electrode gap used was varied inversely with the pressure, becoming, for example, 1.0 mm. at 6-atm. pressure. In earlier work at 1-atm. pressure, the ignition limit was independent of whether initiation was achieved by a hot wire or by a 5 to 6-mm. spark gap supplied by a Ford spark coil.

RESULTS

The ignition limits obtained are plotted in Figure 2. Each run is designated by two points, showing the interpolated or extrapolated vapor compositions at, respectively, the last sparking before ignition and the first sparking that caused ignition. Between 2- and 6-atm. pressure, the ignition limit was found to be constant at 20.7 mole % hydrogen peroxide in the vapor. This value is probably not significantly changed by moderate variations in the ratio of water to oxygen in the vapor (*1*). At atmospheric pressure, the limit was found here to be 25.6 mole %, slightly lower than the previously established value of 26.0 mole % (*2*). This difference may well reflect the fact that different criteria were used in the two studies for determining whether or not ignition had occurred, and that used here is probably slightly more sensitive.

By this technique, the vapor temperature increased slightly with increasing pressure, being about 155° C. at 30 p.s.i.a. and 192° C. at 95 p.s.i.a. Although, in general, increased temperature might be expected to lower the ignition limit, variation of vapor temperature here by 20° C. or so at a fixed pressure gave no noticeable effect on the limit, within the accuracy of determining it by this method.

No theoretical explanation is at present available for the apparent constancy of the limit in the range of 2- to 6-atm. pressure. For mixtures of various combustibles such as methane, carbon monoxide, and hydrogen with air, the ignition limit sometimes decreases and sometimes increases with pressure. In some cases the change with pressure is insignificant over a wide pressure range.

In runs in which a flame did not propagate back to the boiler, an over-all hydrogen peroxide material balance was made. The loss of hydrogen peroxide by decomposition amounted to less than 1 to 2% for all runs at pressures up to about 45 p.s.i., but increased to a maximum of 7% at higher pressures. It is believed that this decomposition occurred primarily in the liquid phase on boiling. This result was indicated by the amount of decomposition obtained in separate tests at various pressures in which H_2O_2 was boiled in a glass bulb surmounted directly by a reflux condenser, the design being such as to minimize the glass area exposed to hot vapors. The increase in decomposition rate with pressure thus represents the usual effect of increased temperature on reaction rate. Decomposition occurring before the ignition bulb causes the true composition in the bulb to be slightly less than the reported composition because of dilution from the oxygen formed in the decomposition. The correction may amount to a few tenths of a percentage point at about 55 p.s.i.a., but is probably less than one percentage point even in the runs in which the greatest decomposition occurred. However, this means that the ignition limit may in fact decrease very slightly with increased pressure.

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Dynamic Loading of Rupture Disks with Detonation Waves

JAMES A. LUKER and MELVIN J. LEIBSON[1]
Syracuse University, Syracuse, N. Y.

During the last century large groups of engineers and scientists have investigated the properties of materials under stress. The properties of most materials have been defined completely when the materials are subjected to a static stress. However, comparatively little is known about the behavior of materials subjected to dynamic loads.

This investigation dealt exclusively with dynamic loading of rupture disks. Its objective was to establish the relation between the dynamic bursting pressure and the static bursting pressure.

Several investigators have considered this problem. Campbell, Littler, and Whitworth (*1*), in one of the earliest investigations of gaseous detonations, determined the detonation pressure developed by knallgas ($2H_2 - O_2$) using rupture disks. Their work seemed to indicate that the static and dynamic bursting pressure were approximately equal.

Gerstein, Carlson, and Hill (*2*) performed an interesting series of experiments testing rupture disks in a long detonation tube. The disks tested ruptured at dynamic pressures somewhat lower than the static pressure rating. As large thin disks were used, Gerstein postulated that the disks may have failed partially from vibrational fatigue.

[1]Present address, American Locomotive Co., Schenectady, N. Y.

Stewart and Fox (*4*) performed bursting tests on aluminum foil to demonstrate its usefulness in pilot plant development:

Initial pressure atmospheric, pressure applied gradually
Initial pressure atmospheric, pressure applied suddenly
Initial vacuum, pressure applied gradually
Initial vacuum, pressure applied suddenly

He concluded that the ultimate yield stress of the aluminum foil was essentially the same for the different types of loading.

