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Use of RUT large scale combustion test results for reactor applications

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ABSTRACT

Selected results from the large scale combustion RUT experiments are used to derive typical pressure histories for the various combustion regimes that may be expected in reactor situations. These loading functions are compared to the assumptions made in comparable work previously published. Then, a simplified model of the reactor containment building is set up, based on the computation of its natural modes. The structural response is obtained and the global reactor containment building integrity is assessed.

INTRODUCTION

For the safety analysis of severe accidents in PWRs, the hydrogen risk is a key issue with respect to the containment integrity. Hydrogen combustion can affect drastically the resistance of the containment which is the last barrier between the fission products and the environment. The behaviour of this barrier has been usually studied by static pressure analysis and a comparison between Adiabatic Isochoric Complete Combustion (AICC) pressure and ultimate resistance pressure. This could be applied for laminar and slow turbulent deflagration. Nevertheless, in the case of more violent combustion regimes as fast turbulent deflagration, deflagration to detonation transition (DDT) or detonation, a dynamic analysis is needed (the maximum pressure always exceeds the ultime resistance pressure and the time characteristic is too short to assume static loads).

The aim of this paper is to propose a simplified approach for the assessment of these dynamic loads. This work is based on the the different combustion modes observed and recorded in the RUT test facility [1]. These tests are devoted to the onset of DDT in hydrogen, air and steam mixtures. After a selection of characteristic pressure profiles corresponding to different combustion regimes, the simplified model will be described and applied on a generic large dry PWR containment.

1. SELECTION AND ANALYSIS OF PRESSURE LOADS

During the RUT experiments (1995 campaign), three different combustion modes were investigated : fast turbulent deflagration, DDT (critical regime) and stable detonation (figure 1). For each combustion mode, a representative test has been selected. The following table contains the main characteristics of these combustion regimes :

Combustion mode	**Test**	**[H2] vol% dry**	**[H2O] vol%**	**ΔP_{AICC}* (MPa)**	**ΔP_{CJ}* (MPa)**	**ΔP_{max} (experiment - MPa)**	**Time characteristic (ms)**
Fast turbulent deflagration	Stm7	17.5	25.7	0.299	0.65	0.9	20.
DDT (critical regime)	Stm3	16.5	15.1	0.327	0.71	1.37	6
Stable detonation	Stm4	24.8	24.8	0.396	0.84	1.93	0.1

*** calculated with STANJAN 3 [4]**

Table 1

The time characteristic is defined by the delay needed to reach the maximum pressure. This parameter exhibits an order of magnitude variation between fast turbulent deflagration and stable detonation. The maximum overpressures recorded during the experiments are always higher than the AICC and the Chapmann-Jouguet (CJ) overpressures. For the fast turbulent deflagration, the flame velocity is around 700 m/s. This value reachs around 1200-1400 m/s for DDT depending on the sensors location and the CJ conditions are obtained for the stable detonation (1650 m/s).

In the case of static analysis, typical values around 0.75 MPa are used to define the ultimate pressure for large dry PWR containment (double concrete containment). If the maximum pressure obtained in the RUT tests is compared to this ultimate pressure, the containement cannot sustain this level of static pressure.

In order to perform dynamic analysis, the PI (Pressure versus Impulse) diagram is more convenient to compare these three combustion modes (figure 2). The highest impulse is obtained for the fast turbulent deflagration compared to DTT or detonation case. This high impulse is coupled with a relatively high pressure value compared to the other regimes where high pressures are obtained for low impulses : this means that the fast turbulent deflagration has a higher effect on structures with low eigen frequencies. To identify the frequency domain where the fast turbulent deflagration is more effective, a Fourier analysis of the experimental signals was done (figure 3). The power spectral density (PSD) is representative of this frequency effect. Fast turbulent deflagrations are more sensitive below 20 Hz and above, DDT give the highest response. A low frequencies, fast turbulent deflagration could be considered like imposed force to the structure.

