NEDO-10812 73NED49 Class I April 1973

25

LICENSING TOPICAL REPORT

HYDROGEN FLAMMABILITY AND BURNING CHARACTERISTICS IN BWR CONTAINMENTS

B. C. Slifer T. G. Peterson

Approved:

L. K. Holland, Manager Systems Engineering

ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC COMPANY SAN JOSE, CALIFORNIA 95114



8205210160 820507 PDR FOIA HIATT72-182 PDR

DISCLAIMER OF RESPONSIBILITY

This report was prepared as an account of research and development work performed by General Electric Company. It is being made available by General Electric Company without consideration in the interest of promoting the spread of technical knowledge. Neither General Electric Company nor the individual author:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information disclosed in this report may not infringe privately owned rights; or
- B. Assumes any responsibility for liability or damage which may result from the use of any information disclosed in this report.

TABLE OF CONTENTS

	ABSTR	RACT	• •					×				*		*	×	×			÷									1-1
1.	INTRO	DUCTION															÷.							,				1.1
	1.1	Purpose .		2.1											÷.					1		1						1.1
	1.2	Conclusions										*								1				*	•			1.1
	1.3	Recommendation					Ĵ			ļ	1	Ĵ	, ,	2	Ĵ	Ĵ	ŝ	ļ	Ŷ			ļ	÷,	3	ļ		ĺ,	1.2
2.	FLAM	MABILITY LIMITS			Ċ,			1	1						1	i,	1			Ĵ.				1	١.	Ľ	5	2.1
	2.1	Description of Exp	eriment	5 .									1		2			0	1	2			0	0				2.1
	2.2	Discussion of Resul	ts	2.2					<u>а</u>	÷			1	÷.				3	÷.			1		1	Ċ.			2.7
	2.3	Application to BWF	R Conta	ainm	ent	ts		÷.		÷		÷			ŝ	ì	Ĥ	÷	÷		ļ	,	ļ	i,			ł	2-10
3.	BURN	ING CHARACTERIS	TICS												l						Ľ,					i,		3-1
	3.1	Test Results								÷.	÷		÷.	2	÷.		-0	ŝ.			2			0	3			3.1
	3.2	Discussion of Resul	ts			- 2			÷.	0						÷.							1		1	1	1	21
	3.3	Burning Rate Mode	1.		ŝ	÷	ļ	,	÷			÷		÷.	Ĵ	÷	÷.	Ĵ	Å,	÷.			ì	Ì		×	÷	3-11
4.	EFFEC	TS OF HYDROGEN	BURN	ING	0	NE	SW F	3 0	CON	IT.		IME	EN	TS				÷									j	4.1
	4.1	Maximum Pressures						1.7										ĵ.,				÷.			1	2	÷.	4.1
	4.2	Maximum Tempera	tures								1			Ĉ.	Ĩ.,	÷.		1	Ĩ.						2		1	4.12
	4.3	Detonation Potentia	al .		ŝ	÷			,	÷	, ,	*	ĺ,	*		Ļ	÷.,		÷		Ĵ				ì	į.	ì	4-12
5.	APPLI	CATION TO SAFETY	GUID	E 7																			i.	,				5-1
	REFER	RENCES														÷		*,										R-1
	ACKN	WLEDGMENTS .												÷				,	, i	į.				l	÷			1

APPENDIX

PRESSURE TRANSIENT	FROM FENWAL	TESTS	• •		• •			÷		×			÷	A-1
DISTRIBUTION			Ξ.				١.				í,	1		D-1

LIST OF ILLUSTRATIONS

Figure	Title						Page
2.1	Test Vessel				×	×	2.2
2.2	Flammable Mixtures, Fenwal Data				÷	÷	2.8
2.3	Nonflammable Mixtures, Fenwal Data			÷			2.9
2-4	The Effect of Water Vapor on the Lower Flammability Limit of Hydrogen			×	ł		2.11
3-1	Normalized Pressure Rise H ₂ Combustion in Fixed Volume Containment		×	÷		ł	3-2
3-2	Pressure Rise Versus Hydrogen Concentration, Spark Ignitor			÷	ł	2	3-3
3.3	Comparison of Actual with Theoretical Pressure Rise (Completeness) for Hydrogen Burning in a Closed Vessel	•				÷	3.5
3-4	Average Pressure Rate Versus Hydrogen Concentration		÷.	i.	÷	×	3-7
3-5	Effect of Ignitor Location on Pressure Transients		-	*	•	ł	. 3-9
3-6	Time to Reach Peak Pressure Versus H ₂ Concentration, Central Ignition		×	÷			3-10
3-7	Temperature Rise Versus H ₂ Concentration	1. I.			×	н. ж	3-13
3-8	Final Pressure Versus H ₂ Concentration			÷			3-15
3-9	Correction for Initial Temperature			*		ł	3-16
3-10	Theoretical and Experimental Rise for Spherical Propagation in a 9.6% Methane-Air Mixture in a Cylindrical Vessel with Central Ignition	× .				ļ	3-18
3-11	Steady, Downward Propagation in a Spherical Vessel	×	÷		x		3-18
3-12	Theoretical and Experimental Pressure Rise for Downward Propagation in a Spherical Vessel with Central Ignition		×		į		3-19
3-13	Theoretical and Experimental Pressure Rise for Downward Propagation in a Spherical Vessel with Central Ignition	•			1		3-19
3-14	Theoretical and Experimental Pressure Rise for Downward Propagation in a Spherical Vessel with Central Ignition				-		3.20
3.15	Steady Upward Propagation in a Spherical Vessel, with Central Ignition				s,	÷	3.20
3-16	Theoretical and Experimental Pressure Rise for Upward Propagation in a Spherical Vessel with Central Ignition.						3-22
3-17	Theoretical and Experimental Pressure Rise for Upward Propagation in a Spherical Vessel with Central Ignition						3.22

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
3-18	Theoretical and Experimental Pressure Rise for Upward Propagation in a	
	Spherical Vessel with Central Ignition	3-23
3-19	Theoretical and Experimental Pressure Rise for Upward Propagation in a	
	Spherical Vessel with Central Ignition	3-23
3-20	Flame Propagation Speed Versus H ₂ Concentration	3-25
3-21	Conservative Flame Propagation Speed Versus H_2 Concentration for Upward Propagation	3.32
3-22	Conservative Flame Propagation Speed for Downward and Spherical Propagation Used for Calculations in BWR Containments	3-33
3-23	Conservative Completeness Versus H ₂ Concentration	3.34
4-1	Pressure for H ₂ Combustion in Mark I Drywell	4-2
4-2	Pressure for H ₂ Combustion in Mark II Drywell	4-3
4-3	Pressure for H ₂ Combustion in Mark III Drywell	4.4
4-4	Pressure for H ₂ Combustion in Mark I Supression Chamber	4-5
4-5	Pressure for H ₂ Combustion in Mark II Suppression Chamber	4-6
4-6	Pressure for H ₂ Combustion in Mark III Suppression Chamber	4-7
4-7	Hydrogen Concentration Which Results in the Indicated Design Pressure When	
	Burned Versus Initial Pressure, BWR Containment Drywells	4-8
4.8	Hydrogen Concentration Which Results in the Indicated Design Pressure When	
	Burned Versus Initial Pressure, BWR Containment Suppression Chambers	4-9
4-9	Maximum Hydrogen Concentration (Dry Basis), BWR Drywells	4-10
4-10	Maximum Hydrogen Concentration (Dry Basis), Suppression Chambers	4-11
A-1	Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time	A-1
A-2	Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time	A-2
A-3	Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time	A-2
A-4	Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time	A-3
ê J	Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time	A-3
A-6	Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time	

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
A-7	Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time	A-4
A-8	Fenwal Test Data – Pressure Rise/Initial Pressure Versus Time	A-5
A-9	Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time	A-5
A-10	Fenwal Test Data – Pressure Rise/Initial Pressure Versus Time	A-6
A-11	Fenwal Test Data – Pressure Rise/Initial Pressure Versus Time	A-6

LIST OF TABLES

Table	Title	Page
2-1	Flammability Limit	 2-1
2.2	Summary of Test Results	 2.4
3-1	Geometrical Burning Parameters for Idealized Containment Geometries	 3-29
4-1	Maximum Allowable H ₂ Concentration, Volume Percent, Dry Basis	 4-12

.

.

ABSTRACT

Hydrogen flammability and burning characteristics were determined in a recent experiment under conditions simulating BWR reactor containments following the hypothetical loss-of-coolant accident (LOCA). The data showed that the post-LOCA conditions—in particular, water vapor content—raise the lower flammability limit above 4% by volume hydrogen and reduce the burning rates. The data were also used to develop a conservative burning model. The model shows that BWR containment drywells can burn hydrogen concentrations up to 18% (depending on the design pressure value) without exceeding the design pressure, and hydrogen concentrations up to 12% can be burned in the unvented suppression chambers. These data and analyses demonstrate the large degree of conservatism in the current AEC Safety Guide 7 flammability limits and show that the limits could be safely revised upward a significant amount without endangering containment integrity.

1. INTRODUCTION AND SUMMARY

1.1 PURPOSE

The flammability limits and other criteria of the AEC's Safety Guide 7 are overly conservative when applied to high-pressure containment designs for nuclear reactors. The result of this conservatism is to impose design solutions that are not always in the best interest of safety, especially when the extremely low probabilities of ever reaching a flammable condition in a BWR containment are considered. A recent General Electric topical report, "Hydrogen Generation and the General Electric Boiling Water Reactor," NEDO-10723, reviews all aspects of Safety Guide 7 and the design solutions imposed by it.

The purpose of the present report is to discuss hydrogen flammability and burning characteristics. Recently obtained data are presented, and used to determine the capability of current BWR contained designs to withstand hydrogen deflagrations.

1.2 CONCLUSIONS

The data presented and discussed in this report are consistent with other investigators' findings and thus contribute to form a firm data base upon which reliable and accurate predictions of flammability limits and burning characteristics can be made.

- Increasing water vapor content increases the lower flammability limit of hydrogen, and a water vapor concentration in excess of 50 to 60% completely inerts a hydrogen-air-water vapor mixture.
- Complete combustion of hydrogen is only possible when the hydrogen concentration is at least 8% by volume. Higher concentrations are required for complete combustion as pressure, temperature, and water vapor content are increased.
- Three distinct types of flame propagation can be identified: upward, upward followed by downward, and spherical, in order of increasing hydrogen concentration.
- . The pressure transients associated with each of the three types of flame propagation are predictable.
- The quantities of hydrogen that can be burned in BWR containments range up to 18% in the vented drywells and up to 12% in the unvented suppression chambers.

1.3 RECOMMENDATION

.

Change the Safety Guide 7 flammability limit to a safety limit that is based on the design pressure of the containment and the venting characteristics, if any, of the containment. Alternatively, since the information contained in this report is a clear demonstration of the conservatism of the current Safety Guide 7 flammability limit, other criteria related to hydrogen source terms (in particular, zirconium-water reactions) could be reduced without reducing safety margins.

2. FLAMMABILITY LIMITS

The flammability of hydrogen in air has been extensively studied over the past 50 or 60 years. The most commonly referenced information sources are the Bureau of Mines Bulletins 503 (Coward & Jones, 1952)¹ and 627 (Zabetakis, 1965,)² and the NACA Research Memorandum E57D24 (Drell and Belles, 1957).³ The flammability limit is generally stated as follows for hydrogen in air at atmospheric pressure and room temperature.

Table 2-1 FLAMMABILITY LIMIT

	Volume Perce	ent Hydrogen ^u Alr
	Lean	Rich
Upward Propagation		
Coherent Flame	. 9.0	74
Nonconerent Flame	4.0	
Downward Propagation	9.0	74

(a) Throughout this report and in the literature, hydrogen concentration is presented in terms of volume percent. Under perfect law assumptions, which are applicable in the present case, the terms volume fraction, mole fraction, and the ratio of partial pressure to total pressure are equivalent.