In this investigation belled rupture disks, 1 inch in diameter, were dynamically loaded by detonating a dry stoichiometric mixture of hydrogen and oxygen. The disks were attached to the end of the detonation tube perpendicular to the path of the detonation wave. The materials tested were stainless steel Type 304, nickel, phosphor bronze, and cold-rolled steel.

The ratio of dynamic bursting pressure to static bursting pressure was determined for each type of disk. Dynamic work hardening of the disks was also investigated.

The authors hope that the results of this study will be of value to the design engineer concerned with transient or shock loads.

APPARATUS

The detonation tube was constructed of a 6-foot piece of seamless steel tubing 1.125 inches in outside diameter and 0.687 inch in inside diameter. A spark plug was threaded into one end of the tube. At the opposite end, a rupture disk assembly was attached. A diagrammatic sketch of the apparatus is shown in Figure 1.

The rupture disk assembly was a standard blowout assembly manufactured by the American Instrument Co. It was modified as shown in Figure 1 so that the passage through the assembly matched the internal diameter of the detonation tube and the blowout area of the rupture disks. The rupture disks were seated in the assembly by carefully tightening the retaining plug. A highly polished stainless steel thrust ring was inserted in front of the retaining plug to avoid scratching or twisting the disks.

The rupture disks were also manufactured by the American Instrument Co. The manufacturer's static rating of the disks was used as the static rupture pressure. All disks used were calibrated by the manufacturer in the following manner. Large lots of flat disks (1000 to 5000) were stamped from sheet stock. The disks were annealed, cooled, and prestressed individually to a belled shape. Five per cent of these disks were then ruptured statically, and the average bursting pressure was calculated. If the bursting pressure of the disks tested deviated only $\pm 2\%$ from the average, the lot was deemed satisfactory. If deviations exceeded $\pm 2\%$, the lot was discarded.

Table I presents a complete list of disks used.

EXPERIMENTAL PROCEDURE

Determination of Dynamic Bursting Pressure. The rupture disk to be tested was placed in the assembly and carefully tightened, and the detonation tube was evacuated. Next, the detonation tube was filled with a premixed stoichiometric mixture of dry hydrogen and oxygen. The initial pressure of hydrogen and oxygen was adjusted to a value which would produce a reflected detonation pressure approximately 10% greater than the static rating of the disk. The mixture was then detonated by spark ignition. If the disk did not fracture, it was replaced by an undeformed disk, and the initial hydrogen-oxygen pressure was adjusted to a slightly higher value. This procedure was repeated until an undeformed rupture disk fractured. The initial pressure was then successively lowered to the point the disk was not fractured by the detonation. Thus, the dynamic rupture pressure was clearly established.

If, at the outset, the disk fractured at a reflected detonation pressure 10% greater than the static rating, the above procedure was reversed. The fractured disk was replaced with an undeformed disk and the initial $2H_2 - O_2$ pressure was adjusted to yield a lower reflected detonation pressure. The initial pressure was successively lowered in this manner until a new disk was not fractured by the detonation wave. Next, the initial pressure was successively increased until the resultant detonation fractured the undeformed disk.

Effect of Dynamic Work Hardening on Dynamic Bursting Pressure. The method was similar to that used to determine the dynamic bursting pressure, except for the history of the disk prior to fracture. Undeformed disks were work hardened by being subjected to detonation pressures less than the dynamic bursting pressures. Initial work hardening loads of 95, 90, or 80% of the dynamic bursting pressure were used. After the disk was work hardened by one of these initial loadings, the dynamic bursting pressure was determined in the same way as for an undeformed disk.

In a few cases double work hardening of disks was performed. In these cases the disks were subjected to two detonation blasts below the fracture level. After the double work hardening the dynamic bursting pressure was determined.