The three combustion mode pressure profiles should be compared to analytical formulas usually used or proposed to describe these combustion loads. The first ones have been proposed by Breitung and al. [2] and are given below :

- Fast turbulent deflagration : $\boxed{P(t) = P_1.(1 - e^{\frac{-t}{T_1}}) + P_2.t.e^{\frac{-t}{T_2}}}$
- Deflagration to Detonation Transition and Detonation : $\boxed{P(t) = P_1.(1 - e^{\frac{-t}{T_1}}) + P_2.e^{\frac{-t}{T_2}}}$

In the following, these two formulas will be referred to as FZK formulas.
The second ones are used for blast waves simulation [3] :

- if $0. < t < T_r$ $\boxed{\Delta P(t) = \Delta Pm.\left(\frac{t}{Tr} - \frac{1}{2\pi}\sin\left(\frac{2.\pi.t}{Tr}\right)\right)}$
- if $T_r < t < T_d$ $\boxed{\Delta P(t) = \Delta Pm.\left(1 - \frac{(t - Tr)}{Td - Tr}\right).e^{-\left(\frac{t-Tr}{Td-Tr}\right)}}$

where t is time, T_i, T_r and T_d are time characteristics, P_i are pressures and ΔP_m is overpressure.

The following table proposes values for these parameters according to reference [2] and [3].

Combustion mode	P_1 (MPa)	T_1 (ms)	P_2 (MPa)	T_2 (ms)	ΔP_m (MPa)	T_r (ms)	T_d (ms)
Fast turbulent deflagration	0.399	20	20000 (MPa/s)	2	0.9	0.4	4.
DDT (critical regime)	0.427	10	4.27	0.2	1.37	6.	15.
Stable detonation	0.496	10	19.84	2	1.93	0.1	12.

Table 2

For the first case, Breitung and al. have supposed that P_1 is the AICC pressure, P_2 is 10 times the AICC pressure for DDT, 40 times the AICC pressure for stable detonation and 2000 Mpa/s for fast turbulent deflagrations. For the second case, T_r and ΔP_m correspond to the time characteristic and the maximum overpressure of table 1. T_d is choosen according to the pressure sensor responses.

In this paper, the comparison between experimental results and analytical formulas is presented only for fast turbulent deflagration (figure 4). The pressure profile deduced from blast wave formula is closer to the experimental results than the FZK formulas which seem more conservative.

2. EIGEN FREQUENCIES OF THE CONTAINMENT BUILDING

A simplified 2D axisymetric model has been used to describe a typical large dry PWR containment. Shell elements are used. The basemat and the containment walls are assumed to be prestressed concrete with a thickness of 0.9 m for the containment and 4.5 m for the basemat. Concerning the boundary conditions, we have assumed that the basemat is connected to the soil via 2 springs (one for z axis and one for the rotation θ).

The CASTEM2000 [5] code has been used to obtain the lowest eigen frequencies of the building. Only the frequencies involving wall strain are of interest in this study. These eigen frequencies are obtained assuming a maximum displacement equal to 1. The following table describes the results obtained :

Eigen frequency (Hz)	Participating factor (%)	Comments
12.47	18.7	eigen mode shape in fig 5.1
14.01	11.7	eigen mode shape in fig 5.2
18.73	8.5	eigen mode shape in fig 5.3
22.01	2.0	eigen mode shape in fig 5.4

Table 3

The participating factor is defined as the ratio between the modal mass and the total mass. The sum of these participating factors is an indication of the completeness of the study. This value is only 40.9 % due to fact that the main participant mode is the swaying (5.05 Hz) which represents 48.7% but involves no wall strain. In this study, the combustion is supposed to start in the center of the building and the pressure loads are supposed to be axisymetric. In this case, the swaying mode is not requested.

The first and the third eigen frequency are related to the fundamental mode and the second and the fourth ones are corresponding the the first Fourier harmonic (mode 1).

3. SIMPLIFIED DYNAMIC ANALYSIS - ONE-DOF OSCILLATORS

The total volume of the RUT facility is about 480 m^3. This scale is representative of inner rooms of a real containment and it is large enough to assume that the recorded pressure profiles are typical of real containment combustion loads.

Assuming elastic behaviour, the containment response to the hydrogen combustion loads could be represented by a sum of movements : ovalisation, swelling... Each mode could be modeled by a one-dof mass-spring system with a pulsation ω. The global motion of the containment will be the motion of a system of one-dof oscillators each one corresponding to a eigen frequency of the building.

For the three combustion modes defined previously, the maximum displacement has been studied by solving the following equation of motion :

$$\boxed{\frac{\partial^2 x}{\partial t^2} + a_m \frac{\partial x}{\partial t} + \omega^2 x = \frac{\Delta P(t)}{\rho e}}$$

where x is the displacement, a_m is the damping coefficient, ω the eigen pulsation, ΔP the overpressure, ρ the density of concrete and e the thickness of the walls. Only $a_m = 0$ is considered in this study and to be more realistic values between 5 and 30% should be used.

