initial pressure with 50 and 55 percent steam mole fractions respectively. These two tests with the 60% BR ring/disk obstacles at an initial pressure of one atmosphere correspond to similar tests with 30% BR ring obstacles carried out by Slezak at 1 atmosphere initial pressure. At 55% mole fraction steam, with 60% BR ring/disk obstacles, the flame did not propagate the length of the tube and the pressure rise was very small. Hence the triggering limit must be not much greater than 55% steam. For the 30% BR ring obstacles at 1 atmosphere initial pressure, the flame did propagate the length of the tube, at 17 m/s.

At 50% mole fraction steam, the maximum flame propagation speed down the tube with 60% BR ring/disk obstacles at 1 atmosphere initial pressure was 205 m/s, and the pressure approximated the AICC pressure (see table 5). Because the pressure approximated the AICC pressure, this has been identified as the flame acceleration limit. In the corresponding test with the 30% BR ring obstacles at 1 atmosphere initial pressure measured by Slezak, the maximum flame propagation speed was 167 m/s and the pressure also approximated the AICC. These values have been included in Table 7.

Both sets of tests measured flame propagation outside the flammability limits measured by Marshall [1], and both showed significant flame acceleration at 50% steam mole fraction. From this limited number of tests, there does not appear to be a significant difference in behavior with the 30% and 60% blockage at $ER = 1.0$. This is a surprising result. Additional tests will be required to confirm this indication. These values have been included in Table 7.

4.7 Tests at $ER = 0.5$

4.7.1 60% BR Ring/Disk Obstacles - 1 Atmosphere

Only one test was carried out at $ER = 0.5$ with the 60% BR ring/disk obstacles and an initial pressure of 1 atmosphere, test 33. There was a benign burn at 34.5% mole fraction of steam. This is in accord with the corresponding test by Slezak using the 30% BR ring obstacles.

5.0 CONCLUSIONS

5.1 HDT Measurements

The summary of information on the location of the triggering limits, the full-length burn limits, the flame acceleration limits and the DDT limits is shown in Table 7 in section 4.3.1. These data were plotted in Figures 16-18 together with Marshall's flammability limit data [1] and estimates of the DDT limit. The DDT limit occurs when the detonation cell size is approximately the inner diameter of the obstacles. Only one point in Figure 16 is significantly outside the DDT limit estimate. In cases where a data point in Table 7 is given as more or less than a value, or a range, the point plotted is the authors' best estimate. Table 7 values and ranges should be used for quantitative calculations, with the appropriate applied conservatism.

Question marks appearing next to data points on the figures 16-18 flag potential uncertainties. The points in question were either extrapolated, interpolated within a range, or represent a potentially significant experimental error.

In order to maximize the utility of the data, many of the limits were estimated by extrapolation of the measured data. Such extrapolations involve a great deal of uncertainty. We recommend conservatism in the use of the data to account for the uncertainty.

Only for tests with the 30% BR ring obstacles on the rich side at 3 atmospheres initial pressure and on the lean side at 1 atmosphere initial pressure are there a sufficient number of tests to define all four of the limits discussed.

Figure 16 shows data for rich tests with the 30% BR ring obstacles at an initial pressure of 3 atmospheres, including triggering limits (open circles), full length burn limits (open triangles), flame acceleration limits (shaded squares), and DDT limits (shaded circles). Recall that the benign burning region was defined as the range of mixtures between the triggering limit and the flame acceleration limit.

The data for the rich tests with the 60% BR ring/disk obstacles at one atmosphere initial pressure, Figure 17, are less complete, showing only triggering and flame acceleration limits. More tests would be needed to amplify and confirm these results.

The data of Slezak for lean tests with the 30% BR ring obstacles at an initial pressure of one atmosphere are plotted in Figure 18. There were sufficient tests done at 1 atmosphere pressure to define the behavior, no tests were done at higher initial pressure.

The data for rich tests with the 60% BR ring/disk obstacles at 3 atmospheres pressure are too fragmentary to plot.

