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A Preliminary Analysis on DDT Possibility Estimation in a Nuclear Power Plant

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Abstract

The possibility of DDT due to hydrogen combustion during SBO and LBLOCA accident sequences with/without igniters of an advanced light water reactor is estimated using the qualitative evaluation methodology. For the SBO sequence without igniters, hydrogen concentration in IRWST compartments of the advanced light water reactor reaches up to 70% in maximum and maintains over 13% for about 50 min, which is known to a minimum value of DDT. The DDT possibility exists for about 20 min. For the SBO sequence with igniters, the hydrogen concentration is still well over 13% but it maintains only for about 2.5 min. DDT possibility exists intermittently twice for 1.5 min because of the oxygen starvation. There is no DDT possibility for the LBLOCA sequence with/without igniters.

I. Introduction

Hydrogen can be generated by fuel cladding oxidation during severe accidents of the nuclear power plants. Hydrogen released to the containment can burn in two modes that is, deflagration and detonation which should be considered for the requirement of licensing. Through the safety analysis, it has been generally concluded that large dry containments are capable of withstanding a deflagration load but not a detonation one. The detonation phenomena by direct initiation is considered unlikely to occur because it is postulated to have a very high ignition energy. Detonation, however, does not keep away from the danger since in some conditions, a deflagration can lead to a detonation. In an ALWR containment, detonation is most likely to occur by flame acceleration and DDT rather than by direct initiation [1,2].

For hydrogen control, 10CFR 50.34(f) requires that combustible concentration of hydrogen will not collect in areas where detonation could cause loss of containment integrity. However, the hydrogen collection is inevitable during severe accidents. Thus, it is necessary for the quantitative method to evaluate DDT possibility of the hydrogen concentration collecting during and after severe accidents. Unfortunately, there are no analytical models to describe complete set of DDT event at present. The main issue is the question of detonation onset possibility in given mixture volume of known composition under any circumstances (including unfavorable one).

For the past few decades, DDT criteria had been developed through several small-scale experimental results. Accordingly, there have been lots of limitations in applying these criteria to nuclear power plant. Two methodologies for evaluation of DDT possibility in a nuclear power plant have been developed. In 1989, M.P. Sherman[3] suggested a method to evaluate DDT potential based on test data which was obtained from a comparatively large-scale experimental test facility, FLAME. The DDT potential was determined using the rank table which was combined the mixture detonability (the hydrogen concentration) with the geometric features conductive to DDT. This methodology, however, has a lot of uncertainties to evaluate the DDT potential of the nuclear power plant since it is difficult to quantify the geometric features conductive to DDT to consider the compartment size and geometric feature. Also, it is recently found that hydrogen mole fraction for possibility of DDT exists at around 12.5% which is lower than previously known mole fraction. EPRI used the results of the small scaling tests in ALWR report[4]. However, the scaling effects is not maintained because the mixture conditions of the two tests is initially different. The small scale experiments could not be directly applied to the practical large scale enclosures due to the scaling of the chemical time and the fluid dynamic time.

Since FLAME experiment, several large-scale DDT experiments considering various combinations of obstacles have been performed to date to find the DDT potential criteria. The methodology used in this paper is based on the recent experimental data-base for DDT possibility[5,6].

The objective of this paper is to investigate a quantified DDT evaluation methodology and to estimate the possibility of DDT in a containment of a nuclear power plant during severe accidents. The DDT possibility estimation is carried out by applying the DDT onset criteria to different local atmosphere conditions obtained from the CONTAIN code analysis for SBO and LBLOCA accident sequences.

2. Methodology

2.1 Zr Oxidation Fraction in a Reactor Vessel

DDT possibility under the postulated severe accidents of a nuclear power plant is closely related to the hydrogen amount resulting from Zr oxidation in a reactor vessel. For determination of Zr oxidation fractions, previous studies such as experimental data, analytical results, and regulation of future plants - System80+ and EPR have been reviewed. From the experimental data for the Zr oxidation fraction in a vessel, the maximum oxidation is lower than 75% except NRU FLHT-5 where the fuel temperature maintains around the 1700K about

3,000sec. It is argued that this time scale in this experiment is rather long compared to the plant scale[7]. For the representative several severe accident sequences, the analytical results of the Zr oxidation fraction shows that the oxidation fraction in a vessel is lower than 75%. The USNRC completed the design certification of ABB-CE System80+ where the 100% Zr oxidation fraction in a vessel is used and the Westinghouse AP600[8] is also under review on this basis. France and German also consider 100% oxidation of the active core in a reactor vessel for future plants. The amount of hydrogen generated by 100% MWR(Metal Water reaction) in a reactor vessel is considered for local hydrogen concentration analysis.