Solving this equation with CASTEM2000, the following table for the maximum displacement is obtained using experimental values for ΔP(t) :

Eigen Frequency (Hz)	**Fast turbulent Deflagration (mm)**	**DDT (mm)**	**Stable Detonation (mm)**
12.47	45.	10.	7.4
14.01	37.	9.9	7.3
18.73	22.	9.4	7.0
22.01	16.	9.0	6.7

Table 4

The highest values are computed for the fast turbulent deflagration. As forseen in the Fourier analysis, this combustion regime gives the maximum amplification of the pressure loads. For DDT and stable detonation, the values vary in the same range between 6.7 and 10 mm which is a factor of 4 less then the fast turbulent deflagration response.

Comparing the experimental signal to the analytical formulas for fast turbulent deflagration, the maximum displacements are as follows :

Eigen Frequency (Hz)	**Experimental signal (mm)**	**FZK formulas (mm)**	**Blast waves (mm)**
12.47	45.	58.	61.
14.01	37.	49.	52.
18.73	22.	33.	34.
22.01	16.	26.	26.

Table 5

The analytical values are always higher that the experimental ones but in the same order of magnitude. The conservative aspect of the FZK formulas on the maximum pressure is reduced in terms of maximum displacement. In the frequency domain of 10-20 Hz, the power spectral density for the blast wave formulas is higher than the others, the experimental PSD is always smaller than the analytical formulas. The DSP difference between FZK and blast waves formulas becomes smaller at 25 Hz. This confirms the results obtained for the maximum displacement.

4. RESISTANCE CRITERIA

Combining the maximum displacement and the modal stress, the stresses can be obtained for the 3 combustion regimes. In our hypothesis, the building is supposed to be made of concrete only. So, we have choosen to apply a resistance criteria based on the maximum of the principal stress tensor which is a quite good representation of concrete behaviour. The values computed for this criteria are summarized in the following table :

Eigen Frequency (Hz)	Fast turbulent Deflagration (MPa)	DDT (MPa)	Stable Detonation (MPa)
12.47	10.7	2.4	1.7
14.01	33.4	8.9	6.6
18.73	9.5	4.2	3.1
22.01	15	8.6	6.5

Table 6

On the one hand, these values should be compared to an elasticity limit of an homogenous concrete containment (σ, ε) diagram (figure 6). The first slope represents the elastic behaviour of the concrete and the second one is the elastic behaviour of the steel prestressing cables. On the other hand, if we assume that the eigen modes are independent, the maximum stress could be calculated with a quadratic average

$$\sigma_{\max} = \sqrt{\sum_i \sigma_i^2}$$

and the values are as follows :

Fast turbulent Deflagration (MPa)	DDT (MPa)	Stable Detonation (MPa)
39.3	13.3	9.9

Table 7

With these simplified analysis, the following conclusions should be pointed out :

- fast turbulent deflagration : this kind of pressure loads is the most sensitive for the containment. The criteria is exceeded twice and for all the frequencies, the value is arround or higher than the yield limit of the concrete. The maximum values are observed for the first harmonic of the Fourier analysis and the lowest for the fundamental frequency. With the quadratic square root mean value, the value is twice the highest yield limit (dome region).
- DDT : for all the frequencies, the values are below the lowest elastic limit and the containment is able to sustain this kind of pressure loads. The margin with the elasticity limit is a factor between 2 or 3. If we consider the quadratic average, the value is equal to the lowest elastic limit (cylinder area).
- Stable detonation : this pressure load is the most insensitive one and the concrete walls have an elastic behaviour. The same conclusion appears if the quadratic average is used.

CONCLUSION

According to the analysis presented here, fast turbulent deflagration seems to be the most challenging combustion regime in terms of mechanical behaviour of the containment compared to DDT and stable detonation (in which cases the pressure loads are too fast compared to the slow motion of the containment).

The comparison between experimental loads and analytical pressure loads is satisfactory. The values proposed by FZK are a little bit conservative in terms of maximum pressure but the computed effect is the same compared to the experiment or the other analytical formulas.

At the present time, this analysis should be considered as a preliminary study due to fact that there are many hypothesis and simplification. One of these main hypothesis, is that the pressure loads are supposed to be uniform on all the containment walls. Regarding the current safety analysis, these combustion regimes are supposed to appear locally in some inner rooms. This analysis should be refined to take into account this local effect. The modelisation used should also be enhanced for example, with a better description of the concrete walls (non linear behaviour).