5.1.1 Hydrogen Rich Mixtures with 30% Blockage at 3 Atmospheres

The triggering, full-length burning, flame acceleration and DDT limits, shown in Figure 16, are nearly parallel lines. Hence, on the rich side, the benign burning ranges, in steam mole fractions (measured horizontally) and in hydrogen mole fractions (measured vertically), are nearly constant. For constant steam fraction, the benign burning regions is approximately 4-5% hydrogen in width. For constant hydrogen concentration, the width is about 4-5% steam. For constant equivalence ratio, the benign burning range depends on equivalence ratio: about 11% steam for $ER = 5$; about 8.5% steam for $ER = 2.38$.

A more conservative definition of a benign burning region, from the full-length burn limit to the flame acceleration limit, would reduce these ranges: about 2-3% hydrogen at constant steam fraction, and about 1.5-2.5% steam at constant hydrogen mole fraction. For constant $ER = 5$, the burning region is reduced to 7% steam.

The most liberal definition, from the triggering limit to the DDT limit, would increase these ranges significantly: 5-8% hydrogen for rich dry mixtures; about 6% steam for constant hydrogen concentrations; about 14-16% steam for $ER = 5$; and about 12% steam for $ER = 2.38$.

The above data show that, for the conditions of these experiments, there does exist a benign burning region on the rich side. Whether the size of the region is adequate for safe deliberate ignition schemes, assuming the geometry and conditions of interest are simulated by the the above experiments, depends on the speed at which conditions change compared to the time required for the igniters to burn the volume.

The second interesting conclusion from Figure 16 is the comparison of the triggering limits to Marshall's flammability limits [1]. The two lines are not parallel. The triggering limit is inside the flammable range down to $ER = 2.38$. Marshall's data were taken at elevated pressures ranging from about 2.8 atmospheres at $ER = 2.38$ to 3.7 atmospheres at the dry rich limit. If we assume that triggering limits should be the same as flammability limits, then the limit differences could be attributed to the differences in initial pressure. Hence, over this range of equivalence ratio, the two sets of data imply that increasing pressure widens the flammability limit. This conclusion would contradict our own observation that increasing pressure narrows the flammability limit, based on the trigger limits measured for 60% BR obstacles at $ER = 5$. The effect of pressure on flammability and triggering limits is discussed further in Sections 5.1.2 and 5.2.

5.1.2 Hydrogen Rich Mixtures with 60% BR Ring/Disk Obstacles at 1 Atmosphere Pressure

The most obvious conclusion from the triggering and flame acceleration limits shown in Figure 17 for the 60% BR Ring/Disk obstacles at 1 atmosphere initial pressure is that the benign burning region is much narrower than the benign burning region discussed at 3 atmospheres with 30% BR. The range of steam mole fractions in the benign burning region varies from about 5% near $ER = 1.0$ to about 2% at $ER = 5$. The corresponding hydrogen mole fraction ranges are only about 1-1.5% wide. For dry, rich hydrogen-air mixtures, the benign burning region may be as small as 1% hydrogen.

This narrowing of the benign burning region is very evident in Table 7. For dry rich mixtures, the combination of decreased pressure and increased obstacle obstruction reduced the benign burning range from about 4% hydrogen to as little as 1%. At $ER = 5$, the reduction was from 11% steam to as little as 2%. For $ER = 2.38$, the flame acceleration limit was increased by at least 6.5%, and possibly more than 9% steam; although we have no data for the corresponding triggering limit, the extrapolated line in Figure 17 implies that the benign burning region is only about 1-2% steam wide, much smaller than the 8.5% steam range seen for 3 atmosphere and 30% BR.

The triggering limit in Figure 17 is again not parallel to Marshall's flammability limit curve [1]. For much of the range the triggering limit is outside Marshall's flammable region. The difference is largest at $ER = 1$, where Marshall's initial pressure is ≈ 2.4 atmospheres. However, the conclusion on pressure dependence between the HDT data and Marshall's measurements is now opposite to that of Section 5.1.1 (i.e., HDT data compared to Marshall's data for equivalence ratio greater than 2.38). The assumption that increasing initial pressure moves the flammability limit to the left is consistent with our and Marshall's measurements at $ER = 1$.

