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Lessons learned from a supercritical pressure BLEVE in Nihon Dempa Kogyo Crystal Inc.

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ABSTRACT

On December 7, 2009, a 50-foot-tall high-pressure vessel ruptured in the Nihon Dempa Kogyo Crystal, Inc. facility in Belvidere, Illinois. Several projectiles rapidly traveled outward from the facility, killing a truck driver 650 feet away and injuring an employee in another building 435 feet away. This paper summarizes the lessons learned from this incident both on causal and consequential aspects. Stress corrosion cracking was identified as the failure mechanism by the U.S. Chemical Safety and Hazard Investigation Board. After analyzing the operating conditions and the aftermath, this incident has been identified as a Boiling Liquid Expanding Vapor Explosion (BLEVE) under a supercritical pressure. A consequence analysis of the incident is performed where overpressure and fragment distance are calculated, together with safety distance estimation. Additionally, other safety-related problems, such as safety culture, management inside the corporation, and communication between this facility and the government are discussed.

1. Introduction

On December 7, 2009, at approximately 2:30 pm, one 50-foot high-pressure vessel of Nihon Dempa Kogyo Crystal Inc. (NDK) ruptured. A white cloud of steam and debris rapidly expanded outward from the facility, traveled onto the interstate, and dissipated within seconds. As reported in the investigation report of U.S. Chemical Safety and Hazard Investigation Board (CSB) and some local news that no fire was observed in this incident; a 100-lb-piece of steel beam hit a truck driver 650 feet away and killed him; another 8600-lb-piece hit the wall of a building, where about seventeen people were working inside, and one employee near the wall was injured (CSB, 2013). NDK and an adjacent business were significantly damaged. While it was not able to determine the total amount of damage to the physical structure, NDK gave an estimation of half a million U.S. dollar loss for its inventory assets and in-use fixed assets, (NDK, 2009). The plant has been abandoned ever since. In May 2015, it was demolished (WIFR, 2015).

The NDK facility is located in a light industrial area in Belvidere, Illinois. It has conducted hydrothermal syntheses in eight 50-foot-high reaction vessels to produce high purity quartz crystals since 2003. Isothermal hydrothermal syntheses was firstly proposed by Nacken (Nacken, 1945) and the Woosters (Wooster and Wooster, 1946). The operating temperature and pressure through the whole process were required to be around the critical point of water (Walker, 1953). Different alkaline solutions can be used to meet various crystal requirement. For example, sodium hydroxide (NaOH) can help produce high purity crystal with an extremely low growth rate, while sodium carbonate (Na_2CO_3) increases the production rate but compromised the purity (Walker, 1953).

The investigation report of U.S. Chemical Safety and Hazard Investigation Board (CSB) presented the materials and operating conditions in the ruptured vessels (CSB, 2013):

- 800 gallons of 4% sodium hydroxide (NaOH) water solution
- A small amount of lithium nitrate ($LiNO_3$)
- Raw mined quartz
- Temperature: 700 °F (371 °C)
- Pressure: 29,000 psig (2000 bar)
- Batch cycle: 100–150 days

A schematic of the vessel is shown in Fig. 1. Seed crystal racks were installed at the top of the vessel with a lower temperature. When the fluid reached the crystal racks, the crystals precipitated and formed the desired product.

It is the purpose of this paper to analyze and summarize the

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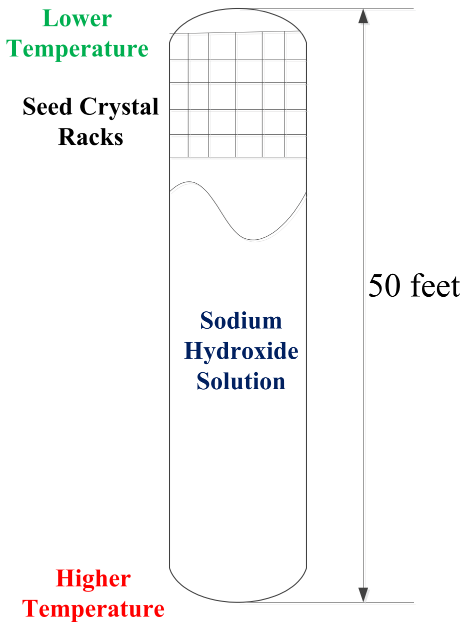

Fig. 1. Schematic of the vessel (based on description of CSB report).