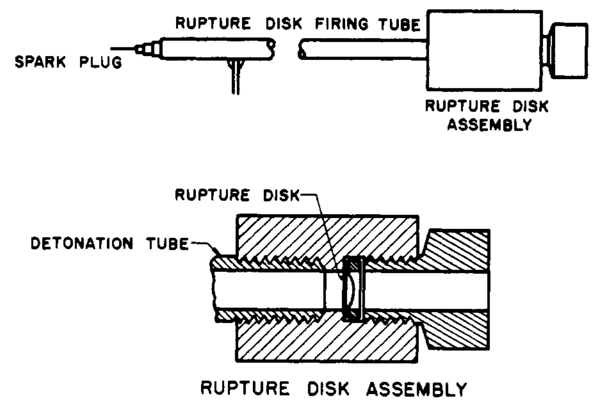

Figure 1. Rupture disk apparatus

Table I. Static Rating of Rupture Disk ± 2%, P.S.I.A.

Carbon Steel	Nickel	Phosphor Bronze	Stainless Steel Type 304	
903	340	1540	1390	5280
2850	1250	2070	1880	6240
			2620	7240
			3450	9100

DETERMINATION OF REFLECTED DETONATION PRESSURE

Dynamic loads were applied to rupture disks by subjecting the disks to the impact of a detonation wave. Thus, it was necessary to establish the reflected detonation pressures which result from detonating dry stoichiometric hydrogen-oxygen mixtures. The stable reflected detonation pressures were determined using the calculated pressures of Luker, McGill and Adler (*3*). The parts of their results used are summarized below:

P_1 Initial Knallgas Pressure, Atm.	P_2 Reflected Detonation Pressure, Atm.	P_2/P_1
1	42.84	42.84
5	231.9	46.38
10	476.3	47.63
30	1501	50.03

These results were plotted as reflected detonation pressure versus initial knallgas ($2H_2 - O_2$) pressure, and a least squares

Table II. Comparison of Dynamic Bursting Pressure to Static Bursting Pressure

Disk Rating, P.S.I.A.	Material	Dynamic Bursting Pressure, P.S.I.A.	Dynamic Bursting Pressure / Rupture Disk Rating
1390	SS 304	1770	1.27
1880	SS 304	2510	1.34
2620	SS 304	3390	1.29
3450	SS 304	4140	1.20
5280	SS 304	7000	1.33
6240	SS 304	7950	1.27
7240	SS 304	8840	1.22
9100	SS 304	11650	1.28
340	Nickel	630	1.85
1250	Nickel	2140	1.71
1540	Phosphor bronze	2770	1.80
2070	Phosphor bronze	3670	1.77
903	Cold-rolled steel	1300	1.43
2850	Cold-rolled steel	4460	1.56

regression line was fitted. The equation of this line was $P_2 = 46.5\ P_1$. This relationship was used throughout to determine the loading force due to a stable reflected detonation wave.

It was assumed that equilibrium was attained in the normal detonation front and in the reflected wave, and that the reflection was normal. These assumptions would result in a maximum reflected wave pressure. Reflected pressures actually obtained experimentally would probably be somewhat lower. The authors, however, believe that the calculated stable reflected detonation wave pressure provides an excellent standard for use in comparing dynamic and static loading.

RESULTS AND DISCUSSION

The results of this study are tabulated in Tables II and III and represented graphically in Figures 2 and 3. In determining the dynamic bursting pressures, the maximum difference between the fracture point and the nonfracture condition deemed allowable was 1 p.s.i.a. dry hydrogen and oxygen pressure—i.e., 46.5 p.s.i.a. dynamic pressure. In most cases the bursting pressure was determined more precisely than the allowable maximum.

The mechanism of disk failure was shear. The largest percentage of the disks failed by shear at the periphery; however, some exhibited radial failure.

The arithmetic average ratio of the dynamic bursting pressure to the rupture disk rating was determined to be:

Stainless steel Type 304	1.28
Nickel	1.78
Phosphor bronze	1.79
Cold-rolled steel	1.50

In Figure 2 the dynamic bursting pressure is plotted against rupture disk rating. For stainless steel Type 304 the ratio of dynamic bursting pressure to rupture disk rating varied from 1.20 to 1.36. However, the straight line with a slope of 1.28 presented for stainless steel Type 304 in Figure 2 resulted in a correlation coefficient of 0.998. Thus, it was concluded that the relationship between dynamic bursting pressure and rupture disk rating was linear.