5.1.3 Hydrogen Lean Mixtures with 30% BR Ring Obstacles at 1 Atmosphere

The results on the lean side shown in Figure 18 are very different from those on the rich side. There is a large difference between the flame acceleration and the DDT limits. The width of the benign burning region, defined from the triggering to the flame acceleration limits is in the range of 2.5% - 3% hydrogen. Since the limit curves are only slowly varying functions of steam mole fraction, the benign burning region corresponds to a large change in steam mole fraction. If we consider a hydrogen-air-steam mixture at $ER = 0.5$ in a volume where steam is condensing, the width of the benign burning region corresponds to a change of 14% steam but only 2.5% hydrogen.

5.2 The Effect of Initial Pressure

The primary purpose of carrying out experiments with the 60% BR ring/disk obstacles was to give an indication of the effect of obstacle geometry on the flame acceleration and DDT behavior of hydrogen-air-steam mixtures. Some of the tests in the data base were carried out at one atmosphere initial pressure and some at 3 atmospheres initial pressure. The higher pressure was, at least initially, of more interest. However, it was not initially realized that the pressure difference would have an effect on the results and complicate the comparison.

The limited data we have on the effect of pressure for the same obstacle set are shown in Figures 9, 11 and 12, and in Table 7. In some cases, direct comparisons can be made for different pressures with the same obstacle configuration. For 60% BR obstacles, the triggering limit is lower for 3 atmospheres compared to 1 atmosphere, although the effect could be very small (perhaps only 1% hydrogen). For the same obstacles, it also appears that the flame acceleration may also be lower, although the magnitude of the change cannot be determined from the data.

For $ER = 5$ and 60% BR, the increased initial pressure moved the triggering limit from above 20% steam to some value less than 16.6%. The flame acceleration limit must also have been reduced by the pressure effect, since the flame acceleration limit of about 17.7% at 1 atmosphere is already above the triggering limit at 3 atmospheres.

These data imply that the triggering and flame acceleration limits move to more reactive mixtures as the pressure is increased from one to three atmospheres, although this effect might only be a few percent steam or less. This is in accord with some of the experimental data on the effect of pressure on rich hydrogen-air mixtures. However, since both limits have moved, it is not clear whether the width of the benign burning region will change, or by how much. We also do not know how initial pressure might affect limits for other equivalence ratios.

Section 5.1 seems to provide contradictory evidence on the effect of initial pressure, as deduced by comparing our work to that of Marshall. In the rich hydrogen region, the comparison implies that increasing pressure widens the flammability limit; however, in the vicinity of stoichiometric conditions, the comparison implies the opposite - in agreement with our internal comparisons as shown in Figures 9-12. Considering our work, and the earlier work reported by Boyack, it is difficult to explain the discrepancies. If we apply higher confidence levels to our own measurements, we conclude that increasing initial pressure tends to narrow flammability limits, although the effect is relatively small - a few percent or less.

The basic problem with determining the effect of initial pressure is that the effect is small. Previous investigators had no reason to be overly concerned with relatively small effects. However, changes of a few percent in triggering and flame acceleration limits could have strong effects on benign burning regions, which are only a few percent wide themselves.

5.3 The Effect of Obstacle Geometry

The effect of obstacle geometry for rich dry mixtures at the same initial pressure of 3 atmospheres is shown in Figures 8a-c and in Table 7. The data imply, but do not prove, that the triggering limit moves to higher hydrogen concentrations (less sensitive mixtures) for higher blockage obstacles; however, the effect, if it exists, may be very small.

The evidence for an increase in flame acceleration limits is much stronger; with 30% BR, a test at 71.5% hydrogen showed no flame acceleration; but with 60% BR, a test at 71.7% hydrogen resulted in a highly accelerated flame. However, additional data would be required to quantify the magnitude of this effect, which may also be limited to a few percent hydrogen.

In contrast to these results for rich mixtures, the data for stoichiometric mixtures ($ER = 1$) do not show any clear effect of obstacle configuration on triggering or flame acceleration limits.

Based on our review of the literature (Section 3.0), we expected the more severe obstacle configuration ($BR = 60\%$) would move the flame acceleration limits to less sensitive mixtures, but probably would have little effect on the triggering limits. Our limited data indicate either that this effect may be small, or that it may depend on conditions of the tests that are not currently understood. More tests would be required to better establish the effect of obstacle configuration.