The USAEC's Safety Guide 7 of March 10, 1971⁴ implies that a mixture shall be considered flammable when the hydrogen concentration is greater than 4 volume percent and the oxygen concentration greater than 5 volume percent. The Safety Guide 7 limit for hydrogen concentration is trius apparently based on the limit for upward propagation of a noncoherent flame. The difference between coherent and noncoherent flames is basically in the degree of completion of the reaction. A noncoherent flame is composed of separate globules that only propagate in the upward direction and do not consume all of the hydrogen. A coherent flame (i.e., one with a distinct, continuous flame front) will propagate both in the upward and downward directions and consume essentially all of the hydrogen in the mixture. The most significant effect of whether a flame is coherent or noncoherent is in the pressure transients associated with combustion of hydrogen-air mixtures in a closed volume vessel. These effects will be discussed at length in Section 3.

The important point to note in the present discussion is that the limits presented in Table 2-1 are for air-hydrogen mixtures at atmospheric pressure and room temperature. BWR containments under post-LOCA conditions are at higher pressures, temperatures, and water vapor content than those at which the limits are stated. Also, the stated limits are based on experimental work which was done on laboratory equipment in which hydrogen was ignited either in relatively small tubes (0.8 to 21 cm in diameter) or smaller spherical vessels (12 cm diameter maximum).' The BWR containments are, of course, of much larger dimensions. Because of these differences, the General Electric Company contracted Fenwal, Inc.,* to run a series of hydrogen flammability and burning tests at conditions simulating post-LOCA BWR containment pressures, temperatures, and water vapor content in a test vessel an order of magnitude larger than those described here.

The description of those tests and equipment, the test results, and a discussion are presented in this Section.

2.1 DESCRIPTION OF EXPERIMENTS

2.1.1 Experimental Apparatus

6

The hydrogen flammability tests were conducted in a 134-cubic-foot test vessel with a design pressure of 500 psig, as illustrated in Figure 2-1. The interior of the vessel is stainless steel clad. For these tests, it was equipped with externally mounted infrared electric heaters to provide the desired elevated test temperatures. The temperature is controlled by a temperature controller utilizing a thermistor probe fastened to the external wall of the vessel. The

* Fernwal, Inc., Ashland, Massachusetts, 01721.

3



NOTE: * IGNITION SOURCE LOCATION

Figure 2-1 Test Vessel (134 cubic feet)

internal temperature is monitored by means of an iron-constantan thermocouple located in a thermowell extending into the vessel and used in conjunction with a temperature recorder.

Transient pressures are monitored by means of a pair of strain gage-type pressure transducers mounted on a port at the side of the test vessel. These units are used in conjunction with a carrier amplifier and recording oscillograph. Timing markers are electronically superimposed on the oscillograph chart to provide a time base to facilitate the determination of rates of pressure rise.

Three types of ignition sources were initially evaluated in the program. A capacitive discharge spark created across a 1/16-inch gap between two electrodes served as one ignition source. The electrodes were stainless steel tubing connected by a graphite rod, over which they were forced fitted. Power for the spark came from a pair of series-wired 525 microfarad capacitors charged to 900 volts. The energy content of the spark is approximately 100 joules.

A No. 8 (strength) electric blasting cap was utilized as a second potential ignition source. It was actuated, using the power source described here for the spark ignitor.

The third ignitor tested consisted of a 2-inch length of eight-strand braided Pyrofuze wire (0.005-inch o.d. of braid). Pyrofuze wire consists of an aluminum core surrounded by a palladium shell. When these materials are brought to an actuating temperature, they alloy exothermically with some violence, which throws the hot materials away from the source material, much as a sparkler throws hot particles. The energy content of the Pyrofuze is 21.5 joules, and it is activated by discharge of the above-described capacitive discharge power supply. The ignitors could be located at the top, center, bottom, or side of the vessel, as indicated in Figure 2-1.

Water may be introduced into the test vessel through a conical spray nozzle. When a high-humidity test is required, one and one-half times the volume of water required to saturate the test vessel's atmosphere at the test temperature is injected into the vessel to evaporate.

2.1.2 Test Variables

The tests were set up to determine the effects of various parameters on both the limits of flammability and burning characteristics. The variables investigated were:

- Type of ignitor
- Location of ignitor
- Hydrogen concentration
- Temperature/pressure/water vapor content.

The last item (temperature/pressure/water vapor content) is really one variable in the BWR containment because it is essentially a fixed volume system into which energy and steam are injected during a LOCA; thus temperature, pressure, and water vapor content are always increased proportionally. The pressure range covered from 0 to 33 psig, and the temperature range from 100 to 222°F. The water vapor volume concentration varied from less than 1% to 44%.

2.1.3 Test Results

Over 70 tests were run at various conditions. Table 2-2 presents all the pertinent information for all tests run. The plotting symbols used for presenting the data on the various graphs and figures throughout the report are also shown in Table 2-2. The pressure traces for those tests in which there was significant pressure rise are in the Appendix.

Table 2.2 SUMMARY OF TEST RESULTS

. . .

.

	Ambient		ent Conditi	Relation 1		- 4	gnitor	H2	Test	H- Cone	entration	Test						
	Test	Temperature (°C)	Pressure (mm Hg)	Relative Humidity (%)	Test Temperature (°C)	Туре	Location	Pressure (mm Hg)	Pressure (mm Hg)	Ambient Pressure (%)	Test Pressure (%)	Relative Humidity (%)	P max (psig)	R av (psi/sec)	R max (psi/sec)	∆₽ (psi)	Δt (sec)	Comments
.C) 1-A	89	752	48	60	Spk	MC	45.6	855.4	6.1	5.3	77	2.0	0.12	0.12	0.0	2.00	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
Q.	1 B	8.9	750	52 5	60	Det	MC	45.6	855.4	6.1	5.3	74	2.0	0.15	0.13	0.9	1.00	And shares a
10) 1 C	8.9	750	44	60	Pyro	MC	45.6	843.1	6.1	5.4	65	11.2	1.6				No ignition
0.	2.A	8.9	755	50	60	Pyro	Top	45.6	853.2	6.0	5.3	60	0.5	1.0	4.0	9.4	0.20	
	2.0	8.9	750	48	60	Pyro	MS	45.6	848.3	61	4.8	69	8.0	1.0	4.7	7.0	7.40	
0	20	8.9	752	55	60	Pyro	Bot	45.6	850.3	6.1	4.8	68	11 ()	2.0	2.3	7.0	6.90	
Ç) 3 A	7.8	752	55	38	Pyro	MC	32.4	752.0	4.3	4.3	8.8	3.0	0.6	4.2	9.1	4.45	
	38	7.2	752	58	38	Fyro	MC	45.6	752.0	6.1	6.1	9.0	120	2.1	1.0	120	6.00	No ignition in one test
1	30	7.8	752	55	38	Pyro	MC	60.8	752.0	8.1	8.1	8.8	30.5	21.4	35.0	32.5	5.80	
0	4 A	3.3	750	52	38	Pyro	MC	30.4	783.6	4.1	3.9	73	0.8	0.06	0.06	0.15	7.60	
4	4 D	3.3	750	50	38	Pyro	MC	45.6	791.4	6.1	57	90	80	0.3	0.55	2.2	2.00	
- 1	4-G	4.4	750	415	38	Pyro	MC	60.8	786.2	8.1	77	80	29.6	12.1	10.20	20.7	7.00	
	4-8	15.7	751	51	71	Pyro	MC	30.4	906.1	4.1	33	63	19.0	1.2.1	19.2	30.2	2.30	the second s
4	4 E	17.8	750	E1	71	Pyro	MC	45.6	905.1	6.1	50	56	6.1	0.70				No ignition in three tests. Typical data
1	8-H	178	750	100	71	Pyro	MC	60 B	915.4	81	6.6	75	16.0	0.28	0.4	2.1	7.00	
	-		-	and 1	(100)	(Pyra)	(MC)			(4)	0.0	(100)	10.0	3.4	7.5	12.8	3.80	
		-	-		(100)	(Pyro)	(MC)			161		(100)			-		-	Not tested
0	4.1	23.3	750	45	100	Pyro	MC	60.8	1318 7	81		76			-	-	-	Not tested
×	-	-	-	-	(100)	(Pyro)	(MC)		1310.7	(8)	4.0	/100+1	-		1990			No ignition in two tests. Typical data
0	6-A	6.7	750	47	38	Sok	MC	60.8	781.0	8.1	7.0	1100+1			-	-		Not tested
V	121			-	(38)	(Det)	(MC)	00.0	101.0	0.1	7.0	10	20.3	1.8	3.3	19.8	10.8	Not a smooth explosion
-	6.0	6.7	250	47	38	Dura	Tee	60.0	700.0	107		(100)			-	-	-	Not testad
2V	6-E	11.1	750	49	38	Pure	AAC.	60.8	700.0	0.1	1.1	86	31.3	7.8	23.0	30.5	3.950	D
0	6.F	11.1	750	49	38	Pure	MC	60.8	788.8	8.1	1.1	89	33.5	17.0	31.0	32.8	1.9	
v	6-G	15.6	750	65	38	Pyro	Bot	60.8	786.2	8.1	7.7	89 91.2	29.5	9.6	16.0	28.8	3.0	

The four tests listed as "Not Tested" are defined by intended test conditions shown in parentheses. They were not conducted because previous similar tests had proven nonflammable.

NOTES: Abbreviations Ignition Source Spk - 100 Joule spark Det - Electric blasting cap

Pyro · Pyrotuze

Ignitor Location

MC - Middle height, center

Top - Top center (6 inches down from vessel wall)

* *

 $\sigma_{\rm f}$

MS · Middle height, side

Bot - Bottom centar (6 inches up from vessel wall)

24

1.

1.

Table 2.2 (Continued) SUMMARY OF TEST RESULTS

1. 1. 1. 1.

. • .