The effect of work hardening upon the dynamic bursting pressure is tabulated in Table III. Phosphor bronze did not exhibit dynamic work hardening, although phosphor bronze work hardens statically. Nickel and cold-rolled steel work hardened, showing an increase in dynamic bursting pressure of 33 and 39%, respectively.

Stainless steel Type 304 was exposed to both single and double work hardening effects. Figure 3 shows in graphical form the relationship among the dynamic bursting pressure

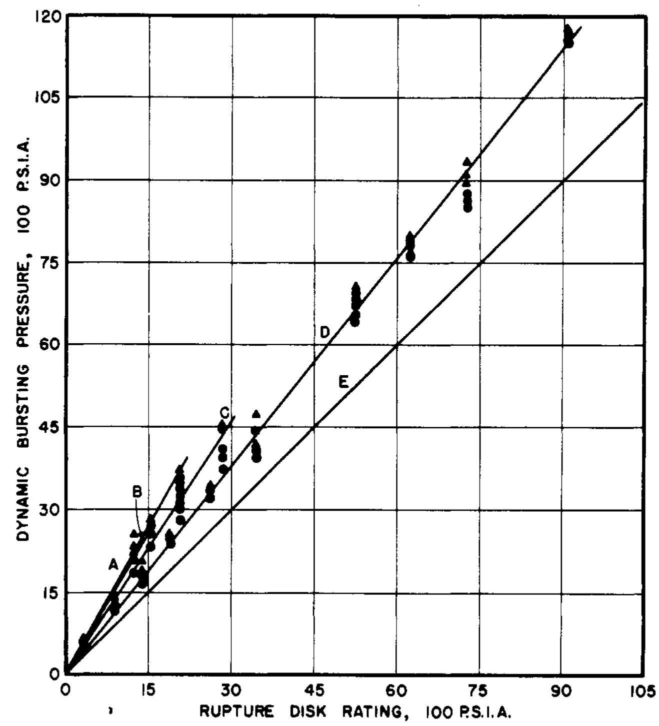

Figure 2. Dynamic bursting pressure versus rupture disk rating

▲ Disk ruptured
● Disk did not rupture
A. Phosphor bronze
B. Nickel
C. Cold-rolled steel
D. Stainless steel Type 304
E. 45° line

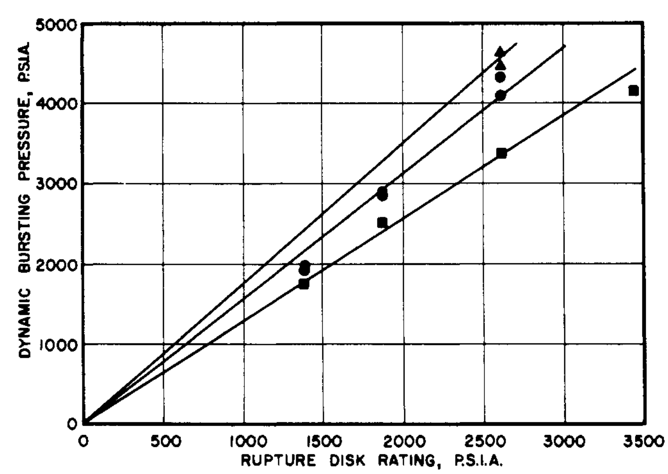

Figure 3. Effect of work hardening on dynamic bursting pressure of stainless steel Type 304 disks

▲ Double work hardening
● Single work hardening
■ No work hardening

Table III. Simple Work-hardening Effect

A	B	C	D	E	F	G
Disk Rating, P.S.I.A.	Material	Dynamic Bursting Pressure, P.S.I.A.	Initial Dynamic Loading, P.S.I.A.	Dynamic Bursting Pressure after Work-Hardening, P.S.I.A.	$\frac{E}{A}$	$\frac{E}{C}$
1390	SS 304	1770	1610	1950	1.40	1.10
1390	SS 304	1770	1680	1910	1.37	1.08
1880	SS 304	2510	2280	2840	1.51	1.13
1880	SS 304	2510	2420	2880	1.53	1.15
2620	SS 304	3390	2790	4070	1.55	1.20
2620	SS 304	3390	3210	4300	1.64	1.27
1540	Phosphor bronze	2770	2510	2770	1.80	1.00
340	Nickel	630	560	840	2.47	1.33
903	Cold-rolled steel	1300	1120	1810	2.00	1.39

with one work hardening effect, the dynamic bursting pressure with a double work hardening effect, and the rupture disk rating. The dynamic bursting pressure increased with work hardening.