2.2 Model

The most important possible parameters for characterizing a mixture sensitivity to evaluate DDT possibility are the reaction zone width l_r, the detonation cell width λ, the critical exit diameter for detonation transmission from a tube to unconfined space, the minimum blast initiation energy, and the critical tube diameter for single head spin detonation propagation. Use of the last three parameters is not possible because there are not enough data available and their experimental determination is rather difficult. It also requires a large-scale test for the lean mixtures of interests here. Only l_r and λ would be used at present[5].

It is assumed that H_2-air-steam mixture in a compartment is uniformly distributed. The experimental results to quantify DDT onset criteria show a correlation between the mixture size or jet size and the detonation cell width [Fig 1]. The minimum scale for forming the detonation wave can be estimated as 7λ in terms of the cell width.

$$L_c = 7\lambda \quad \text{--} \quad (1)$$

where L_c : mixture size or jet size

The mixture size or jet size L_c of Fig. 1 can be comprehended as the minimum characteristic length of mixture for DDT possibility.

Characteristic cloud dimension L

The characteristic length L_n of the H_2-air-steam cloud in compartment number n is calculated from

$$L_n = V_n^{1/3} \quad \text{--} \quad (2)$$

where, V_n is a volume of computational compartment n

Average detonation cell width λ

From the measured data of Fig. 2 for $\lambda_n(XH_2, XH_2O)$, the average detonation cell width λ can obtained for the given mixture conditions[6].

The average composition and detonation cell size of the mixture is used here as a measure of the detonation sensitivity because this evaluation method gave good agreement with the 7λ correlation in the RUT tests with dynamic H_2 injection into the air.

DDT index R

To evaluate the DDT possibility of compartment n, index R is introduced as follows

$$R_n(t) = \frac{L_n}{7\lambda_n} \quad \text{---} (3)$$

Using this index and from Figure 1, one can determine the DDT possibility. From Figure 1. DDT would not occur in the upper part of the figure where R < 1. The compartment characteristic length for this area is less than the minimum DDT characteristic length. In the lower part of the figure where R >1, DDT would occur. In this case, the compartment characteristic length is larger than the minimum DDT characteristic length.

2.3 Example for an Application

Let's assume $V=1{,}000m^3$, $X_{H2}=15\ \%$ $X_{H2O}=10\ \%$ in a compartment. Then, the characteristic length of this compartment, L is 10 m from Eq. (2). From Fig. 2, it is read that λ is approximately 0.8m for the above mixture condition. Since $R=L/7\lambda=10/(7x0.8)=1.78$ is greater than 1, DDT would occur with this mixture and geometrical condition. It is interest to investigate the required geometrical size for DDT possibility at this mixture. If $\lambda_n= L_n/7$ was satisfied, the threshold of geometrical size for DDT possibility at this mixture condition can be obtained. To satisfy this condition, L is 5.6m, which means compartment volume is 176.6 $m^{3.}$

For various hydrogen-steam concentrations having with oxygen concentration 5% or more, which is minimum concentration for hydrogen combustion, the detonation cell size and the minimum DDT characteristic length for DDT possibility are given in Table 1. DDT would occur if a compartment characteristic size for the given mixture is larger than the minimum DDT characteristic length. For example, if hydrogen concentration is 10% under dry conditions, the minimum characteristic length for DDT occurrence should be over the 35m. Vice verse, if the compartment characteristic length is less than 35m, the DDT would not occur.

3. Application to typical future nuclear power plants

Fig. 3 to 5 shows the hydrogen, steam, and oxygen concentrations in IRWST compartments (cell 39 to 42) for SBO sequences without igniters. Considerable hydrogen concentration spikes are shown in these compartments whereas hydrogen concentration in the upper containment is comparatively uniform. The hydrogen concentration is over 13% for the period from 11,200sec to 15,600sec. After 15,600sec hydrogen concentration is around 11%. Two hydrogen concentration peaks over 13% are shown at 11,200 and 12,400sec in IRWST compartments but DDT would not occur because of high steam concentration.