*

		Ambient Conditions			Test Conditions				Ignitor H2 Concentration										
	Test	Temperature (°C)	Pressure (mm Hg)	Relative Humidity (%)	Temperature (°C)	Pressure (mm Hg)	Relative Humidity (%)	Туре	Location	Added Water Pressure (mm Hg)	H ₂ Pressure (mm Hg)	Ambient Pressure (%)	Test Pressure (%)	P max (peig)	R max (psi/sec)	R av (pai/sec)	ΔP (pei)	∆t (sec)	Commenta
0	A 1	30.6	755	47	100.0	1365	71.1	Pyro	MC	625	89.6	11.8	6.5	17.9	2.0	1.1	6.0	6.2	
T	A 2	18.3	749	58	100.0	1364	71.0	Pyro	MC	533	89.0	11.9	6.5	26.9	6.1	2.8	15.0	5.3	
1	A 3	20.2	757	55	100.0	1434	73.5	Pyro	MC	549	105.0	13.9	7.3	25.7	5.6	2.9	18.1	6.3	
- 1	A-4	25.6	757	44	100.0	1390	69.6	Pyro	MC	529	103.0	13.6	7.4	30.5	7.3	3.2	18.3	5.8	
- 1	A 5	26.7	757	44	100.6	1406	67.8	Pyro	MC	515	114.4	15.1	8.1	35.5	7.0	3.4	23.0	6.7	
1	A-6	24.4	757	56	101.7	1419	67.3	Pyro	MC	530	116.0	15.3	8.2	38.0	11.0	-	25.2	-	Pressure recorder started late
1	A.7	31.1	760	48	101.7	1464	72.6	Pyro	MC	570	120.0	15.8	8.2	39.0	12.0	6.4	25.5	4.0	
0	81	16.1	757	61	878	1091	56.5	Pyro	MC	265	78.5	10.4	6.5	13.0	3.7	1.5	7.2	4.8	
T.	8-2	20.0	760	47	90.0	1198	69.9	Pyro	MC	360	78.4	10.3	6.5	19.0	3.7	1.7	10.5	6.0	
1	8-3	24.4	757	40	87.8	1163	69.7	Pyra	MC	325	76.0	10.0	6.5	18.2	4.5	2.4	10.4	4.4	
1	B-4	21.1	758	49	86.6	1194	77.0	Pyro	MC	347	88.3	11.6	7.3	28.5	10.7	5.1	20.0	3.9	
1	8.5	19.4	754	64	87.8	1170	70.2	Pyro	MC	328	825	10.9	7.0	22.5	6.9	3.0	14.3	4.8	
0	C-1	23 9	754	59	71.1	1824	85.7	Pyro	MC	197	119.0	15.8	6.5	45.8	11.1	4.6	25.1	5.4	
1	C-2	21.1	757	57	71.1	1806	73.1	Pyro	MC	168	119.0	15.7	6.6	40.6	10.2	4.8	25.7	5.4	
-1	C-3	19.1	760	64	72.2	1846	80.5	Pyro	MC	196	134.5	17.7	7.3	54.0	13.2	6.6	33.0	5.0	
1	C-4	29.4	756	51	71.1	1800	68.8	Pyro	MC	153	134.5	17.8	7.5	57.0	22.3	9.2	36.8	4.0	
A	DI	23.9	754	66	71.1	954	72.5	Spk	MC	163	37.0	4.9	3.9	-	-	-	-		No ignition
T	D2	23.9	754	66	71.1	963	72.5	Spk	MC	163	46.0	6.1	4.7		-	-	-	100	No ignition
1	03	23.9	754	66	71.1	972	72.5	Spk	MC	163	55.0	7.3	56	5.2	0.1	0.08	0.8	10.0	
-1	04	28 3	753	58	71.1	986	79.5	Spk	MC	178	64.0	8.5	6.5	5.5	0.3	0.11	0.5	4.4	
1	D-5	22.2	754	67	71.1	1001	75.9	Spk	MC	173	74.0	9.8	7.4	6.3	1.2	0.4	1.5	3.3	
1	D6	31.7	754	57	71.1	1024	82.0	Spk	MC	182	84.0	11.1	8.2	8.3	1.4	0.7	2.8	3.8	
办	E-1	26.7	749	64	72.9	979	83.2	Det	MC	203	38.0	5.1	3.9	-	-	-	-	-	No ignition
1	E 2	29.4	750	51	71.1	976	78.8	Det	MC	177	46.0	6.1	4.7	100	-		1.00	100	No ignition
1	E-3	21.1	757	56	71.1	995	77.1	Det	MC	178	56.7	7.5	5.7		200	· · ·	-	100	No ignition
	E.4	26.7	757	45	71.1	1005	76.7	Det	MC	176	65 3	8.6	6.5	100	-	-			No ignition
+	E 5	17.2	759	61	71.1	995	69.0	Det	MC	160	73.5	9.7	7.4	17.1	5.3	2.2	12.5	5.8	
1	E-6	29.4	759	44	71.1	1024	77.6	Det	MC	176	84.1	11.1	8.2	30.0	28.3	12.5	24.8	2.0	

*

×

38

Table 2-2 (Continued) SUMMARY OF TEST RESULTS

. . . .

		Ambi	ent Conditi	one	Ter	t Condition	•		enitor			H ₂ Cond	entration						
	Test	Temperature (°C)	Proseurs (mm Hg)	Relative Humidity (%)	Temperature (°C)	Pressure (mm Hg)	Relative Humidity (%)	Туре	Location	Added Water Pressure (mm Hg)	H ₃ Pressure (mm Hg)	Ambient Pressure (%)	Test Pressure (%)	P mex (psig)	R max (psi/sec)	R av (pel/sec)	∆P (pel)	Ar (mec)	Comments
*	D-7	28 3	760	47	98.9	1380	76.3	Spk	MC	543	52.1	6.8	3.8	-	-		-	-	No ignition
1	8 G	28 3	760	47	98.3	1416	76.3	Spk	MC	543	65.1	8.6	4.6	-	-	-		-	No ignition
1	D-9	28.3	760	47	98 J	1460	76.3	Spk	MC	543	78.1	10.3	5.3	-	-		-		No ignition
- 1	010	28.3	760	47	98.9	1503	76.3	Spk	MC	543	81.1	10.7	5.4	~	-	_	-	-	No Ignition
+	D-11	28.3	760	47	98.9	1534	76.3	Spk	MC	543	94.1	12.4	6.1	15.25	10		0.25		Negligible Δ
1	D 12	28.3	760	47	98.9	1570	76.3	Spk	MC	543	107.1	14.1	6.8	15.95	-	1000	0.25	144	Negligible Δ
Φ	E 7	26.7	751	50	98.9	1553	93.9	Det	MC	673	129.0	17.2	8.3		-		-	-	No ignition
1	E-B	222	753	53	100.0	1450	77.8	Det	MC	580	106.0	14.1	7.3	-		-	1.00	-	No ignition
1	£-9	29.4	753	44	100.0	1446	78.8	Det	MC	585	94.0	12.5	6.5	-	100		-	-	No ignition
	E 10	18.3	758	57	100.0	1461	81.2	Det	MC	608	82.0	10.8	5.6	100	100	-	-	-	No ignition
*	E-11	26.7	758	48	100.0	1458	82.9	Der	MC	617	69.0	9.1	4.7	100	100		-	-	No Ignition
2	E-12	20.0	760	60	100.0	1406	76.4	Det	MC	570	53.0	7.0	3.8		-		-	- 9 ·	No ignition
0	F-1	20.0	760	53	102.7	2357	79	Pyro	MC	656	175.7	23.1	7.5	71.0	14.5	8.5	40.5	4.8	
1	F-2	25.0	760	46	103.3	2373	78	Pyro	MC	656	175.7	23.1	7.4	68.5	14.7	8.9	37.3	4.2	
	F-3	24.0	760	49	105.5	2414	75	Pyro	MC	682	222.3	29.2	9.2	106.0	40.0	19.5	74.0	3.8	
1	F-4	27.0	760	47	104.5	2450	81	Pyro	MC	713	222.3	29.2	9.1	121.0	43.5	24.5	88.3	3.6	
*	F 5	23.0	760	48	104.5	2420	69	Pyro	MC	605	253.3	33.3	10.4	120.0	54.0	25.8	87.9	3.4	
1	F-6	28.0	760	52	104.5	2414	73	Pyro	MC	641	258.5	33.9	10.7	123.0	51.0	30.3	91.0	3.0	

NOTES Abbreviations

Ignition Source Spk - 100 Joule Spark

Det - Electric Blasting cap

Pyro - Pyrotuze Ignitor Location

MC - Middle height, center Top - Top center (6 inches down from vessel wall) MS - Middle height, side

• . •

Bot - Bottom center (6 inches up from vessel wall)

2.2 DISCUSSION OF RESULTS

2.2.1 Comparison with Other Data

There have been at least two other investigators who have looked at hydrogen flammability in atmospheres of higher than room temperatures and/or pressure. Yeaw and Shnidman^s investigated the flammability limits of hydrogen and other gases in fuel-air-water vapor mixtures. The experimental apparatus used was a 350-cc spherical glass explosion pipet (8.7 cm diameter) with a centrally located spark igniter. The tests were run at atmospheric pressure, but with temperatures varying from 68 to 187°F with 100% relative humidity, thus resulting in absolute water vapor concentrations of 2.3 to 60.1 volume percent. Both the upper and lower flammability limits of hydrogen were determined at these conditions.

Zabetakis⁶ of the Bureau of Mines determined the flammability limits (upper and lower) of hydrogen in air at 0 psig and 100 psig at 300°F. The range of water vapor concentrations was from 0 to 60 volume percent. The reference report (AECU-3327) did not contain a description of the experimental apparatus, but the high pressures at which some of the tests were run would indicate some sort of steel pressure vessel was used.

By separating the data currently under discussion into two groups, one for flammable mixtures and the other for nonflammable mixtures, a comparison can be made with the flammable limits of Yeaw and Shnidman, and of Zabetakis. Figure 2-2 is a plot of the flammable data group using the coordinates of Yeaw and Shnidman. All the data (with the exception of one point) fall within both the limit line of Yeaw and Shnidman and the limit line of Zabetakis (for 100 psig and 300°F). Figure 2-3 is a plot of the nonflammable data group. It can be seen that the only data points that fall within the flammable limits are those for which the ignition source was a detonator.

It can be seen from these two figures that the current group of data agrees quite well with past experimental data taken under similar but different conditions. Therefore, a high degree of confidence can be placed in these tests as well as those of Yeaw and Shnidman, and of Zabetakis.

2.2.2 Sensitivity of Limits

The sensitivity of the flammability limits is evaluated relative to each of the primary test variables that were identified in Subsection 2.1.2. In addition, the effect of the size of the vessel is also evaluated.

2.2.2.1 Type of Ignitor

As discussed in Subsection 2.1.1, three types of ignitors were evaluated: a capactive discharge spark, a Pyrofuze ignitor which acts like a sparkler, and an electric blasting cap. The flammability of the mixtures appears to be about equal for either the spark or the Pyrofuze ignitors. The blasting cap, on the other hand, is a poor ignitor relative to the other two types, as indicated by the number of data points that fall within the limit lines in Figure 2-3.

2.2.2.2 Location of Ignitor

Four different locations of the Pyrofuze ignitor were evaluated: center, top, bottom, and side. No sensitivity was indicated in the flammability limit at any of these locations.

2.2.2.3 Hydrogen Concentration

The flammability limit is, of course, sensitive to the hydrogen concentration. However, as indicated by the data in Figure 2-2, the flammability of the mixture is not a function of hydrogen concentration alone but hydrogen and water vapor concentration combined.

2.2.2.4 Temperature/Pressure/Water Vapor Content

The effects of temperature and pressure on the flammability limits have been reviewed by others.^{1,3} Over the temperature and pressure ranges of interest in BWR containments and as simulated in the Fenwal tests, the effects



.

Figure 2-2 Flammable Mixtures, Fenwal Data

NEDO-10812

3

2.8

1



č



.

2.9

are small and tend to cancel each other. Increasing temperature lowers the flammability limit, but less than 1% for a 200°F increase. increasing pressure tends to have the opposite effect up to about 5 atmospheres.

Some sensitivity of flammable limits with temperature and pressure would seem to be indicated when comparing Yeaw and Shnidman's results with those of Zabetakis. The Fenwal data fall within the extremes of the pressures and temperatures investigated by Yeaw and Shnidman and by Zabetakis, and over the range of hydrogen and water vapor concentrations tested, could be said to agree with either the Yeaw and Shnidman limit or the Zabetakis limit. Therefore, the flammability limits do not appear to be particularly sensitive in the pressure and temperature range tested by Fenwal and of interest in BWR containment analysis.

Water vapor content has a direct effect on the flammability limits, with the effect becoming more pronounced as water vapor concentration increases. For example, Yeaw and Shnidman found that if the water vapor concentration exceeded 60.1 volume percent, the mixture was nonflammable, regardless of hydrogen concentration. Zabetakis found an even more pronounced effect in that his limiting water vapor concentrations were 51% at 100 psig and 49% at 0 psig.

A more direct presentation of the effect of water vapor concentration is shown in Figure 2-4.

2.2.2.5 Size of Vessel

The size of the vessel does not appear to have a significant effect on flammability limits. The size of the test vessel used by Zabetakis was not specified, but Yeaw and Shnidman used a glass spherical vessel of 8.7 cm (3.4 in.) in diameter. The Fenwal vessel was 6 feet in diameter. Any differences noted in the data are small and are more likely due to the differences in temperature and pressure than to vessel size. Coward and Jones,' for example, discuss the variation in the flammable limit with temperature and pressure, but not with vessel size. The limits stated by Coward and Jones are, in fact, derived from tests conducted in a wide variety of vessel sizes, although all are relatively small.

2.3 APPLICATION TO BWR CONTAINMENTS

The current set of data, along with the data of Yeaw and Shnidman and of Zabetakis, can be used to establish flammability limits more realistic than the current AEC Safety Guide 7 criteria of 4 volume percent hydrogen when oxygen concentration exceeds 5 volume percent. The manner in which the data are applied to define a true safety limit cannot be discussed, however, until the burning characteristics of hydrogen are examined in Section 3.



.

.