For one work hardening effect the dynamic bursting pressure increased an average of approximately 16%. The dynamic bursting pressure increased an average of approximately 34% when the disk was dynamically work hardened a second time. However, the dynamic bursting pressure after a double work hardening showed an increase of only an average of 8% over the increase caused by a single work hardening effect.

CONCLUSIONS

Rupture disks used in this study exhibited a higher bursting pressure under dynamic loading than under static loading.

The relationship between dynamic bursting pressure and static bursting pressure was linear for all disks tested.

Stainless steel Type 304, nickel, and cold-rolled steel exhibited dynamic work hardening.

Phosphor bronze did not dynamically work harden.

Stainless steel Type 304 will progressively dynamically work harden.

ACKNOWLEDGMENT

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Knallgas and Knallgas-Steam Mixtures at High Initial Temperature and Pressure

Calculated Detonation Parameters and Adiabatic Constant-Volume Explosion Properties

JAMES A. LUKER, PAUL L. McGILL,[1] and LEONARD B. ADLER[2]
Syracuse University, Syracuse, N. Y.

Explosive gas mixtures at certain conditions react in a radically different manner from that normally found in gaseous combustion. This reaction is characterized by an extremely high propagation rate of the combustion wave into the unburned gas, equal to several times the speed of sound, and by pressures behind the wave front much higher than those found in constant-volume adiabatic explosions. For this phenomenon, called detonation, many experimental velocity and some pressure and density measurements have been made for various gas mixtures. Since the work of Chapman and Jouguet around 1900, many theoretical calculations of detonation wave properties have been made which show satisfactory agreement with experimental values. Therefore, calculated detonation parameters provide valuable design information for the safe handling of detonable gas mixtures.

The specific mixtures considered here are knallgas ($2H_2$-O_2) and knallgas saturated with steam. The latter mixture is of particular interest in the atomic energy field because one of the characteristics of homogeneous reactors, in which the nuclear fuel is dissolved in an aqueous medium, is that molecular hydrogen and oxygen are produced in approximately stoichiometric proportions by radiation effects. Thus, a potentially explosive or detonatable gas mixture at high pressure and temperature may be formed. Naturally, the reactor components must be designed to withstand the pressures resulting from any explosion or detonation which might occur.

Gas mixtures which could be produced under typical reactor operating conditions were considered. This range of interest covered the region from room temperature and atmospheric pressure to 300° C. and 150 atm. Presented in Table I are the specific initial conditions considered for dry knallgas and saturated knallgas-steam mixtures.

For each initial condition the detonation pressure, temperature, velocity, and the composition of the detonation products at thermodynamic equilibrium were calculated. These same detonation parameters were also calculated for a reflected detonation wave. The reflected pressure, being more than twice as great as the detonation pressure, is of primary importance since equipment damage will most likely occur at points of reflection. These results represent normal and reflected parameters for stable detonations.

During the formation of a detonation in the transition from deflagration to detonation, pressures significantly higher than

Table I. Initial Properties of Mixtures with Composition in Mole % Knallgas

Pressure, Atm.	Temperature, °K.				
	298.16	423	473	523	573
	Composition, Mole %				
1	100	. . .	. . .	. . .	. . .
5	100	5.78	. . .	. . .	. . .
10	100	51.8	. . .	. . .	. . .
16	. . .	. . .	3.70	. . .	. . .
30	100	83.4	46.0	. . .	. . .
43	. . .	. . .	. . .	7.26	. . .
50	100	89.8	66.4	18.3	. . .
70	100	92.5	75.4	38.6	. . .
90	100	94.1	80.4	50.5	4.11
110	100	95.1	83.6	58.3	17.0
130	100	95.7	85.8	63.8	26.5
150	100	96.2	87.5	67.8	33.9

[1] Present address, Atomic Power Division, Westinghouse Electric Corp., Pittsburgh, Pa.
[2] Present address, Brookhaven National Laboratory, Upton, N. Y.