The DDT possibility in the IRWST compartments No. 2 and No. 3 could be determined as follows. The hydrogen concentration of the IRWST compartments No. 2 and No. 3 in Fig. 3 is about 20 %. From Table 1, the minimum DDT characteristic length for the mixture, H_2=20%, H_2O=15% is 2.8m. As the characteristic lengths of the IRWST compartments No. 2 and No. 3 is 5.9m, DDT would occurs at these compartments when steam concentration is less than 15%. From the Fig 4 one can read the steam concentration is less than 15% before 14,000sec, the IRWST compartments No. 2 and No. 3 would be detonable from 12,800 to 14,000sec for 20 minutes. For the period 14,000 to 15,400sec, the IRWST compartments No. 2 and No. 3 would not detonable since steam concentration is beyond 15%. The IRWST compartments No. 2 and No. 3 would be also detonable at 15,600 sec when peak hydrogen concentration is appeared.

For SBO with igniters, Fig 6 to 8 shows the hydrogen-steam-oxygen concentrations of the IRWST compartments. Totally, hydrogen concentrations are lower than that of SBO sequence without igniters except for the value near 12,800sec. The time period showing beyond 13 %, about 2.5 min, is much shorter than about 50 minutes of SBO without igniters. Also, the hydrogen concentration except for the peak period is less than 6 % and decreases faster than the case of without igniters. DDT possibility range is shortened because the oxygen is starved. There still exists the DDT possibility in a part compartment of IRWST even if igniters are operated. However, the period for DDT possibility is shortened comparing to the case without igniters.

DDT possibility of other compartments such as the compartments connected with IRWST compartments is also analyzed because these compartments would be the relatively high hydrogen concentrations. For SBO of without/with igniters, these compartments connected with IRWST is beyond 13%. But, it is not possible to occur DDT because of high steam concentration.

For LBLOCA sequences without igniters, though the hydrogen concentration over 13 % is maintained. The possibility of DDT in S/G compartments where source data release does not exist because of high steam concentration. For LBLOCA with igniters, there is no DDT possibility.

4. Conclusions

Based on the recent experimental data, the DDT onset criteria is able to apply easily for DDT estimation of a nuclear power plant without user subjective. The DDT possibility is estimated by applying this criteria with various local atmospheric conditions obtained from the CONTAIN code analysis for two accident sequences.

In case of SBO without igniters, the hydrogen concentration in IRWST compartments reach up to 70% and maintains over 13% for about 50 min. The DDT possibility exists for about 20 min. There is no DDT possibility for other compartments except for IRWST. In case of SBO with igniters, the hydrogen concentration is still over 13% but it maintains only for about 2.5 min. DDT possibility is appeared twice for 1.5 min because of the oxygen starvation. There is no DDT possibility for LBLOCA sequence with/without igniters.

The methodology used for DDT possibility estimation basically involves uncertainties because DDT onset criteria is obtained from the experimental data base. The 50% blockage for the IRWST vent flow path is used in this analysis, however, ABB/CE system 80+ analysis result shows that the increasing of vent flow path area decreases the hydrogen concentration of the IRWST.

Acknowledgement: Local hydrogen concentration used in this paper is obtained from KOPEC.

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Table 1. The detonation cell width under the assumed mixture conditions and the corresponding minimum characteristic length for DDT

		Name	Steam Concentration(%)							
			0	5	10	15	20	25	30	35
Hydrogen Concentration (%)	10	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	5/35	5/35	N	N	N	N	N	N
	13	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.3/2.1	1/7	4/28	N	N	N	N	N
	15	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.15/1.05	0.4/2.8	1/7	5/35	N	N	N	N
	18	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.05/0.35	0.1/0.7	0.3/2.1	1/7	5/35	N	N	N
	20	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	0.05/0.35	0.15/1.05	0.4/2.8	1.3/9.1	5/35	N	N
	25	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	0.05/0.35	0.1/0.7	0.2/1.4	0.7/4.9	2/14	N
	30	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	D	0.03/0.21	0.1/0.7	0.3/2.1	0.8/5.6	3/21
	35	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	D	D	0.09/0.63	0.3/2.1	0.7/4.9	2/14
	40	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	D	0.07/0.49	0.15/1.05	0.4/2.8	1.2/9.6	4/28
	45	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	0.05/0.35	0.1/0.7	0.3/2.1	1/7	4/28	N
	50	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	0.05/0.35	0.1/0.7	0.3/2.1	0.9/6.3	3/21	N	N
	55	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.05/0.35	0.09/0.63	0.2/1.4	0.7/4.9	3/21	N	N	N
	60	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.1/0.7	0.2/1.4	0.5/3.5	3/21	N	N	N	N
	65	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.2/1.4	0.5/3.5	2/14	N	N	N	N	N
	70	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.5/3.5	1.5/10.5	5/35	N	N	N	N	N
	75	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	1.0/7	5/35	N	N	N	N	N	N
	80	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	3/21	N	N	N	N	N	N	N