5.4 Combined Effects of Obstacles and Initial Pressure

One of the most significant results of these tests is that the combined effects of decreasing initial pressure and increasing blockage ratio raised the flame acceleration limits significantly. This narrows the region of benign combustion. For rich dry mixtures, the limit was raised from 71% hydrogen to 75%. For $ER = 5$, the increase was from 5% steam to about 18%. For $ER = 2.38$, the increase was from 30.5% steam to a value in the range 37 to 40% steam, or possibly higher.

Because of the limited data, it was not possible to separate out the effects of pressure and obstacle ratio. However, it is conceivable that the effects may be synergistic; i.e., that both effects together had a greater effect than would be observed by either effect separately. Indeed, the combined effect may be greater than the sum of the two separate effects.

5.5 Deflagration-to-Detonation Transition Limits

The only tests in which the DDT limits were observed were the rich tests with the 30% BR ring obstacles and 3 atmospheres initial pressure and similar lean tests at 1 atmosphere initial pressure. We computed the ratio of the inner diameter of the obstacle rings, d , to the detonation cell width, λ , for these tests to see if DDT limits corresponded to a given value of d/λ . We also did the same with the work of Brehm [13]. The DDT limit was found to roughly correlate with the ratio, d/λ , being in the range 0.3 to 1.0. This compares to the work of Peraldi, Knystautas, and Lee [13] who found $d/\lambda \approx 1.0$ for DDT. By this criterion, the onset of DDT should have been inhibited by the use of the 60% BR ring/disk obstacles. Without any tests in the DDT range with this set of obstacles, this cannot be verified.

Appendix A. Error Analysis

There are two kinds of errors. "Accuracy" represents the closeness of measurements to the true values. "Precision" refers to the way in which repeated observations conform to themselves; i.e., to the dispersion of the observations. Precision evaluations include estimates of mean values and deviations of the measurements, regardless of how closely the mean value approaches the "true" value. In general, precision varies with the square root of the number of observations upon which it is based.

For the HDT measurements reported in this paper, precision errors are believed to be greater than accuracy errors.

A.1 Estimates of Accuracy

The primary dependent variables are the four combustion limits discussed in Section 4.2. The independent variables that are used to compute these limits include: initial concentrations of hydrogen, air and steam; initial gas temperatures and pressures; combustion-generated pressures; and flame speeds.

A.1.1 Errors in Composition

The mole fractions of the three species are determined entirely by their partial pressures and the gas temperature. Pressure is measured with a Bourdon gauge; temperature is measured with a thermocouple.

This analysis is based on the work of Stamps et al. [14] and Tieszen et al. [3]. The theory is given in an article by Moffet [15].

For most tests, the order of filling the HDT is dry air, hydrogen, and steam. However, some tests at 3 atmospheres initial pressure and high steam mole fractions used the order dry air, steam, and hydrogen. It will be assumed that the uncertainty associated with these latter tests is the same as the majority of tests. Let

P_1, T_1 = absolute pressure and temperature after dry air fill

P_2, T_2 = absolute pressure and temperature after the H_2 fill

P_3, T_3 = absolute pressure and temperature after steam fill

Let ϕ = equivalence ratio. Functionally $\phi = \phi(P_1, T_1, P_2, T_2)$;
 X_s = steam mole fraction, $X_s = X_s(P_3, T_3, P_2, T_2)$.

The uncertainty, δR , of any dependent variable R , is a function of the independent variables X_i (T or P), the sensitivity of R to changes in X_i , and the associated errors in

the measurement of X_i , δX_i . R represents the measured values of the concentrations of air, hydrogen, and steam.

$$\delta R = \left\{ \sum_{i=1}^N \left[\frac{\partial R}{\partial X_i} \delta X_i \right]^2 \right\}^{1/2}$$

Each uncertainty, δX_i , is a combination of fixed and variable errors. A fixed error is any error that will not change during the course of the experiment, such as the tolerance on a pressure gauge. The variable error is estimated from the standard deviation of any fluctuations that occur during the recording of the variable, such as fluctuations in the digital temperature readout.