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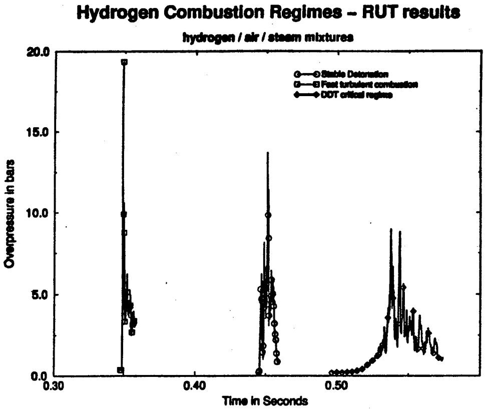

Figure 1: Typical hydrogen combustion regimes in the RUT tests - Overpressure profiles

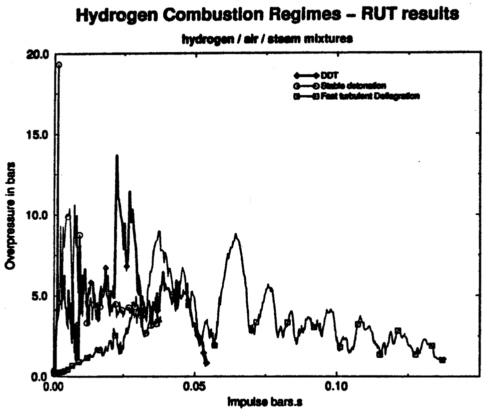

Figure 2: Pressure Impulse diagram for the three combustion regimes selected

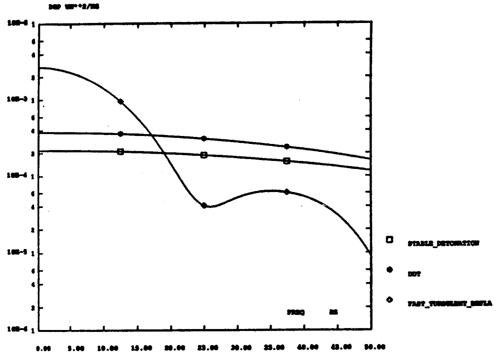

Figure 3: Power Spectral Density analysis

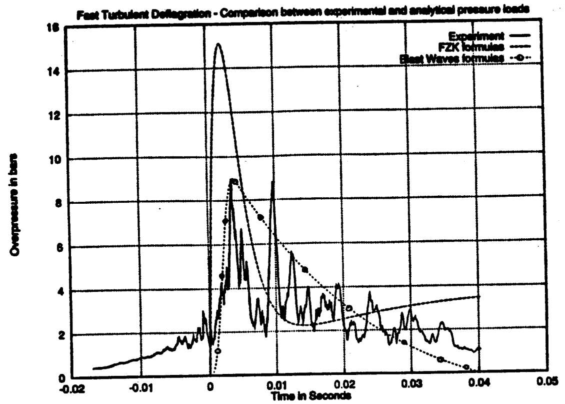

Figure 4: Comparison between experimental results and analytical formulas for fast turbulent deflagration pressure profiles

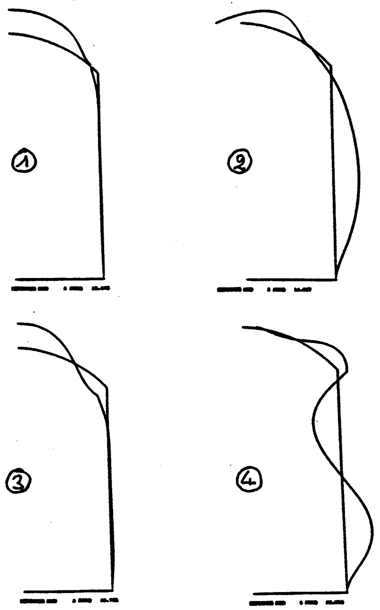

Figure 5: Eigen mode shapes

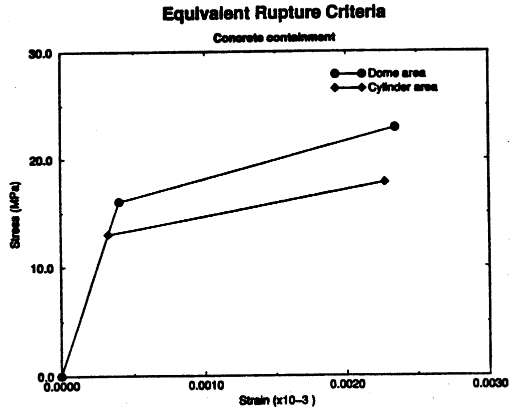

Figure 6: Equivalent rupture criteria for the concrete containment