3. BURNING CHARACTERISTICS

Knowledge of the manner in which hydrogen burns following ignition is important in determining the true hazard limits associated with hydrogen-air mixtures. Flammability limits alone only bound the problem in identifying the region within which some burning can occur. The type of combustion that does occur can vary from separated flame globules that propagate only in the upward direction, to coherent flames that propagate uniformly at subsonic velocity in all directions, to supersonic detonation waves. The type of combustion that occurs has a strong effect on damage potential to closed containers such as reactor containment buildings.

The Fenwal data provided additional insight into the burning characteristics of hydrogen under conditions expected in BWR containments following a LOCA. These data will be discussed in the following sections. The Fenwal data, along with other investigators' data, will also be used to develop a conservative model for the prediction of maximum pressures in a BWR containment resulting from burning.

3.1 TEST RESULTS

The test results that are of particular interest in discussions of burning characteristics are the peak pressure resulting from combustion in a closed vessel and the pressure-time history. A comparison of the measured to the predicted maximum pressure gives an indication of the degree of completion of the reaction. The pressure-time history gives insight into the rate of the reaction.

3.1.1 Maximum Pressure Rise

The measured peak pressure (P_{max}) and the maximum pressure rise (ΔP) are listed in Table 2-2. A more useful parameter is the pressure rise relative to the initial pressure ($\Delta P/P_o$). This parameter is plotted against hydrogen concentration in Figure 3-1.

3.1.2 Pressure Rates

The time at which the peak pressure occurred is shown in Table 2-2. Also listed in Table 2-2 are the average and maximum pressure rates recorded in the tests. Plots of the relative pressure rise against time for most of the tests are in the Appendix.

3.2 DISCUSSION OF RESULTS

3.2.1 Maximum Pressure Rise Sensitivity

Figure 3-1 shows that the relative pressure rise is sensitive to a number of parameters:

- Type of ignitor
- Hydrogen concentration
- Temperature/pressure/water vapor content.

The effect of each of these parameters will be discussed individually.

3.2.1.1 Type of Ignitor

Of the three types of ignitors tested (see Subsection 2.1.1), ignition by the Pyrofuze ignitor resulted in the highest pressure rise for any given set of initial conditions. The spark ignitor gave much lower pressure rises when the hydrogen concentration was less than about 8%. The results for the detonators were somewhat mixed, with the pressure rise being extremely low for one set of conditions and almost as high as the Pyrofuze data for a another set of conditions.

The spark ignitor data agree very well with those of Furno, et al.' The Furno data were taken in a 12-foot-diameter sphere with a centrally located spark ignitor as the ignition source. Figure 3-2 is a plot of Furno's measured pressure rises versus hydrogen concentration compared with the Fenwal results. Both sets of data show the same characteristic



3-2



Figure 3-2 Prossure Rise Versus Hydrogen Concentration, Spark Ignitor

of very small pressure rises until the hydrogen concentration exceeds about 8%. As shown in Figure 3-1, the Pyrofuze ignitor caused higher pressure rises than the spark ignitor under similar conditions (i.e., hydrogen concentration, temperature, etc.). Because of the "sparkler" characteristics of the Pyrofuze ignitor, a large number of ignition sources were actually provided throughout the test vessel rather than a single source at one location as in the case of the spark ignitor. Therefore, it was likely that a number of "flamelets" rather than just one were started throughout the test vessel. The result was that more hydrogen was consumed and, hence, higher pressure rises were recorded.

The results with the detonator were somewhat conflicting. For one set of conditions, the pressure rises were less than recorded for the spark ignitor. Under the other set of conditions, the pressure rises were higher than the spark ignitor results but less than would be expected for a Pyrofuze at those same conditions. In any case, the most significant result was that the detonator did not result in a combustion-supported detonation wave propagating through the gas mixture.

3.2.1.2 Hydrogen Concentration

As already discussed, the spark ignitor results were extremely sensitive to hydrogen concentration, with virtually no significant pressure rises occurring until the hydrogen concentration exceeds 8%.

Some of the characteristic differences between upward and downward flame propagation were discussed in Section 2. Figure 3-2 demonstrates most graphically the effect of those differences on maximum pressure rise. At concentrations less than about 8%, flames will only propagate in the upward direction. The hydrogen flame at these lower concentrations is actually a small flamelet, or globule of hot gas, which rises through the gas mixture because of buoyancy. The actual burning process is diffusion controlled, and the flame will extinguish itself when the hydrogen concentration falls below some critical value.⁷ Thus, there will always be some residual hydrogen in the vessel following this type of combustion. Furno measured considerable quantities of residual hydrogen following tests in which the sparking was continued for 2 to 5 seconds, resulting in higher pressure rises than the single spark tests; hence this presumably means that more hydrogen was actually consumed than in the single-spark tests. In one test, only about 19% of the original hydrogen was consumed, and in the other, only 5%. These values were for original concentrations of 6.9% and 7.4%, respectively. The measured pressure rises for these two tests were completely compatible with the amounts of hydrogen actually consumed. Therefore, the low-pressure rises in Figure 3-2 at less than 8% hydrogen concentration indicate that only very small amounts of the hydrogen (less than 10%) were actually consumed in the deflagration.

It was only after the hydrogen concentration exceeded about 9% that no residual hydrogen was measured in the test vessel, during Furno's experiments. As a result, the pressure rises associated with these higher concentrations are much closer to the theoretical values, with most of the difference remaining caused by heat losses from the gas to the test vessel.

The Pyrofuze ignitor, by providing more ignition sources, caused higher pressure rises at the lower concentrations than the spark ignitor. Even with the Pyrofuze ignitors, the test pressure rises still were much less than would be predicted for complete combustion of the hydrogen. This can be seen in Figure 3-3 which shows the ratio of the measured maximum pressure rise (ΔP) to the theoretical maximum pressure rise (ΔP_{max}), assuming completion combustion, plotted against hydrogen concentration. It can be seen that hydrogen concentration must exceed from 7.5% to 9%, depending on type of ignitor and initial conditions, before near-theoretical pressure rises are achieved. Again, as has been previously discussed, the differences are caused by the manner in which the flame propagates through the mixture at the various concentrations.

3.4



Figure 3-3 Comparison of Actual With Theoretical Pressure Rise (Completeness) for Hydrogen Burning in a Closed Vessel

3.2.1.3 Temperature/Pressure/Water Vapor Content

Comparison of the pressure rises at a given hydrogen concentration in Figure 3-1 shows that the results have a strong dependence on the initial environmental conditions. Some effect of initial conditions is expected and predictable, as can be seen in the following equation for the predicted relative pressure rise (which is derived in Subsection 3.3.1):

$$\left(\frac{\Delta P}{P_o}\right)_{\text{Adiabatic}} = \frac{\Delta u^o (H_2)}{\overline{C_v} T_o} + \left(\frac{n_f}{n_o} - 1\right).$$
(3.1)

The relative pressure rise is thus sensitive to the initial temperature, T_o , and the composition of the final mixture, in that the value for the average specific heat, \overline{C}_v , is affected by composition. Water vapor content has a fairly strong effect on the specific heat. The heat of combustion, Δu^o , is only slightly affected by temperature. The ratio of the final to the initial number of moles (n_v/n_o) is practically unity in the lean mixtures of interest in the present discussion; therefore, the quantity in parentheses is essentially zero. Thus, after variations in \overline{C}_v and T_o are properly accounted for, the relative adiabatic pressure rise is directly proportional to the relative amount of hydrogen reacted ($[H_2]$).

The theoretical adiabatic pressure rises were calculated for each of the conditions tested and compared with the actual pressure rises measured in the tests. Figure 3-3 is a plot of the ratio of the measured over the theoretical pressure rise versus hydrogen concentration. If the amount of hydrogen reacted and the heat losses were the same in each of the tests at a given hydrogen concentration (and using the same type of ignitor), all of the points in Figure 3-3 would be expected to fall on the same line. This was obviously not the case.

The fraction of the theoretical pressure achieved in the tests decreased roughly in proportion to increases in initial temperature and water vapor content. It was shown in Section 2 that increasing water vapor content raised the lower flammability limit of hydrogen; therefore, it is possible that the reaction between hydrogen and oxygen was inhibited by the presence of water vapor. In Subsection 3.2.2, the rates of the reactions are discussed, and it is noted that the reaction rates were slower at higher initial water vapor content. Thus, since more heat losses would be expected before the peak pressure was reached, the peak pressure would be expected to be proportionally lower than if the reaction had proceeded at a faster rate.

3.2.2 Pressure Rate Sensitivity

Pressure rate data from experimental tests in closed vessels, unlike the maximum pressure rise data, are not independent of the geometry of the test apparatus. Zabetakis^a, for example, has stated that the time to reach peak pressure in spherical vessels can be expressed by an equation of the form,

$$t_{\text{peak}} = K \sqrt[3]{V}, \qquad (3.2)$$

where K is an experimentally derived parameter and V is the volume of a spherical vessel. Thus, for a given set of initial conditions, the time to reach the peak pressure (or any intermediate pressure) is directly proportional to the cube root of the containing vessel's volume. This concept has experimental verification⁴ over a wide range of vessel sizes (2 to 1000 cubic feet) and, in ferre gives a conservative (i.e., low) prediction of the time to reach peak pressure as vessel size is increased.

Since the average pressure rate is simply the peak pressure divided by the time to reach the peak pressure, it follows from the preceding arguments that the average pressure rate should be inversely proportional to the cube root of the volume of the vessel. This proportionality was used in comparing the Fenwal and Furno⁷ test results. Figure 3-4 is a plot of the average pressure rate from both the Fenwal and Furno test results. The average pressure rates from Furno's tests were adjusted by multiplying them by the cube root of the ratio of the Furno-to-Fenwal vessel volumes. There is good agreement between the adjusted Furno data and the Fenwal spark ignitor data at the lower concentrations. At higher concentrations (>10% hydrogen), the Fenwal data appear to be approaching the same rate as the adjusted Furno data. The reasons for the disagreement between the Pyrofuze and spark ignitor data are discussed in Subsection 3.2.2.1.





3.7

Equation (3-2) was derived by Zabetakis[®] from the concept that the pressure transient can be described in terms of a flame moving at a constant velocity through the vessel. Accurate prediction of a pressure transient is therefore dependent on (1) the selection of the correct flame spark, and (2) an accurate description of how the flame moves through the vessel. This concept is followed through in Subsection 3.3 in which a burning rate model is developed and the model is compared with the transient pressure rate data.

It is shown in Subsection 3.3 that the transients can be accurately described regardless of the complexity of the burning process, i.e., upward propagation of small flamelets, upward followed by downward, or spherical flame propagation. The remainder of this section is devoted to describing the effect of various parameters on the test results.

3.2.2.1 Type and Location of Ign/tor

The pressure transients associated with the spark ignitor (Figure A-4) are trivial because only a very small amount of the total hydrogen available was consumed. The average pressure rate agrees well with Furno's data, as shown in Figure 3-4.

The differences between the pressure rates for the Pyrofuze and spark ignitors are proportional to the differences between the maximum pressure rises as shown in Figure 3-1. Since the average pressure rate is simply the peak pressure divided by the time to reach peak pressure, it follows that the time to reach peak pressure was not significantly affected by the type of ignitor used. This is shown (later) in Figure 3-6 which is a plot of the time to reach peak pressure versus hydrogen concentration. There is no indication of any significant differences in the time to reach peak pressure due to the type of ignitor used.

Several locations of the Pyrofuze ignitor were tested. The pressure transients for ignition at the center, bottom, top, and side are shown in Figure 3-5; the hydrogen concentration was 7.7% for all tests. The transients for ignition at the center and bottom practically coincide, with the peak pressure being reached in about 2 seconds. Ignition at the top resulted in the slowest transient, with the peak pressure being reached in about 4 seconds. Ignition at the side was between the two extremes, with the peak pressure being reached in about 3 seconds.

