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Ignition of flammable hydrogen/air mixtures by mechanical stimuli. Part 1: Ignition with clean metal surfaces sliding under high load conditions

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ABSTRACT

The conditions under which ignition will occur with sliding of clean metals (SS 304 and carbon steel) at high mechanical loading and velocity are investigated in part 1 of this study. A Monte-Carlo analysis has been undertaken to indicate the likely range of variation in the surface temperature with uncertainty in the parameters of most importance. It is concluded that ignition of flammable hydrogen in air atmospheres due to friction between clean metal surfaces will readily occur at high mechanical loading and sliding velocities where surface temperatures can exceed 900 °C. Even with loading of ≈0.9 tonnes, there was no experimental evidence to suggest that ignition could occur with clean surfaces of the materials investigated at velocities less than 1 m/s. However, given the theoretical relationship between generated surface temperature and properties of the sliding metals, it is indicated that ignition would be much more likely to occur at such velocities with harder metals. The study also shows that the raised surface temperature brought about by increasing sliding velocity is of greater significance than the reduction in contact duration between hot spots and individual kernels of partially ignited gas.

Introduction

Hysafe with other concerned bodies (reported by Kotchourko et al. [1]) have recently addressed the existing knowledge gaps in hydrogen safety and identified mechanical ignition as a research area that requires further attention. Whilst the focus of the present study is directed towards possible ignitions occurring during nuclear decommissioning operations the study has relevance to many other activities involving flammable hydrogen atmospheres.

Large quantities of nuclear waste material exist in silos and facilities throughout the world. In nuclear waste, hydrogen can be produced, either electrolytically through corrosion of materials such as Magnox fuel cladding (99% magnesium) or by radiolysis of aqueous solutions. Due to elapsed time during the storage of some of these materials, it is likely that there are considerable quantities of hydrogen gas contained within the corroded sludge beds. The necessity for removing these waste materials and storing them safely elsewhere involves the possible hazard of an ignition event occurring with released hydrogen gas. An important aspect of the decommissioning process is therefore to fully understand the likelihood of hydrogen being ignited if such a gas release occurs. To produce a robust safety case, it has been common in the industry

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to assume that formation of a flammable hydrogen in air mixture will inevitably lead to a deflagration. However, there are significant pessimisms in many areas in such safety cases including hydrogen generation and release rates and in particular ignition probability. The safety case usually assumes the probability of ignition of a flammable mixture as one which may be possibly orders of magnitude different to the real behaviour. This can lead to considerable over engineering and operational/maintenance costs causing major delays in the decommissioning of plant.

To obtain a realistic appreciation of the likelihood of an ignition event occurring during industrial scale operations, all of the possible scenarios that can lead to ignition sources must be identified including electrostatic (Ingram et al. [2]) and mechanical (Jones et al. [3] and Averill et al. [4,5]). Of these, it is considered in the context of nuclear decommissioning operations that those relating to surface heating or sparking caused by mechanical stimuli such as sliding contact or impacts between metallic bodies or a metallic body and a concrete silo wall are particularly important. In the EU both manufacturers and employers are now required under the respective ATEX100a [6] and ATEX137 [7] Directives to assess the possibility of ignition from mechanical impacts. Whilst there is considerable and long term experience in designing mechanical equipment for use in flammable hydrocarbon/air mixtures, as noted by Kramer [8], this is not the case for easily ignited gases including hydrogen. Without that experience to draw upon, greater reliance will be placed on available test data and models as the hydrogen economy grows and use becomes more varied and widespread. For more background information and a detailed account of the recent (2006) state of general knowledge concerning hydrogen ignition by mechanical and other stimuli, the reader is referred to Chapter 3 of the HySafe Biennial Report [9a].

Although there is relatively little experimental data or theoretical discussion available in the literature for ignition of hydrogen mixtures by mechanical stimuli, friction between sliding surfaces has long been known to cause ignition of flammable gas mixtures. Jones et al. [3] have obtained experimental data in LSBU laboratories for the ignition of hydrogen in air mixtures through accidental mechanical impact. With a 7 kg stainless steel projectile fired at an inclined carbon steel plate at velocities up to 12 m/s, it was shown that ignition is possible under a wide variety of conditions where pyrophoric surface contamination is present. However, there were no ignitions in the experiments carried out with clean metal surfaces. The ignition of hydrogen in air mixtures by controlled glancing impacts was investigated in a recent study by Averill et al. [4,5]. In the experiments, it was again found that ignitions did not occur with clean metal but did so readily when pyrophoric material (magnesium) was smeared onto the impact plates. There also appeared to be substantially reduced impact energy required for ignition when compared to the results of drop weight experiments. This was considered to be the result of the additional normal force applied to the hammer head (after the initial impact) increasing the surface temperature.

Little is known concerning the mechanical loading conditions necessary for ignition to become possible when clean metal surfaces are involved, however, the temperatures generated on sliding friction of materials pertinent to nuclear decommissioning have been the subject of recent study at LSBU. The results of this study suggested that ignition of hydrogen/air mixtures could occur as a consequence of sliding friction if sufficiently high mechanical loading is applied. Temperature measurements were made using a dynamic thermocouple method (Averill et al. [10]) and a thermal analysis carried out (Averill et al. [11]) to derive theoretical relationships for calculating surface temperatures. Underpinned by the work of Archard [12], Bhushan [13] and others, it was demonstrated that the maximum temperature produced with rapid sliding contact between bodies could be expressed by the equation

$$\theta_{\max} - \theta_b = \frac{1.6\mu p_f^{3/4} F_n^{1/4} v^{1/2}}{\pi^{1/4}\left(k\rho c_p\right)^{1/2}}$$

where the symbols have the following meaning

c_p: specific heat
F_n: normal force
k: thermal conductivity
p_f: material flow stress in pure shear
v: velocity of sliding
μ: dynamic coefficient of friction
ρ: density
θ_b: bulk temperature
$\theta_{\max}$: maximum temperature

It was clear from the experimental measurements with Ni/carbon steel and inconel alloy 600/stainless steel 304 couples that very high temperatures can be generated even at relatively low sliding velocities [10]. In circumstances where experimental measurement is not possible owing to the nature of thermoelectric emfs of the coupling metals (e.g. carbon and stainless steel), the analytical expression above will allow a good estimate of the transient surface temperature to be obtained.

Proust et al. [14] have proposed some simple modelling for practical applications where for frictional applications, a critical rubbing power is calculated equal to or smaller than 1 m/s. Rubbing generated by a continuously revolving wheel contacting a slider at these velocities can result in ignition of propane/air, ethylene/air and hydrogen/air mixtures. In the HySafe guidance on ignition of hydrogen by hot surfaces and mechanical stimuli [9b] it is considered, on the basis of the auto-ignition temperature, that the temperature of hot spots should not go beyond 560 °C. Although this auto-ignition temperature may be considered to be rather high in comparison with some other flammable vapours it was clear from the MECHEX EU project that ignition of hydrogen in air mixtures by hot surfaces can occur at temperatures close to the auto-ignition temperatures. Providing (as is the case with continuous rotating contact), that the temperature is maintained for a long enough time period, even a very small hot surface area will suffice to initiate ignition. From a practical safety viewpoint, the minimum velocity during sliding friction that is associated with the onset of ignition is of great interest. Whilst it has been generally considered in the past that sliding velocities below about 1 m/s do not represent a significant