The error in the equivalence ratio is

$$\delta \Phi = \beta \frac{T_1 P_2}{T_2 P_1} \left\{ \left[\frac{\delta T_1}{T_1} \right]^2 + \left[\frac{\delta T_2}{T_2} \right]^2 + \left[\frac{\delta P_1}{P_1} \right]^2 + \left[\frac{\delta P_2}{P_2} \right]^2 \right\}^{1/2}$$

where β is the ratio of air moles to hydrogen moles at stoichiometric condition, 2.387. The error in the steam mole fraction, X_s , is given by

$$\delta X_s = \frac{T_3 P_2}{T_2 P_3} \left\{ \left[\frac{\delta T_2}{T_2} \right]^2 + \left[\frac{\delta T_3}{T_3} \right]^2 + \left[\frac{\delta P_2}{P_2} \right]^2 + \left[\frac{\delta P_3}{P_3} \right]^2 \right\}^{1/2}$$

The temperatures T_1 , T_2 , T_3 are measured by a single type K thermocouple inserted into one of the HDT wall ports. The temperature desired is the molar mean temperature of the gas in the HDT. The uncertainty is a combination of that due to nonuniformities of temperature in the tube, instrument error in the meter reading the thermocouple output, and possibly any stray voltages present. Looking at the references and from experience, the uncertainty may be $\pm 1^\circ\text{C}$. Conservatively assume $\delta T_i = 2^\circ\text{C}$. Since $T_i = 383\text{ K}$ for all tests, $\delta T_i/T_i = 0.005$.

Examining the pressure calibrations before and after the first set of tests, the shift in the calibrations is generally below 0.05 inches of Hg (1.27 mm). Conservatively assume that $\delta P_i = 0.10$ inches Hg (2.54 mm). For a fixed uncertainty, δP_i , the relative uncertainty $\delta P_i/P_i$, is highest at the lowest absolute pressure. The highest uncertainty will occur for the one atmosphere tests. For these tests, typically $P_1 = 7 - 25$ inches Hg. Hence at worst $\delta P_1/P_1 = 0.014$. The second pressure would be in the range 10 - 30 inches Hg. Hence $\delta P_2/P_2 = 0.010$. Assuming $P_2/P_1 = 2$, we obtain $\delta \Phi = 0.089$. For an equivalence ratio of 2.38, the error is $\pm 3.4\%$; the percentage errors would be lower for higher equivalence ratios.

The highest uncertainty in steam concentration is at the lowest values of steam. For 14% steam, $\delta X_s = 0.01$, or equivalently, $\pm 0.01/0.14 = \pm 7\%$. Both $\delta \phi$ and δX_s will be lower for the tests performed at higher pressures and steam concentrations. The actual errors about each measurement can be determined by applying the above equations to each data point. This was done, for example, in Reference 18.

A.1.2 Errors in Flame Speed

The thermocouples used to measure flame speeds are used only as time-of-arrival gauges; the magnitude of the reading is not important. Errors in flame speeds are believed to be negligible compared to other errors, because of their redundancy.

A.1.3 Errors in Combustion Pressure

The three dynamic pressure transducers were calibrated prior to the tests (see Section 2.0). The standard deviation from the mean ranged from about 0.5% to 1.5%.

The error in dynamic pressure measurements influences the determination of the flame acceleration limit. It is incorporated into the precision errors discussed below.

A.2 Estimates of Precision

The most important sources of error are related to precision. These are the errors related to the determination of the dependent variables (combustion limits) from the raw data, and to the reproducibility of the tests. Because of programmatic constraints, direct measurements of precision could not be done. The test matrix was too small to allow for the test repetitions that would be required. Hence, the estimates discussed here are uncertain.

Precision errors affecting the determination of the limits include errors in gas composition and the density of the test points in the vicinity of the limits. This latter error we call the limit-location error; it is the most important source of error, especially for a sparse matrix of tests.

One contribution to the precision errors in gas composition can be estimated using the spread of equivalence ratios. These errors are different from the composition accuracy errors discussed in Section 1.1.1. There, we estimated the uncertainties about the measured values, assumed to be equal to the mean value. Here, we are concerned with variations in the measured (mean) values from test to test; i.e., data taken in a particular regime, e.g., $ER = 5$, were all assumed to be at that value; however, referring to Tables 4 and 5, we see that the measured values of ER differed from the target values.

For the first series of tests using 30% BR (Table 4), the spread in ER is very small. For $ER = 5$, the spread is generally less than 2 parts in 500, or 0.4%. For $ER = 2.38$, the spread is less than $.011/2.38 = 0.5\%$.