The same trend in these results was found in tests done at lower concentrations (4.8 to 5.3% hydrogen). The meaning of these results is not clear, especially when compared with Furno's results. Furno reported on the time to reach peak pressure for one ignition at the bottom of the 12-foot test vessel as being 5.7 seconds, with an initial hydrogen concentration of 7.2%; with ignition at the center, the time to reach the peak pressure was about 4 seconds. Thus, Furno's tests gave different relative results than Fenwal's test for sensitivity of the burning rate to the location of the ignitor. The difference in test results between Furno and Fenwal is probably attributable to the difference in ignitors; Furno used a spark ignitor and Fenwal, a Pyrofuze ignitor.

The results with the detonator were compatible with the results using the Pyrofuze ignitors.

3.2.2.2 Hydrogen Concentration

Figure 3-6 is a plot of the time to reach peak pressure versus hydrogen concentration. Three sets of data are shown: Furno's' from the 12-foot-diameter sphere, Fenwal's from the 6-foot-diameter sphere, and Dieterlin's'-size of vessel unknown, but probably on the order of 1 to 2 feet in diameter. The Furno' and Dieterlin' data clear' show the transition from upward propagation to upward plus downward propagation at about 8% hydrogen is antration.

The Fenwal data tend to follow the same trends as the Furno and Dieterlin data, although there is considerably more scatter in the data, which is probably due to the widely varying initial conditions under which the Fenwal data were obtained.

Above about 6.5% hydrogen, increasing hydrogen concentration results in continuous, smooth decrease in the time to reach peak pressure without any further discontinuities. At about 12% hydrogen, the flame propagation speed is fast enough that buoyancy effects become negligible and spherical flame propagation occurs in which a spherical flame front moves uniformly in a radial direction away from the ignition source.







Figure 3-6 Time to Reach Peak Pressure Versus H₂ Concentration, Central Ignition

(%) NEDOUGAH

3.10

NEDO-10812

3.2.2.3 Temperature/Pressure/Water Vapor Content

Effects of the foregoing parameters in hydrogen-air burning characteristics are virtually nonexistent, especially at the low hydrogen concentrations of interest. The survey by Drell and Belles³ discusses the effects of pressure and temperature on burning velocity. For the lowest hydrogen concentration recorded (27%), increasing initial temperature increased the burning velocity. Over the temperature range of interest in BWR containments (70°F to about 250°F), the burning velocity increased almost 70%. The Fenwal data do not indicate anywhere near that degree of change in the pressure rates or time to reach peak pressure as a function of temperature.

The effect of pressure also is not readily available from the literature. For lean hydrogen-air mixtures, however, the available data³ indicate that increasing pressure would decrease burning velocity but the effect would be small. There is little noticeable effect of pressure on the Fenwal data.

The effect of added diluents on burning velocity can be found in a number of sources,^{16,11,12} but the diluents discussed are either nitrogen or carbon dioxide, not water vapor. It is expected, however, that water vapor would have a similar effect on burning velocity as other diluents. Again, however, direct comparisons with the Fenwal data are difficult because the literature data are all at relatively high hydrogen concentrations (>20%). At these high concentrations, the added diluents have a strong effect on burning velocity, but if the data are extrapolated to the lower hydrogen concentrations, the effect would be predicted to be much less.

The Fenwal data (see Figures 3-4 and 3-6) do indicate, however, that burning velocity was reduced as the temperature, pressure, and water vapor content increased. The data seem to indicate that the strongest effect is due to the water vapor content of the gas mixture.

3.3 BURNING RATE MODEL

In a closed vessel, the pressure rise due to the combustion of a hydrogen-air mixture may be predicted from the burning rate. In turn, the burning rate depends on the geometry of the vessel and velocity of the propagating flame front. Depending on the concentration of hydrogen in the initial mixture, the type of flame propagation is either upward, downward, or spherical.

Upward propagation is characterized by an incoherent flame front and incomplete combustion of the initial hydrogen.^{1,7} The burning front is propagated upward by the buoyancy of small individual flamelets. The existence of these flamelets is attributed to the different ratas of diffusion of hydrogen and oxygen.¹¹ The generally accepted lean limit of upward propagation is 4% hydrogen.^{1,2,3}

Combustion of mixtures with sufficiently high concentrations of hydrogen (8.5 to 9%) results in upward followed by downward propagation of a coherent flame front. Data indicate that the combustion of hydrogen in the downward propagation regime is essentially complete.^{1,7} The recommended lean limit for downward propagation in a hydrogen-air mixture varies from 8.5%⁷ to 9.0% hydrogen.^{1,3}

At still higher hydrogen concentrations, the propagation is isotropic and the flame front is a concentric spherical shell. In this case, the propagation is sufficiently rapid that the convective rise of combustion products does not affect the propagating flame front. At hydrogen concentrations greater than 11 to 12% hydrogen, the data indicate spherical propagation.⁷

A model will be developed in the following subsections that describes each of these types of burning processes.

3.3.1 Maximum Pressure Rise

is

Since the propagation speed of a combustion wave for the hydrogen concentrations under consideration is much less than the speed of sound, the pressure will be essentially equalized throughout the vessel at any instant. The maximum possible pressure rise is determined by assurning complete combustion of hydrogen with no heat losses to the vessel walls. The complete reaction is:

$$x_{N_2} N_2 + x_{O_2} O_2 + x_{H_2} H_2 + x_{H_2O} H_2O \rightarrow$$

Energy + $x_{N_2} N_2 + (x_{O_2} - \frac{1}{2} x_{H_2}) O_2 + (x_{H_2O} + x_{H_2}) H_2O$

The combustion energy is absorbed by the mixture of combustion products and inerts. The overall energy balance

$$\Delta U = \bar{C}_{v} n_{f} (T_{f} - T_{o}) = n_{o} [H_{2}] \Delta u^{0}, \qquad (3.3)$$

where $[H_a]$, n_o, and T_o are, respectively, the mole fraction of hydrogen, total moles, and temperature of the initial mixture before combustion; ΔU^o is the combustion energy per mole of hydrogen; and ΔU , n_v, $\overline{C_v}$, and T_v are, respectively, the internal energy difference, total moles, average specific heat at constant volume, and temperature of the product mixture. Assuming ideal gas behavior, the ratio of the final pressure P_v to the initial pressure P_o is:

$$\frac{P_f}{P_o} = \frac{n_f T_f}{n_o T_o}, \qquad (3.4)$$

Solving for T, from Equation (3-3) and substituting into Equation (3-4) gives

$$\left(\frac{\Delta P}{P_{o}}\right)_{max} = \frac{P_{f} - P_{o}}{P_{o}} = \frac{\Delta u^{o} [H_{2}]}{\overline{C}_{v} T_{o}} + \frac{n_{f}}{n_{o}} - 1.$$
(3.5)

This result is the maximum possible pressure rise for the complete, adiabatic (no heat losses) combustion of a hydrogen mixture in a closed vessel.

The average molar specific heat at constant volume is defined as

$$\bar{C}_{v} = \frac{u_{f} - u_{o}}{T_{f} - T_{o}}.$$
(3.6)

where u and u, are, respectively, the internal energies per mole of product mixture at T, and T_o. The internal energy of the product mixture is determined by averaging over the molar concentrations of the constituents:

$$u = \frac{\sum_{i} n_{i} u_{i}}{\sum_{i} n_{i}} = \frac{\sum_{i} n_{i} u_{i}}{n_{f}}, \qquad (3.7)$$

where n, and u, are, respectively, the moles and internal energy of the various constituents. The final temperature T, must be assumed to calculate \overline{C}_{ν} . To ensure accuracy, this assumed value should be approximately equal to the theoretical value of T, calculated from Equation (3-3). The predicted temperature rise is shown in Figure (3-7) as a function of initial hydrogen concentration and water vapor content. These curves were calculated from Equation (3-3).





The maximum possible pressure rise in hydrogen-air-water vapor mixtures is shown in Figure (3-8) plotted against initial percent of hydrogen for three initial water vapor concentrations. Equation (3-5) was used for the calculations. The pressure rise increases sharply with initial hydrogen concentration. Increasing $[H_2]$ by 4% increases the ratio $(\Delta P/P_o)_{max}$ by approximately 1.0. This strong dependence is attributed to the high combustion energy of the H₂-O₂ reaction.

The results in Figure 3-8 are for $T_o = 140^{\circ}$ F. To correct for difference values of initial temperature, the factor χ is presented in Figure 3-9. For $T_o \neq 140^{\circ}$ F, the maximum pressure rise is given by

$$\left(\frac{\Delta P}{P_{o}}\right)_{max}^{T_{o}} = \chi \left(\frac{\Delta P}{P_{o}}\right)_{max}^{T_{o}} = 140^{\circ} F$$

(3-8)

where χ is a function of T_e.

3.3.2 Pressure Transient Prediction

This subsection presents theoretical models for predicting the rate of pressure rise in a closed spherical vessel for the combustion of a gaseous mixture. Separate models are proposed for spherical, downward, and upward propagation. In all cases, equal pressure throughout the vessel is assumed at any instant. The combustion wave is modeled as a surface of discontinuity, moving with constant propagation speed, across which the change from the unburned to the burned state takes place.

3.3.2.1 Spherical Propagation

For spherical propagation with central ignition, Zabetakis² proposes that the pressure rise, $\Delta P/P_o$, at time t after ignition, is proportional to the volume of gas burned:

$$\frac{\Delta P}{P_o} = \frac{K}{V} (S_u t)^3.$$
(3.9)

where V is the vessel volume, S_o is the constant burning velocity,* and K is an empirically determined constant. In Figure 3-10 the calculated pressure using Equation (3-9) is compared with the experimental pressure produced by the combustion of a 9.6% methane-air mixture in a 9-liter cylinder.* The constant K was calculated from the experimental data at 70 milliseconds. The theoretical pressure rise is terminated at the maximum pressure P_m which is calculated from Equation (3-5).

Figure 3-10 shows that the predicted pressure follows very closely the experimental pressure until about 75 milliseconds. Zabetakis attributes the subsequent deviation to heat losses to the vessel walls, and to the interference of the cylinder walls with the spherical combustion wave. The maximum experimental pressure is about 95% of the maximum predicted pressure ΔP_m . If the combustion is complete, this 5% deviation is attributed solely to heat losses.

"Lewis and yon Elber" define the burning valocity as "the valocity of the reaction zone front with respect to the unburned gas."



Figure 3-8 Final Pressure Versus H, Concentration

**



INITIAL TEMPERATURE, TO (°F)

Figure 3-9 Correction for Initial Temperature

3.3.2.2 Downward Propagation

For a spherical enclosure with central ignition, Furno' describes the flame propagation in the downward regime as an initial upward propagation followed by a slow, steady, downward propagation which consumes essentially all of the combustible gas. Consider a linear flame front propagating downward with constant velocity S_r from the top of the sphere, as shown in Figure 3-11. Assuming that the pressure rise ΔP is proportional to the volume of burned gas V_b, and that heat losses to the walls are proportional to the surface area exposed to the burned gases A_b, the ratio of the pressure rise at time t to the maximum pressure rise is

$$\frac{\Delta P(t)}{\Delta P_{\text{max}}} = \frac{V_{\text{b}}(t)}{V_{\text{b},\text{max}}} - Q \frac{A_{\text{b}}(t)}{A_{\text{b},\text{max}}},$$
(3.10)

where $V_{b,max}$ and $A_{b,max}$ are, respectively, the total spherical volume and surface area, ΔP_{max} is the maximum pressure rise from Equation (3-5), and Q is an empirically determined constant related to the heat losses. From simple geometry,

$$I_{\rm h}(t) = \frac{\pi}{2} h^2(t) \left[3R_{\rm e} - h(t) \right]$$
(3-11)

$$A_{\rm h}(t) = 2\pi R_{\rm e} h(t),$$
 (3.12)

where R_s is the sphece radius, and $h(t) = S_s t$ is the location of the flame front relative to the top of the sphere as shown in Figure 3-11. Substituting the foregoing results into Equation (3-10) and rearranging gives the ratio of pressure rise to initial pressure as

$$\frac{\Delta P(t)}{P_{o}} = \left(\frac{\Delta P}{P_{o}}\right)_{max} \left\{ -\frac{1}{4} \left(\frac{S_{f}t}{R_{s}}\right)^{3} + \frac{3}{4} \left(\frac{S_{f}t}{R_{s}}\right)^{2} - \frac{Q}{2} \left(\frac{S_{f}t}{R_{s}}\right) \right\}, \qquad (3.13)$$

where ($\Delta P/P_o)_{max}$ is the maximum pressure (adiabatic, complete-combustion) from Equation (3-5).

