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An analysis of the hydrogen explosion in the Fukushima-Daiichi accident

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ABSTRACT

An analysis of the amount of hydrogen taking part in the explosions that happened during the Fukushima-Daiichi (Unit 1) nuclear power plant accident is presented herein. Through a series of analytic approximations and numerical calculations of increasing complexity, it has been possible to estimate that 130 kg of H_2 was involved in the explosion. Also, the strength of the resulting explosion was examined determining that even with a significantly smaller amount of hydrogen taking part, a devastating explosion would have occurred regardless.

Introduction

Three severe core melt down accidents have occurred in history [1]. The first one, the Three Mile Island disaster, happened in the United States on March 28th 1979. The second accident took place in Chernobyl, Ukraine, Soviet Union on April 26th 1986. The last catastrophe, the Fukushima Daiichi accident, occurred in Japan on March 11th 2011.

A hydrogen accumulation in the containment building may have occurred caused by several reactions following a severe accident in a nuclear reactor [2]. The main sources of hydrogen that must be taken into account are the oxidation of Zircaloy by steam, the radiolysis of water, the reaction between water and boron carbide and the interaction of the molten core with the concrete of the containment.[1] Independently of its origin, the hydrogen released in the reactor accumulates inside the containment usually as a heterogeneous and probably stratified semi-confined layer of hydrogen-air or hydrogen-air-steam mixture. The ignition of such a layer can lead to strong pressure loads and severe structural damage.

Several works consider an accident involving the combustion of a large amount of hydrogen from a nuclear engineering perspective in Boiling Water Reactors, e.g. Refs. [1–6]. In these dedicated studies, the threat of a large scale hydrogen detonation, causing the rupture of the containment and allowing the radioactivity to be released in the environment,

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[1] The thermal decomposition of the concrete results in steam and carbon dioxide. These can further react with the metals in the melted core oxidizing them and thereby producing hydrogen and carbon monoxide.

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has clearly been identified. These sources establish that a design criterion, that must be considered for the construction of the containment building, is to withstand a large scale hydrogen detonation.

The sequence of events of the accident that can be found in the mono-graphic reports [1,5–11] is a significant information in order to understand the catastrophe. The owner of the reactor, TEPCO [7], provides a very detailed schedule, which has been the basis of the chronology appearing in most other documents considering this issue [8–10]. The record covers in depth the development of the accident for each of the reactors independently, providing a detailed and separate timetable for each of them.

On March 11th 2011 at 14:46 an earthquake of magnitude 9.0 on the Richter Scale occurred close to the north-east coast of Japan. Following the established procedure, the Fukushima Daiichi power plant shut down automatically to initiate its cool down after suffering no apparent damage due to the earthquake. At the moment of the accident, of the six reactors available, only three were operational, units 1 to 3. Unit 4 was completely de-fueled and units 5 and 6 were shut down for maintenance. Approximately one hour later, a tsunami with a 14 m wave height reached the power plant and originated critical damage. Concretely, it disabled the emergency power supply interrupting the shut down procedure, induced a complete black-out and destroyed the sea water pumps of the station.

The lack of electrical power disabled the delivery of cold water necessary to keep the core fully covered and cooled. The destruction of the water pumps and the black-out prevented access to the ultimate heat sink. The boil-off in the cores produced steam that raised the vessel pressure. This was relieved opening the ADS valves and bringing the steam to the suppression chamber. The water level in the reactor nucleus went down gradually until it dropped to a level of about halfway down the core. At the same time, the suppression pool started to become saturated and the pressure in the containment started to increase rapidly. Due to the lack of water, the steam generation rate became too low to cool down the fuel rods. The clad temperature increased and when the temperature reached 1400 K the Zircaloy oxidation by steam started, initiating the production of hydrogen. The temperature continued to grow and when a value of 3100 K was reached, melting point of the uranium dioxide, the melting of the core also started. Approximately 16 h after the initiation of the event, the fuel and the control rods were completely melted. Desperate attempts to maintain the cooling of the core through battery power had proven unfruitful when they become completely exhausted after eight hours of utilization.

Meanwhile, the pressure in the suppression chamber and in the primary containment continued to increase, overtaking and surpassing the design limits. Finally, the venting was initiated twenty four hours after the initiation of the event when the pressure had risen to twice that of the design values. The gases that were vented involved steam, radioactive species and hydrogen. Additional unintended discharges through leak paths and cracks created in the primary container vessel during the pressurization event cannot be excluded.

The hydrogen finally accumulated at the roof of the reactor building, an area which was only lightly plated. The hydrogen ignited, blowing up a large section of the roof and of the lateral walls and dispersed a significant amount of volatile fission products. The explosions occurred 24.8 h after initiation of the event in Unit 1, 68.2 h after initiation of the event in Unit 3 and in Unit 4, a serious hint of explosion in form of strong noise, has to be considered 87.9 h after initiation of the event [7].

It is most remarkable that Unit 4, which was de-fueled, also suffered an explosion. The accepted theory is associated with the back-flow of gases from Unit 3 during venting [8]. Due to the piping arrangement, it is plausible that this back-flow may have brought hydrogen into the building of Unit 4 via a reverse flow. The other two possibilities explaining this event look much less probable. They are, firstly, that the spent fuel pool of unit 4 was heated starting the oxidation of the Zircaloy and generating hydrogen. The second possibility is that the hydrogen used to refrigerate the main electric generators caused the explosion.

It is important to underline that, between the possible causes of the explosion in Unit 1 there is a consensus [7–11] that identify it as a hydrogen deflagration or detonation. Al others possible causes, like steam explosion or gasification of combustible liquids, should be disregarded following these sources. The previous studies also determine that the oxidation of Zircaloy cladding is the most intense source able to generate hydrogen [1,5–11].

The analysis of the hydrogen explosion that happened in the Fukushima Daiichi accident (Unit 1), and concretely the assessment of the amount of hydrogen that reacted in the explosion of Unit 1 and the damage it caused, is the objective of this article. The procedure that was followed consists in performing successive analysis of increasing complexity in order to obtain results that successively converge to a most probable quantity. Evaluation of the amount of hydrogen participating in the explosion section is initiated with a review of the amount of hydrogen generated during the accidents. Next, the amount participating in the explosion is assessed algebraically considering the speed of the shock wave and the size of the products generated during the explosion. Qualitative considerations on the hydrogen release from the point of view of combustion science is undertaken next in a section that contains some qualitative considerations on the hydrogen release from the point of view of combustion science. Those are mainly aimed at the estimation of the acceleration potential and combustion regime of the combustible gaseous mixtures involved. Numerical simulations of the explosion are subsequently carried out to refine previous analysis. As a result, a final amount of hydrogen involved in the explosion is obtained, assessing its destructive power.

Evaluation of the amount of hydrogen participating in the explosion

Amount of hydrogen generated during the cooling system failure

The knowledge of the amount of hydrogen generated during the accident is a significant magnitude for the present study