For the second series using 60% BR (Table 5), the spread was significantly greater. For $ER = 5$, the largest deviation, $0.288/5.288 = 5.4\%$, occurred for test 26. Unfortunately, this was one of only two tests performed in this regime, and it therefore played a key role in the determination of the triggering and flame acceleration limits. The error would tend to move the flame acceleration limit to the right in Fig. 11a, towards less sensitive mixtures. Neglecting test 26, the spread in ER was less than 1.7% for $ER = 5$. For $ER = 2.38$, the spread was less than $.011/2.38 = 0.5\%$.

Other sources of error, both systematic and random, are possible during the conduct of the HDT tests. Efforts have been made to insulate the HDT, uniformly heat it, and ensure that the gases are uniformly mixed and homogeneous. However, it is possible that isolated small cold spots might result in local condensation of steam. It is not possible to estimate these kinds of errors, without simply repeating several tests to calculate means and standard deviations. A conservative estimate might be $\pm 2\%$ of the separate mole fractions.

It is also not possible to precisely determine a limit without conducting at least three very closely spaced tests, one slightly above the limit, one below, and one very close to it. This is almost never possible in a limited series of tests, especially with a large number of variables. The limit-location errors associated with insufficient data vary significantly, and have been addressed throughout this report in discussing the results and conclusions.

In principle, a reliable estimate of error is possible with a large number of tests. For example, consider Figure 10 where a comparatively large number of tests were performed. Several additional tests would need to be performed in the vicinity of 1% steam to more accurately determine the DDT limit; and in the vicinity of 5% steam to more accurately determine the flame acceleration limit. The triggering limit is well characterized. Given these additional measurements, error bars based on accuracy determinations (Appendix A.1) would be plotted together with the means of the measurements. Three curves would then be fitted through the three points in each measurement (lower bound, mean, and upper bound). The regions where these three curves crossed the key combustion limit boundaries (C-J detonation speed, AICC pressure, and no-burn) would then provide the best measure of the precision of the derived limits.

The precision of the estimated limits varies greatly with the different test series and test regimes. No objective blanket statement can be made concerning overall precision.

A.3 Overall Error Estimation

The largest sources of errors deal with precision and the translation of the measured quantities into limit determinations. The only accurate way to measure these uncertainties is to perform repeated tests. In the absence of such tests, we can only provide a subjective estimate of the overall error.

Where a significant number of tests were performed over the range of interest, e.g., Figure 10, we would estimate that steam and hydrogen mole fractions have associated errors of approximately $\pm 1-2$ absolute percent. For example, in Figure 10, the triggering and flame acceleration limits are roughly $16 \pm 1-2\%$ and $5 \pm 1-2\%$ steam, respectively. For test regimes with much more sparse data, e.g., Figure 11 with two data points, the associated errors could be $\pm$ several absolute percent.

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HYDROGEN MOLE FRACTION

Figure 1. HYDROGEN-AIR-STEAM
COMBUSTION REGIMES

CROSS BAR IS APPROXIMATELY 39° FROM VERTICAL
 8 HOLES EQUALLY SPACED ON 7 5/8" RADIUS BC
 13/16" DIAMETER

A ---- A

Figure 2
RING OBSTACLES WITH 30% BLOCKAGE RATIO

RINGS - 1/2" MILD STEEL PLATE, QUANTITY = 30

O.D. = 16.81 ", I. D. = 10.58 "; Tolerances = ± 0.01 "

**Figure 3.
60% BLOCKAGE RATIO RING OBSTACLES**

DISKS - 1/2" MILD STEEL PLATE, QUANTITY = 15
O.D. = 13.07 "; Tolerances = ± 0.01 "

Figure 4.
60% BLOCKAGE RATIO DISK OBSTACLES

Figure 5.
THE EFFECT OF PRESSURE ON
HYDROGEN-AIR FLAMMABILITY LIMITS AT ROOM TEMPERATURE

Figures 6a, 6b.
RICH HYDROGEN-AIR TESTS WITH NO STEAM
30% BLOCKAGE RATIO RING OBSTACLES
INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 310 \text{ kPa}$ (45 psia)

Figure 6c.
 RICH HYDROGEN-AIR TESTS WITH NO STEAM
 30% BLOCKAGE RATIO RING OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 310 \text{ kPa}$ (45 psia)