In Figures 3-12, 3-13, and 3-14, the predicted pressure rise using Equation (3-13) is compared with the experimental pressure for three hydrogen-air-water vapor mixtures ranging from 9.2 to 10.7% hydrogen. The initial concentration of water vapor varies between 25 and 30% in all three cases. The flame propagation speed (S_i) was taken as the sphere diameter divided by the experimental time to reach maximum pressure after ignition. The heat loss constant Q was determined from the slope of the pressure decay curve following maximum pressure.

In all three comparisons, excellent correlation of theoretical and experimental results is indicated. Slight deviations during the transient are attributed to irregularities in the "linear" flame front, especially near the vessel walls. In Figure 3-12 the maximum experimental pressure is predicted exactly; whereas, for Figures 3-13 and 3-14, it is overpredicted by about 5%. Since it is unlikely that there is any residual hydrogen in the latter two cases, the discrepancies are attributed to underestimating the heat loss constant Q in Equation (3-13). In comparing the maximum experimental pressure ($\Delta P/P_o$)_{max} in the three cases shown, heat losses account for a 20 to 25% reduction in the maximum observed pressure.

3.3.2.3 Upward Propagation

A theoretical model for pressure rise in the upward propagation regime must account for the imcomplete combustion of hydrogen. For central ignition in a spherical vessel, consider a linear flame front propagating upward from the center plane of the sphere as shown in Figure 3-15. The flame propagation velocity S_i is assumed constant. Using the assumptions of Subsection 3.3.2.2, the ratio of pressure rise to maximum pressure rise is given by Equation (3-10). Assuming


TIME AFTER IGNITION (msec)

Figure 3-10 Theoretical and Experimental Rise for Spherical Propagation in a 9.6% Methane-Air Mixture in a Cylindrical Vessel with Central Ignition



Figure 3-11 Steady, Downward Propagation in a Spherical Vessel



Figure 3-12 Theoretical and Experimental Pressure Rise for Downward Propagation (9.2% H₂) in a Spherical Vessel with Central Ignition







Figure 3-14 Theoretical and Experimental Pressure Rise for Downward Propagation (10.7% H₂) in a Spherical Vessel with Central Ignition



Figure 3-15 Steady Upward Propagation in a Spherical Vessel, with Central Ignition

that the effect of the incomplete burning of hydrogen on the pressure rise is proportional to the burned volume $V_{o}(t)$, the ratio of the pressure rise to the maximum pressure rise is

$$\frac{\Delta P(t)}{\Delta P_{max}} = \frac{V_{b}(t)}{V_{b, max}} - C' \frac{V_{b}(t)}{V_{b, max}} - Q \frac{A_{b}(t)}{A_{b, max}}, \qquad (3-14)$$

where C' is a constant of the incomplete combustion of hydrogen. By defining

$$C \equiv \frac{\Delta P}{\Delta P_{max}}$$
(3.15)

and assuming that the maximum experimental pressure rise, ΔP , occurs when the flame front reaches the top of the sphere, then the constant C' is, from Equation (3-14),

$$C' = 1 - C - Q.$$
 (3-16)

Since combustion is confined to the upper half of the sphere, then $V_{b,max} = 2/3\pi R^3$ and $A_{b,max} = 2\pi R^2$. From simple geometry,

$$V_{b}(t) = \frac{2\pi}{3} R_{s}^{3} - \frac{\pi}{3} h^{2}(t) [3 R_{s} - h(t)]$$
(3.17)

$$A_{\rm b}(t) = 2\pi R_{\rm e}^2 - 2\pi R_{\rm e} h(t), \qquad (3-18)$$

where $h(t) = (R_s - S_s t)$ is the vertical distance of the flame front from the top of the sphere. Combining the above results gives the pressure rise for upward propagation:

$$\frac{\Delta P(t)}{P_{o}} = \left(\frac{\Delta P}{P_{o}}\right)_{max} \left\{ -\frac{(Q+C)}{2} \left(\frac{S_{f}t}{R_{s}}\right)^{3} + \frac{1}{2} (Q+3C) \left(\frac{S_{f}t}{R_{s}}\right)^{2} \right\}.$$
(3.19)

where $(\Delta P/P_o)_{max}$ is the maximum possible pressure rise (adiabatic, complete combustion).

In Figures 3-16 through 3-19, theoretical calculations are compared with experiment for hydrogen-air-water vapor mixtures. For these four cases, the initial concentration of hydrogen varied between 4.8 and 8.1% while the water vapor concentration varied from zero to 39%. The flame propagation speed (S_r) was taken as the sphere radius divided by the time to reach maximum experimental pressure. The heat loss constant Q was calculated as described in Subsection 3.3.2.2. Experimental data for each case were used to calculate the combustion-completeness constant C.

For all cases, the theoretical curve overpredicts the slowly increasing experimental pressure during the early part of the transient. A probable explanation is that the model assumes the flame front is instantaneously established across the midplane of the vessel, resulting in an overpredictich of the initial hydrogen consumption rate. In fact, the propagation is probably hemispherical during the early part of the transient, as indicated by the cubic nature of the experimental curve. Following this period, both theoretical and experimental curves exhibit a region of constant pressure rise, and then a leveling-off to maximum pressure.

The maximum predicted pressure occurs shortly before the experimental peak pressure because, near the end of the transient, heat losses to the vessel walls are greater than the energy supplied by combustion. In Figures 3-16 through 3-18, the maximum experimental pressure is less than 50% of the maximum possible pressure $(\Delta P/P_o)_{max}$ given by Equation (3-5). This is due partly to heat losses, but mostly to incomplete hydrogen combustion. In Figure 3-19, the experimental pressure is almost 90% of the maximum possible, suggesting the onset of downward propagation in which combustion is more complete.



TIME AFTER IGNITION (sec)

Figure 3-17 Theoretical and Experimental Pressure Rise for Upward Propagation (6.4% H₂) in a Spherical Vessel with Central Ignition



TIME AFTER IGNITION (sec)

Figure 3-18 Theoretical and Experimental Pressure Rise for Upward Propagation (7.3% H₂) in a Spherical Vessel with Central Ignition



Figure 3-19 Theoretical and Experimental Pressure Rise for Upward Propagation (8.1% H) in a Spherical Vessel with Central Ignition

3.3.2.4 Empirical Parameters

In the foregoing text, the flame front was idealized as an infinitely thin, plane combustion wave propagating with constant velocity through a quiescent atmosphere. Adiabatic compression¹⁶ of the unburned gas by the propagating flame front was ignored. It was assumed that the speed, geometrical shape, and direction of propagation of the wave depend on the isitial hydrogen concentration. While the physical mechanism and geometry of the flame propagation is more complex than assumed here, the justification for this simplified model is the agreement with experimental data.

Given the empirical parameters S_r , C, and Q — which depend on the initial mixture composition — the burning rate, and thus the pressure transient, may be predicted. The mean flame propagation speed (S_r) is the length of flame propagation divided by the time to reach maximum pressure. The flame speed versus hydrogen concentration is shown in Figure 3-20. Both the Fenwal data and Furno's data' for upward and downward propagation are shown. For upward propagation, the flame speed increases with hydrogen concentration and reaches a maximum at about 8% hydrogen. This is followed by a transition region in which the flame speed decreases, and then by steady downward propagation (greater than 8.5%) in which the flame speed increases with hydrogen concentration.

The empirical constant C [Equation (3-14)] defines the experimental deviation from the maximum theoretical pressure due to incomplete combustion and heat losses. Figure 3-3 shows the constant C versus hydrogen and water vapor concentration for experimental data. For upward propagation, the combustion constant increases sharply with hydrogen concentration, indicating more complete combustion. Increasing the water vapor concentration subdues the pressure rise. However, the observed effect in Figure 3-3 is more pronounced than that predicted by the theoretical curves in Figure 3-8, indicating that water vapor may somewhat inhibit hydrogen combustion. For initial water vapor concentrations greater than 20%, hydrogen combustion is generally less than 60% complete for all data in the upward propagation regime. As discussed in Subsection 3.2.1.1, hydrogen combustion is less than 10% complete for single-spark ignition in mixtures with less than 8% hydrogen. Thus, in the upward propagation regime, more complete hydrogen combustion is expected from the "sparkler-like" Pyrofuze ignitor than from a single, isolated ignition source.

The heat loss term, Q, was derived from the negative slope of the experimental pressure transient curves following the completion of the burning.

3.3.3 Burning Rate Model for BWR Containments

In Subsection 3.3.2, a burning rate model was presented which accurately predicts the pressure transient for the combustion of a hydrogen-air-water vapor mixture in a closed vessel. This same model, with the addition of a venting term to account for pressure relief through the BWR containment pressure suppression system, and the following conservative assumptions, will be used to make conservative predictions at pressure transients resulting from hydrogen burning in the containments.

- a. The maximum theoretical pressure rise is based on adiabatic, complete combustion in dry air.
- b. Conservative values which overpredict essentially all data are used for the flame propagation speed.
- c. Interaction of the flame front with walls and other perturbations is ignored.
- d. In the upward propagation regime, the values for the completeness factor C overpredict almost all data points. The completeness data are deemed conservative in that they are for the "multi-source" Pyrofuze ignitor rather than a single ignition source.
- e. Any effects of water vapor in reducing the completeness have been ignored.
- Complete hydrogen combustion and no heat losses are assumed for hydrogen concentrations greater than 8%.
- 9 No evaporation of water is assumed to take place in the BWR containments during combustion.
- h. No cooling is assumed as the vented gases bubble through the suppression pool, resulting in a conservative calculation for suppression chamber back pressure.





The various configurations of the BWR containment designs will be accounted for individually. Basically (see ske(ch), BWR containments consist of two chambers. The drywell is the chamber directly surrounding the reactor vessel. The drywell is connected to the other chamber (called the suppression chamber, or wetwell, or containment in the case of the Mark III design) through pressure suppression vents submerged to some depth in the suppression pool water which is also contained in the suppression chamber.



3.3.3.1 Temperature and Pressure Calculations

To calculate the burning rate in a reactor containment, assume a uniform combustion wave propagating with constant velocity S, through a quiescent atmosphere. The propagation is either upward, downward, or spherical, depending on the initial hydrogen concentration. Assuming complete, adiabatic (no heat losses) combustion, the maximum possible temperature and pressure rises are given by Equations (3-3) and (3-5), respectively. The completeness constant C, defined in Equation (3-15), accounts for heat losses and the residual hydrogen that does not combust. Assuming that the number of moles of burned gas, $n_{\rm b}$, is proportional to the volume burned V_b, then

$$n_{b}(t) = \frac{V_{b}(t)}{V_{b,max}} n_{o} - \frac{1}{2} \frac{V_{b}(t)}{V_{b,max}} \left\{ C n_{o} [H_{2}] \right\} - n_{vb}(t).$$
(3.20)

where n_e and $[H_2]$ are, respectively, the initial moles and initial molar fraction of hydrogen in the reactor containment, $V_{e,max}$ is the total free volume, and n_{ee} is the total moles of burned gas vented at time t. The second term on the right-hand side of Equation (3-20) represents the decrease in moles due to the reaction:

$$H_2 + \frac{1}{2}O_2 - H_2O_2$$
 (3-21)

The number of moles of unburned gas, n_v, remaining at time t is

$$n_{u}(t) = n_{o}\left[1 - \frac{V_{b}(t)}{V_{b, max}}\right] - n_{vu}(t),$$
 (3.22)

where n_{v} is the total number of moles of unburned gas vented at time t. The average temperature of the containment atmosphere, \overline{T} , based on the number of moles of burned and unburned gases, is

$$\overline{T}(t) = \frac{(n_b(t) T_b + n_u(t) T_u)}{[n_b(t) + n_u(t)]}.$$
(3.23)

The temperature of the unburned gases T_{ν} is the initial containment atmosphere temperature T_{o} in degrees Rankine. The temperature rise of the burned gases, $(T_{b} - T_{o})$, is the product of the completeness factor and the maximum possible temperature rise from Equation (3-3); thus,

$$T_b = T_o + C (T_f - T_o).$$
 (3.24)

Assuming idea! gas behavior,

¢

$$V(t) = \frac{[n_{b}(t) + n_{u}(t)] R \bar{T}(t)}{V_{b, max}}.$$
 (3.25)

where R is the molar gas constant. The reactor containment pressure for constant flame propagation is specified by Equation (3-25) which includes the effects of venting (drywell only) and incomplete hydrogen combustion with heat losses.