N : Not Detonable

D : Detonable in any compartment because the limiting scale is about 0.35m

Fig. 1 Experimental Data on turbulent jet initiation and DDT in confined volumes

Fig. 2 Detonation cell sizes of H2-Air-Steam (375K and atmospheric Pressure)

Table 1. The detonation cell width under the assumed mixture conditions and the corresponding minimum characteristic length for DDT

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Hydrogen Concentration (%)	10	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	5/ 35	5/ 35	N	N	N	N	N	N
	13	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.3/ 2.1	1/ 7	4/ 28	N	N	N	N	N
	15	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.15/ 1.05	0.4/ 2.8	1/ 7	5/ 35	N	N	N	N
	18	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.05/ 0.35	0.1/ 0.7	0.3/ 2.1	1/ 7	5/ 35	N	N	N
	20	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	0.05/ 0.35	0.15/ 1.05	0.4/ 2.8	1.3/ 9.1	5/ 35	N	N
	25	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	0.05/ 0.35	0.1/ 0.7	0.2/ 1.4	0.7/ 4.9	2/ 14	N
	30	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	D	0.03/ 0.21	0.1/ 0.7	0.3/ 2.1	0.8/ 5.6	3/ 21
	35	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	D	D	0.09/ 0.63	0.3/ 2.1	0.7/ 4.9	2/ 14
	40	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	D	0.07/ 0.49	0.15/ 1.05	0.4/ 2.8	1.2/ 9.6	4/ 28
	45	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	D	0.05/ 0.35	0.1/ 0.7	0.3/ 2.1	1/ 7	4/ 28	N
	50	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	D	0.05/ 0.35	0.1/ 0.7	0.3/ 2.1	0.9/ 6.3	3/ 21	N	N
	55	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.05/ 0.35	0.09/ 0.63	0.2/ 1.4	0.7/ 4.9	3/ 21	N	N	N
	60	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.1/ 0.7	0.2/ 1.4	0.5/ 3.5	3/ 21	N	N	N	N
	65	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.2/ 1.4	0.5/ 3.5	2/ 14	N	N	N	N	N
	70	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	0.5/ 3.5	1.5/ 10.5	5/ 35	N	N	N	N	N
	75	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	1.0/ 7	5/ 35	N	N	N	N	N	N
	80	Detonation Cell Width(m)/ Min. DDT Characteristic Length(m)	3/ 21	N	N	N	N	N	N	N

N : Not Detonable

D : Detonable in any compartment because the limiting scale is about 0.35m

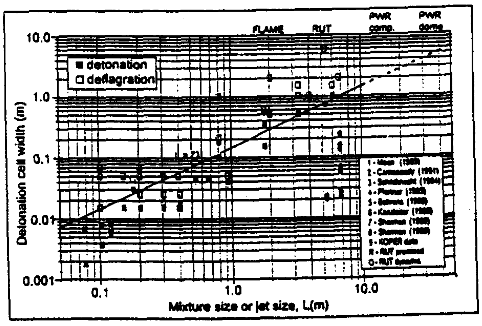

Fig. 1 Experimental Data on turbulent jet initiation and DDT in confined volumes

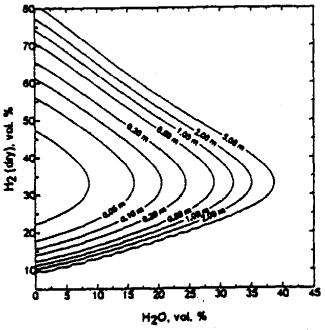

Fig. 2 Detonation cell sizes of H2-Air-Steam (375K and atmospheric Pressure)