Figures 7a, 7b.
 RICH HYDROGEN-AIR TESTS WITH NO STEAM
 60% BLOCKAGE RATIO RING/DISK OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 102 \text{ kPa}$ (15 psia)

Figure 7c.
 RICH HYDROGEN-AIR TESTS WITH NO STEAM
 60% BLOCKAGE RATIO RING/DISK OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 102 \text{ kPa}$ (15 psia)

Figures 8a, 8b. EFFECT OF DIFFERENT OBSTACLES
HYDROGEN-AIR TESTS WITH NO STEAM
30% B.R. RING and 60% B.R. RING/DISK OBSTACLES
INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 310 \text{ kPa}$ (45 psia)

**Figure 8c. EFFECT OF DIFFERENT OBSTACLES
RICH HYDROGEN-AIR TESTS WITH NO STEAM
30% B.R. RING and 60% B.R. RING/DISK OBSTACLES
INITIAL CONDITIONS: T = 110°C, P = 310 kPa (45 psia)**

Figures 9a, 9b. EFFECT OF INITIAL PRESSURE
 RICH HYDROGEN-AIR TESTS WITH NO STEAM
 60% BLOCKAGE RATIO RING/DISK OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 102 \text{ kPa}/310 \text{ KPa}$

NOSTRAMSA.MAP

Figures 10a, 10b.
 RICH HYDROGEN-AIR-STEAM TESTS, E.R.=5.0
 30% BLOCKAGE RATIO RING OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 310 \text{ kPa}$ (45 psia)

Figure 10c.

RICH HYDROGEN-AIR TESTS, E.R. = 5

30% BLOCKAGE RATIO RING OBSTACLES

INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 310 \text{ kPa}$ (45 psia)

Figures 11a, 11b.
 RICH HYDROGEN-AIR TESTS, E.R. = 5
 60% BLOCKAGE RATIO RING/DISK OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 102 \text{ kPa}$ (15 psia)

Figure 11c.
RICH HYDROGEN-AIR TESTS, E.R. = 5
60% BLOCKAGE RATIO RING/DISK OBSTACLES
INITIAL CONDITIONS: T = 110°C, P = 102 kPa (15 psia)

Figures 12a, 12b.
 RICH HYDROGEN-AIR-STEAM TESTS, E.R.=5.0
 30% B.R. RING and 60% B.R. RING/DISK OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 310 \text{ kPa}$ (45 psia)

Figures 13a, 13b.
 RICH HYDROGEN-AIR-STEAM TESTS, E.R.=2.38
 30% BLOCKAGE RATIO RING OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 310 \text{ kPa}$ (45 psia)

Figure 13c.
 RICH HYDROGEN-AIR-STEAM TESTS, E.R.=2.38
 30% BLOCKAGE RATIO RING OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 310 \text{ kPa}$ (45 psia)

Figures 14a, 14b.
 RICH HYDROGEN-AIR-STEAM TESTS, E.R.=2.38
 60% BLOCKAGE RATIO RING/DISK OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 102 \text{ kPa}$ (15 psia)

Figure 14c.
 RICH HYDROGEN-AIR-STEAM TESTS, E.R.=2.38
 60% BLOCKAGE RATIO RING/DISK OBSTACLES
 INITIAL CONDITIONS: $T = 110^{\circ}\text{C}$, $P = 102 \text{ kPa}$ (15 psia)

Figures 15a, 15b.
 RICH 3 atm. HYDROGEN-AIR-STEAM TESTS, E.R.=2.38
 30% B.R.RING and 60% RING/DISK OBSTACLES
 INITIAL CONDITIONS: T = 110°C, P = 310 kPa (45 psia)

HYDROGEN MOLE FRACTION

Figure 16. HYDROGEN-AIR-STEAM LIMITS
30% BR RING OBSTACLES
P = 3 Atmospheres, T = 110°C.

ELBOW16Q.MAP

Figure 17. HYDROGEN-AIR-STEAM LIMITS
60% BR RING/DISK OBSTACLES
P = 1 Atmosphere, T = 110°C.

ELBOW17Q.MAP

Figure 18. HYDROGEN-AIR-STEAM LIMITS
30% BR RING OBSTACLES
P = 1 Atmosphere, T = 110°C.

ELBOW18Q.MAP