3.3.3.2 Volume of Burned Gases for BWR Containments

The ratio of volume burned to total volume in Equations (3-20) and (3-22) depends on the type of propagation and the geometry of the reactor containment. Assuming constant flame propagation speed, the ratio V_b (t)/ $V_{b,max}$ for the idealized containment geometries is presented in Table 3-1 for the three types of propagation. The hydrogen concentration limits for upward, downward, and spherical propagation correspond to those discussed earlier in this section.

In the spherical regime, each containment was modeled as a sphere of volume V_{b.max} and radius,

$$\overline{\mathsf{R}}_{\mathsf{s}} = \left[\frac{3 \,\mathsf{V}_{\mathsf{b},\,\mathsf{max}}}{4\pi}\right]^{1/3}.$$

For this idealized spherical geometry,

$$\frac{V_{b}(t)}{V_{b, \max}} = \left(\frac{S_{f}t}{\overline{R}_{s}}\right)^{3}.$$
(3-26)

Zabetakis² accurately predicted the pressure rise in a cylinder by assuming a spherical (cubic) burning law similar to Equation (3-26).

To facilitate the calculation of V_b (t)/ $V_{b,max}$, the BWR containments were approximated by simple geometries. Protrusions that could perturb the propagating flame front were ignored.

a. Mark I

The free space of the "lightbuib-shaped" Mark I drywell is idealized as a cylindrical annulus. The reactor vessel and biological shield make up the interior cylindrical region. The fraction of volume burned for upward and downward propagation is linear in time, as indicated in Table 3-1. Horizontal flame spread is assumed in the suppression chamber torus, with the propagation speed equal to that of upward or downward propagation, depending on the hydrogen concentration. This is conservative in that the lean limit for horizontal flame spread is about 6% hydrogen.¹ The fraction of volume burned is also linear in time.

b. Mark II

The Mark II drywell is idealized as the annular region of a cone frustrum. With this rather complicated geometry, the fraction of volume burned is different for upward and downward propagation. The Mark II suppression chamber is simply a cylinder and has a linear burning rate.

c. Mark III

Just as with the Mark I, the Mark III drywell is a cylindrical annulus with a linear burning rate. The Mark III containment (suppression chamber) is approximated as a cylindrical annulus up to the height of the drywell and, thereafter, a cylinder to the top of the containment. The burning rates for these two regions are different, as indicated in Table 3-1.

3.3.3.3 Venting From BWR Drywells

The elevated pressures from hydrogen combustion will open the suppression chamber vents, resulting in pressure relief for the BWR drywells. Since the vent openings are located near the bottom of all BWR drywells, it is assumed that only unburned gases are vented for spherical and downward propagation, whereas only burned gases are vented for upward propagation. To determine vent clearing times, the acceleration of water in the vent system is calculated as a function of the drywell pressure, suppression chamber pressure, and vent submergence. For the Mark III containment, separate vent clearing times are calculated for the three rows of vents.

The molar flow rate, N, through the vent is

$$\dot{N}(t) = \frac{AMV_s}{v}$$

where A is the total vent area, V, and v are, respectively, the speed of sound and molar volume of the gases at the vent entrance, and M is the Mach number of the flow, calculated as a function of vent-flow resistance and pressure differential across the vents. For Mark III, the flow rate through each row of vents is calculated separately, taking into account the different submergences. The total molar vent flow up to time t is

$$N(t) = \int_{0}^{t} \dot{N}(\tau) d\tau.$$
 (3.28)

For upward flame propagation, for which only burned gases at temperature T_{a} are vented, n_{va} (t)=N(t) and n_{va} (t)=0. For downward and spherical propagation, for which only unburned gases at temperature T_{a} are vented, n_{va} (t)=0 and n_{va} (t)=N(t). In this latter case, the thermodynamic and venting calculations are terminated when all of the original gas has been either burned or vented.

(3.27)

	Ratio o			
Reactor	Upward Propagation	Downward Propagation	Spherical Propagation	
Containment	$4\% \leqslant [\mathrm{H_2}] < 8\%$	$8\% \le [H_2] < 12\%$	$12\% \leq [H_2] < 18\%$	Comments -
Mark I Drywell	e.	c .	c.)	L = Drywell height
(Cylinder Annulus)	- Set L	- L	R _s	
Mark Suppression			C 1	Horizontal Propagation
Chamber (Torus)		S _f t	R _s	L ≡ one-half of torus circumference
Mark II Drywe ^H		-C +		V = Free Volume
(Annulus of Cone	$\frac{\pi^3 f^1}{12V}$ F ² [3 - 3X + X ²]	$\frac{n_{3}t}{12V}$ D ² [3 - 3X + X ²]		F ≡ Drywell i.d. at base
	+ FD [3X - 2X ²]	+ FD [3X - 2X ²]		D ≡ Biological Shield o.d.
	$+ D^2 X^2 - \frac{\pi D^2 S_{f} t}{4V}$	+ FX ² - $\frac{\pi D^2 S_f t}{4V}$	Sft 3	
	Where $X \equiv \frac{S_f t}{L}$	Where $X \equiv \frac{S_f t}{L}$		
Mark II Suppression		5.1	S + 3	L ≡ distance from
Chamber	$\frac{S_{f}}{L}$		R	water level to top
(Cylinder)			5	chamber
Mark III Drywell				L ≡ Drywell height
(Cutinducal Annulus)	S _f t	Sft	S _f t ³	
(cynnuncar Annunds)	L	L	R	

Table 3-1 GEOMETRICAL BURNING PARAMETERS FOR IDEALIZED CONTAINMENT GEOMETRIES

3.29

2.0

* 1

Table 3-1 (Continued)

and the second second and the second of the second second by the second second second second second second second

* ×

	Ratio			
Reactor	Upward Propagation	Downward Propagation	Spherical Propagation	
Containment	$4\% \leq [H_2] < 8\%$	$8\% \leq [H_2] < 12\%$	$12\% \leq [H_2] < 18\%$	Comments
				기사 영화 가슴 문
fark III Containment	S ₄ tπ C	S _c tπ F ²		V = Free Volume
	$\frac{1}{4V}$ (F ² - D ²) for t < $\frac{3}{5}$	$\frac{1}{4}$ for t < $\frac{L-S}{S}$		D ≡ Drywell o.d.
Cylinder and Annulus)	44 St	4v St		F ≡ Suppression Chamber i.d.
	Π	$S_{f}t \pi (F^{2} - D^{2}) + (L-S) D^{2} \pi$	S _f t ³	L ≡ Suppression
	$\frac{1}{4V}$ (F* S _f t - D*S)	4∨	R.	Chamber height
				above pool
	for t $> \frac{S}{S_f}$	for t $> \frac{(L-S)}{S_f}$		S ≡ Drywell height above pool

(a,b) = (b,b)

The suppression chamber back pressure increases as gases are vented from the drywell. Assuming ideal gas behavior, the increase in suppression chamber pressure, ΔP_{sc} (t), due to the vented gases is

$$\Delta P_{sc}(t) = \frac{N(t) RT_v}{V_{sc}}, \qquad (3.2)$$

where V_{sc} is the suppression chamber free volume and T_s is the temperature of the vented gases as defined above. It is conservatively assumed that the vented gases are not cooled as they pass through the suppression pool. This assumption leads to higher suppression chamber back pressure and lower vent flow rates, thus providing less pressure relief for the drywell during a hydrogen burn.

3.3.3.4 Flame Speed and Completeness

南

0

Conservative values of the flame propagation speed, based on the Fenwal and Furno⁷ data, are used for burning rate calculations in BWR containments. The conservative flame speed curves for upward propagation in Figure 3-21, and downward propagation in Figure 3-22, overpredict essentially all of the data. The curves are conservative by at least a factor of two for two-thirds of the data. The marked decrease in propagation speed in the transition from upward to downward propagation is ignored.

¹/ery little data exist for flame propagation speeds in the spherical regime (between 12 and 18% hydrogen). Payman's data¹³ indicate a propagation speed of 10 ft/sec for combustion of an 18% hydrogen mixture in a 4-liter sphere. The flame speeds used for calculations of spherical propagation in BWR containments are shown in Figure 3-22. At 18% hydrogen, $S_r = 50$ ft/sec compared to Payman's value of 10 ft/sec. Extrapolation of Furno's data to hydrogen concentrations greater than 12% yields propagation speeds which are considerably lower than those shown in Figure 3-22. Hence, the values of S_r used in the model are conservative.

Based on experimental data, a conservative approximation of the completeness factor as a function of hydrogen concentration is shown in Figure 3-23. Burning rates for BWR containments were calculated using this approximation. The completeness increases linearly from zero at 4% hydrogen (lower flammability limit) to 1.0 at 8% hydrogen. The completeness remains at unity for hydrogen concentrations greater than 8%.

The conservatism in using this approximation to calculate burning rates in BWR containments is verified by experimental data and sound physical reasoning. The data of Furno, et al.,⁷ indicate that the lower limit for complete combustion is greater than 8.5% hydrogen. By assuming that C=1.0 for greater than 8% hydrogen, no credit is taken for heat losses in reducing peak pressures. Experimental data^{2,7} indicate that heat losses reduce maximum pressures by 5 to 15% in the downward and spherical propagation regimes. The Fenwal data in Figure 3-23 indicate that the combustion completeness decreases with increasing water vapor content in the upward propagation regime. Extrapolation of the data indicates that zero completeness may be expected at hydrogen concentrations greater than 4% for higher water vapor concentrations. However, the effects of water vapor content have been ignored as dry air was assumed in developing the conservative completeness curve in Figure 3-23.

Furthermore, the evaporation of water — which, in the event of a LOCA, could be significant in a BWR containment — has conservatively been ignored. Including this heat loss effect would reduce the completeness factor and hence the predicted pressure rise. Zabetakis^e cites non-central ignition and interaction of the propagating flame front with walls as factors which can further decrease combustion completeness and thus reduce peak pressures. Finally, the completeness curve in Figure 3-23 is based primarily on the Fenwal test data for a Pyrofuze ignitor, which is much more efficient than a single-source ignitor — at least in the upward propagation regime. Since only single-source ignition would be likely in a BWR containment, additional conservatism is built into the completeness factor.





3



Figure 3-22 Conservative Flame Propagation Speed for Downward and Spherical Propagation Used for Calculations in BWR Containments





4. EFFECTS OF HYDROGEN BURNING ON BWR CONTAINMENTS

4.1 MAXIMUM PRESSURES

4.1.1 Transient Pressure Response

The model developed in Section 3 was used to predict the pressure transients associated with burning various concentrations of hydrogen in BWR containments. Hydrogen concentrations of up to 18%, which is generally accepted as the lower detonation limit in air,¹⁰ were considered (see Subsection 4.3).

Figures 4-1 through 4-3 show the pressure transients in the Mark I through Mark III drywells, respectively. Figures 4-4 through 4-6 show the pressure transients in the Mark I through Mark III suppression chambers,* respectively. All the transients were started, for illustrative purposes, with an initial pressure of 0 psig, temperature of 100°F, and zero relative humidity.