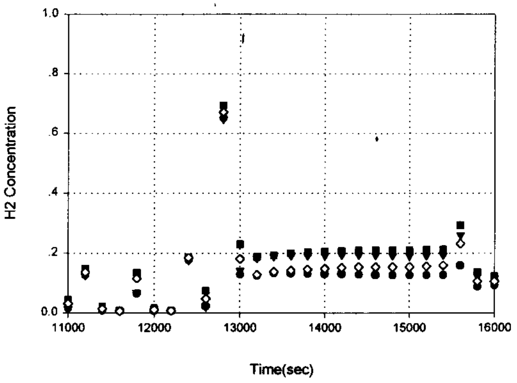

Fig. 3. Hydrogen concentration for SBO without igniters

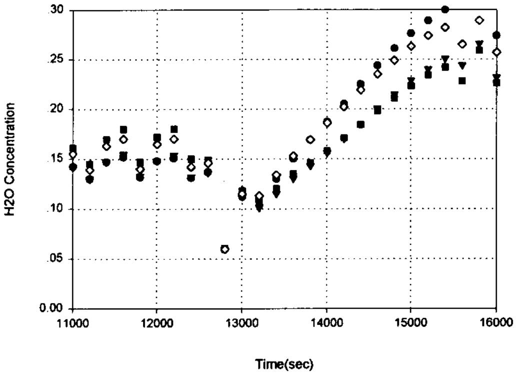

Fig. 4 Steam concentration for SBO without igniters

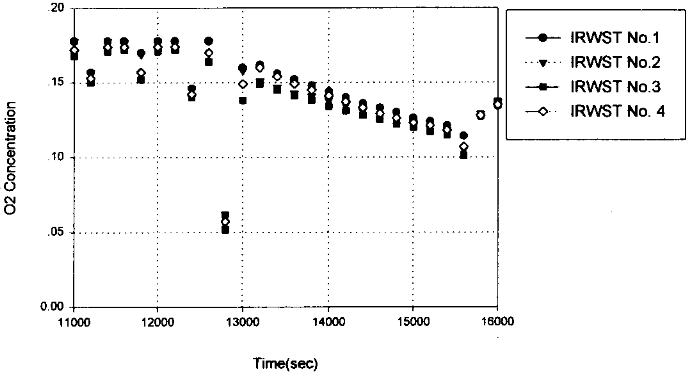

Fig. 5. Oxygen concentration for SBO without igniters

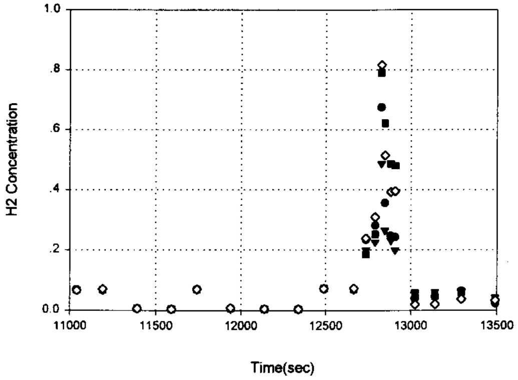

Fig. 6 Hydrogen concentration for SBO with igniters

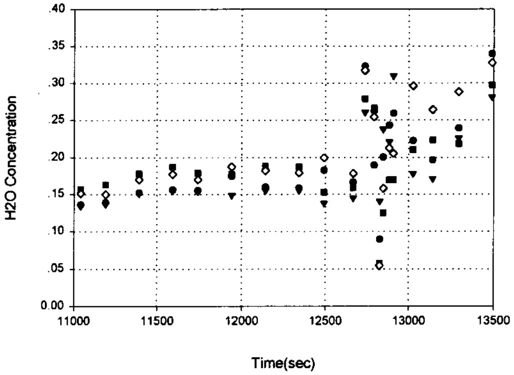

Fig. 7 Steam concentration for SBO with igniters

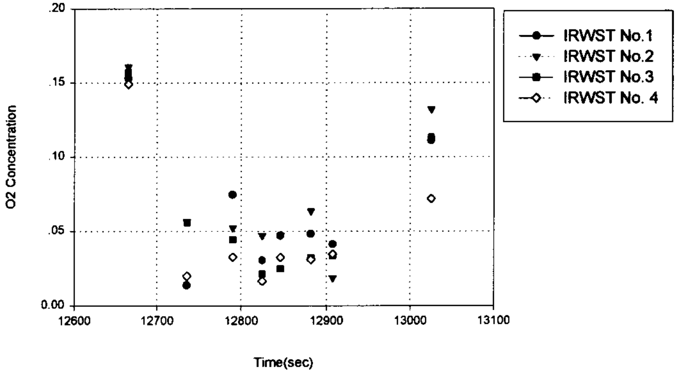

Fig. 8 Oxygen concentration for SBO with igniters