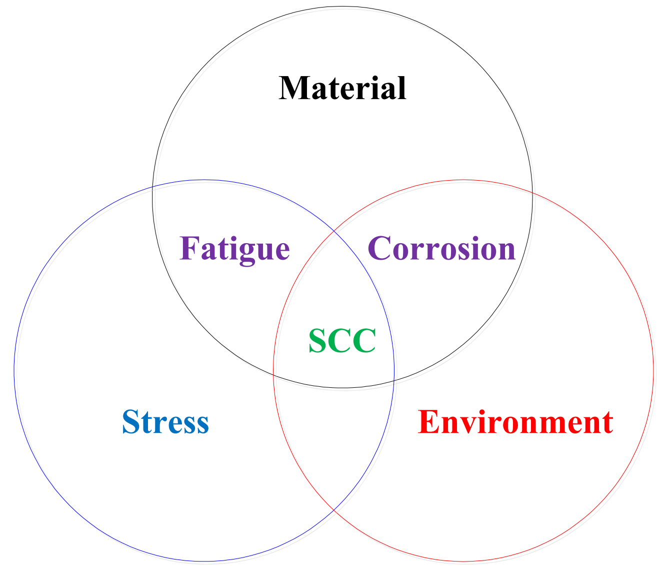

Fig. 2. Three indispensable elements of SCC.

lessons learned from this incident on both causal and consequential aspects:

- Stress corrosion cracking (SCC) was identified as the failure mechanism (CSB, 2013). With a combination of susceptible materials, tensile stress, and a corrosive environment, SCC was expected in low alloy steel in high temperature aqueous environments. Regular inspection and effective SCC control strategy should have been applied.
- An analysis of this incident identified it as a supercritical pressure Boiling Liquid Expanding Vapor Explosion (BLEVE), which indicated this phenomena was not a “black swan”. Concerns about future supercritical BLEVE occurrences call for more attention from the research community.
- Finally, the overall safety culture should have been improved due to other safety-related problems in the organization, such as risk management and communication. Good safety culture means that ground-level programs will follow automatically (Mannan et al., 2013).

2. Stress corrosion cracking

The CSB investigated this incident and found no deviation of operating conditions. National Institute of Standards and Technology (NIST) concluded that the vessel failure was caused by the SCC and the reduction in fracture toughness of the steel (CSB, 2013; Fekete, 2014).

SCC is induced from the combined influence of non-cyclic tensile stress and a reactive environment (Sieradzki and Newman, 1987). Three indispensable elements are needed for causing an SCC, as shown in Fig. 2. In other cases, it is fatigue with only susceptible material and sufficient tensile stress; or corrosion with only susceptible material and a corrosive environment (Ikeda et al., 1983; NPL, 2000).

The existence of an SCC hazard can be expected based on a process hazard analysis (PHA) since all these three indispensable elements were satisfied:

- A susceptible material: The ruptured vessel was constructed from alloy steel to meet the material specification of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code SA-723. It was categorized as Grade 2 Class 2 steel with a 2.3–3.3% nickel composition (ASME, 2015). Compared to Grade 3 Class 3 steel, low concentration of nickel made the vessel even more susceptible, since the addition of nickel is effective in improving the resistance of the surface layer to stress corrosion cracking and the metallurgical structure of the alloy (Ikeda et al., 1983). The Charpy impact test results supported the conclusion that the vessel's ability to absorb energy before failure diminished overtime (CSB, 2013).
- An environment that causes SCC for that material: The environment can be caused by aggressive media, abnormal temperature, electric potential or current, or micro fluids (NPL, 2000). The vessel was exposed to a 4% NaOH solution. Failures of this type have occurred with concentrations of NaOH as low as 5% in water (Canale et al., 2008). Failure takes place when the operating temperature is in the range of 392–482 °F. Also, the concentration of NaOH needed to cause cracking decreases as the temperature is increased (Schweitzer, 1996).
- Sufficient tensile stress to induce SCC: The stress can be either mechanical bulk stresses or internal stresses. In this case, the ruptured vessel experienced extremely high operating pressure (29,000 psi) for 100–150 days per batch. Besides, the vessel also suffered from the internal stresses since the wall of the vessel was too thick to be well-treated. The cylindrical wall was 8.1 inches thick and the top and bottom of the vessels were significantly thicker. The vessel walls were 18.25 inches near the lid and 16.25 at the base (CSB, 2013), which did not meet the ASME Boiler and Pressure Vessel Code requiring a 7-inch thickness limitation for quenching a closed-end vessel for this particular alloy (ASTM, 2010).

While NDK relied on the acmite coating (NaFeSi2O6) to form a protective layer, the investigation found SCC cracks under this coating (CSB, 2013), which indicated that the acmite coating was insufficient to prevent SCC. Possible reasons were that the acmite coating was damaged during the process of removing products or cleaning, or that the acmite coating was not efficient since research found that reaction time, reactants, temperature, and other factors