4.1.2 Effect of Initial Conditions on Predicted Peak Pressure

The effect of different initial pressures on peak pressure is considered in Figures 4-7 and 4-8. These two figures show the hydrogen concentrations that result in peak design pressure when burned as a function of the initial pressure in the drywell and suppression chamber, respectively. These results were based on assuming dry air; thus, the pressure rise calculations were maximized. Most added pressure in BWR containments is due to the partial pressure of water vapor. Therefore, any significant increase in pressure is accompanied by a significant increase in the water vapor concentration in the air. For example, a Mark I containment with a pressure of 19 psig has a 44% water vapor concentration. As we have seen, this amount of water vapor can have a significant effect on the burning process, especially below hydrogen concentrations of about 9%. Therefore, Figures 4-7 and 4-8, by ignoring the effects of water vapor content at the higher pressures, have a considerable amount of conservatism in them.

4.1.3 Maximum Allowable Hydrogen Concentration

Figures 4-7 and 4-8 can be used to conservatively determine the maximum amount of hydrogen that can be tolerated in BWR containments. To do this, the concentration of hydrogen was converted from the wet basis to the dry basis. Throughout this report, concentrations have been on the wet basis, i.e., the water vapor content is considered as part of the total gas mixture. The actual water vapor content of the containment following a LOCA is actually changing as a function of time, and is dependent on a number of factors, including the conservatism of analytical assumptions, the number of RHR heat exchangers presumed to be available, and whether containment sprays are actuated or not. Putting the hydrogen concentration on a dry basis removes the arbitrary nature of the water vapor content. Hydrogen concentration on the dry basis is actually the mole or volume fraction of the total noncondensible gases that is hydrogen; thus, it represents the value a "wet" gas mixture would reach if all the water vapor were condensed. The "dry" concentration is related to "wet" concentration by the following equation:

$$[H_2]_{DRY} = [H_2]_{WET} \left(\frac{{}^{P}_{NONCOND.} + {}^{P}_{H_2O}}{{}^{P}_{NONCOND.}} \right).$$

A conservative calculation of the dry basis concentration can be done by assuming the pressure of the noncondensible gas is 14.7 psia, thus ignoring any sensible heat additions to the noncondensible gases which raise their partial pressure to some value higher than atmospheric.

This approach was taken in constructing Figures 4-9 and 4-10 (which show allowable dry hydrogen concentrations) from the allowable wet concentrations of Figures 4-7 and 4-8. Figures 4-9 and 4-10 show the maximum allowable dry hydrogen concentration as a function of initial pressure for the drywells and wetwells, respectively. To further remove

"The "suppression chamber" of the Mark III containment is simply called the containment, but in order to maintain consistency in terminology, the use of "suppression chamber" will be applied to the Mark III in this report.

















•





.











-











Figure 4-10 Maximum Hydrogen Concentration (Dry Basis), BWR Suppression Chambers (Conversion of Figure 4-8 to Dry Basis)

.

٩

the arbitrariness of containment pressure, a single value for the maximum allowable dry basis concentration can be determined by selecting the minimum value from the curves between zero psig and the maximum expected long-term peak pressure. (The short-term peak pressure in the drywell was not considered since that condition persists for only a few seconds at the most immediately following the blowdown and occurs only when the drywell atmosphere is essentially 100% steam.) Reasonable maximum values for long-term peak pressures are 25 psig for the Mark I and Mark II containments, and 12.5 psig for the Mark III. The limiting dry hydrogen concentrations thus obtained are summarized in Table 4-1.

Table 4-1

MAXIMUM ALLOWABLE H2 CONCENTRATION, VOLUME PERCENT, DRY BASIS

		Drywell (%)	Suppression Chamber (%)
Mark	I	18	12
Mark	II	12	10
Mark	M	10	6

4.2 MAXIMUM TEMPERATURES

The maximum temperatures associated with hydrogen burning are not as important from a safety viewpoint as the peak pressures. Even though the gas temperatures may exceed 3000°F, practical experience and theoretical calculations indicate that the damage potential is low. For example, ordinary household wiring with PVC insulation was used throughout the Fenwal tests to supply electricity to the ignitors and the mixing fan. And Zabetakis, et al., described the condition of a block house in which hydrogen concentrations of up to about 34% were exploded as follows: "...little fire damage was encountered; in general, the wooden members in the weak-wall were only singed, paper and frayed rope were ignited on occasion, and electrical insulation was essentially unaffected by the flame."¹⁴

Also, while the gas temperatures may be high, the mass and heat capacity of the gas is k w relative to surrounding walls, structures, and suppression pool; therefore, absorption of the sensible heat of the gas by these structures will result in only modest temperature rises. An earlier topical report presented calculations which showed that if all the energy in the gas were transferred to the steel drywell wall, its temperature would increase about 100°F, or if all the energy were transferred to the suppression pool water, its temperature would increase only a few degrees.¹⁵

It appears from these chiservations, therefore, that the potential for damage due to high gas temperatures following burning is low, or can be made so through proper design specifications for equipment located inside the containment.

4.3 DETONATION POTENTIAL

Any hydrogen concentration in the range between 18.3 and 59 volume percent is within the defined limits of detonability.¹⁰ However, a detonation will not necessarily occur even if the concentration were within the above limits. Lewis and Von Elbe¹⁰ reported on experiments which showed, for a given spark energy, that detonation is more easily set up in smaller than in larger tubes, and that an established detonation wave can be converted to a normal combustion wave by suddenly widening the tube. Pigford, in an AEC research and development report, further commented on the effect of geometry on the propagation of detonation waves, noting that a fully formed detonation wave will degenerate by progressing "into an expanding system or by allowing it to encounter obstructions such as a wire helix, baffles, numerous bends and elbows, or a series of expanding and converging sections to bring about irreversible energy losses. Experiment has shown that attempts to detonate a combustible mixture enclosed in a large sphere by ignition in the center will fail, as would be expected, even if a detonation wave that has progressed through a tube that terminates in the center of the sphere is the source of ignition.¹¹² In a later AEC research and development report, Porter reported a series of tests in which mixtures of from 30 to 50 volume percent hydrogen in air were ignited in 1/2-inch and 2-inch Schedule 40 pipes, and in a 4.5-foot-diameter by 6-foot straight side tank. Detonations did occur in the pipes, but when the pipes were connected to the tank and the detonation wave was allowed to propagate into the tank, the mixture in the tank burned but did not detonate.¹⁸

A study by Cassutt, et al., showed that detonations in free space of a 32% hydrogen-air mixture only occurred if a sufficiently strong initiating source were available. The minimum initiating source that gave a detonation was 2 grams of Pentolite. The use of a blasting cap (about 1/2 gram of explosive), flame, hot wire, or spark did not cause a detonation.¹⁷ Zabetakis, et al., ignited various mixtures of hydrogen-air in a 21 x 13.3 x 13.5-foot (3770 cubic foot) block house.¹⁴ They found that ignition of 30% hydrogen-air mixtures with an "electric match" did not produce a detonation, but a 34% hydrogen-air mixture apparently detonated.⁴ This result is somewhat unexpected in light of the discussion of Pigford¹² and the results of Porter¹⁴ and Cassutt, et al.,¹⁷ as previously discussed.

The information presented here indicates that if a detonable hydrogen-air mixture were present in a BWR containment, the probability of the mixture's detonating upon ignition would be low. However, the results of the experiments of Zabetakis, et al.,¹⁴ indicates that hydrogen-air mixtures may detonate under certain conditions, at least when the hydrogen concentration exceeds about 30%.

"Peak pressures were not measured but deduced from analyses based on the observed degree of damage sustained by various pieces of equipment.

5. APPLICATION TO SAFETY GUIDE 7

Since the technological bases for many of the criteria in the USAEC's Safety Guide 7⁴ are not clear, it is difficult to relate new information to the criteria and to express what impact that new information should have on the criteria. If the current Safety Guide 7 criterion of not exceeding 4 volume percent hydrogen is based on the assumption that any burning in a reactor containment is entirely unacceptable, then the information in this report certainly disproves that assumption, and there are basically two courses of action that could be taken:

- a. Change the current 4% hydrogen limit to a scaled safety limit which reflects both the design pressure of the containment in question and the venting characteristics of that containment, if any.
- b. Reduce the level of conservatism in the other criteria of Safety Guide 7* as an indication that the current study represents a clear demonstration of the conservatism of the current flammability limit.

*All aspects of Safety Guide 7 are reviewed in the topical report, "Hydrogen Generation and the General Electric Boiling Water Reactor," NEDO-10723.**

REFERENCES

- Coward, H. F. and Jones, G. W., *Limits of Flammability of Gases and Vapors;* U.S. Bureau of Mines Bulletin 503, 1952.
- Zabetakis, M. G., Flammability Characteristics of Combustible Gases and Vapors, U.S. Bureau of Mines Bulletin 627, 1965.
- Drell, I. L. and Belles, F. E., Survey of Hydrogen Combustion Properties, NACA Research Memorandum RM E57D24, Washington, 1957.
- 4. AEC Safety Guide 7, dated March 10, 1971.
- 5. Yeaw, J. S. and Shnidman, L., "The Extinction of Gas Flames by Steam," A.G.A. Proceedings, 1938, pp. 717-745.
- Zabetakis, M. G., Research on the Combustion and Explosion Hazards of Hydrogen-Water Vapor-Air Mixtures, (AECU-3327) September 4, 1956.
- 7. Furno, A. L., et al., Thirteenth Symposium (International) on Combustion, 1971, p. 593.
- Zabetakis, M. G., "Dire and Explosion Hazards at Temperature and Pressure Extremes." Preprint of paper presented at the Symposium on "Chemical Engineering Under Extreme Conditions," A.I.Ch.E., June 1965.
- Dieterlin, F., "Versuche über die Zündgrenzen von Wasserstoff Luftgemischen in der Explosionsbombe," Techn. Mechan. u. Thermodynamik, 1, 12, p. 429, December 1930.
- 10. Lewis, B. L. and von Elbe, G., Combustion, Flames, and Explosions of Gases, Academic Press, Inc., New York, 1951.
- 11. Gaydon, A. G. and Wolfhard, H. G., Flames: Their Structure, Radiation, and Temperature, Chapman and Hall, Ltd., London, 1960.
- 12. Pigford, T. H., Explosion and Detonation Properties of Mixtures of Hydrogen, Oxygen, and Water Vapor, (ORNL1322) August 14, 1952.
- 13. Payman, W., First Symposium (International) on Combustion, p. 51, 1937.

.

٠

- 14. Zabetakis, M. G., Furno, A. L., and Perlee, H. E., "Hazards in Using Liquid Hydrogen in Bubble Chambers," Bureau of Mines, Report of Investigations 6309, 1963.
- 15. Ianni, P. W. and Liffengren, D. J., Considerations Pertaining to Containment Inerting, (APED-5654) August 15, 1968.
- 16. Porter, J. B., Analysis of Hydrogen Explosion Hazards, (DuPont Report DP-1295) July 1972.
- 17. Cassutt, L. H., Maddocks, F. E., and Sawyer, W. A., A Study of the Hazards in Storage and Handling of Liquid Hydrogen, Arthur D. Little, Inc., AD 607 834, undated.
- Wilson, R. M. and Slifer, B. C., Hydrogen Generation and the General Electric Boiling Water Reactor, (Licensing Topical Report NEDO-10723) February 1973.

ACKNOWLEDGMENTS

Special appreciation is due Mr. L. B. Nesbitt, whose experience and extensive technical library significantly contributed to this report. Other General Electric personnel who provided technical guidance and support include Dr. J. E. Hench, and Messrs. P. W. Ianni, and D. J. Liffengren. Messrs. H. R. Cutler and E. A. Omotoso of Fenwal, Inc., must also be commended for the manner in which they conducted the test program.

3

- 24

APPENDIX PRESSURE TRANSIENT FROM FENWAL TESTS

This Appendix comprises Figures A-1 through A-11.



Figure A-1 Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time





1

Figure A-3 Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time

11. 10



Figure A-4 Fenwal Test Data - Pressure Rise/Initial Pressure Versus Time




NEDO-10812







Figure A-11 Fenwal Test Pata - Pressure Rise/Initial Pressure Versus Time