Analysis of the Catastrophic Rupture of a Pressure Vessel

On July 23, 1984, an explosion followed by a fire occurred at a petroleum refinery in Chicago, killing 17 people and causing extensive property damage [1]. NBS was requested by the Occupational Safety and Health Administration (OSHA) to conduct an investigation into the failure of the pressure vessel that eyewitnesses identified as the initial source of the explosion and fire. This vessel was an amine absorber tower used to strip hydrogen sulfide from a process stream of propane and butane. The vessel was 18.8 m tall, 2.6 m in diameter, and constructed from 25 mm thick plates of type ASTM A516 Grade 70 steel.

The investigation was complicated by the damage caused by the explosion and fire. The explosive force had been sufficient to propel the upper 14 m of the vessel a distance of 1 km from its original location, while the base remained at the center of the subsequent fire.

Sections of the vessel were shipped to NBS in August 1985, where a multi-disciplinary team sought the cause of the failure. The team was led by Harry McHenry, who was the Deputy Chief of the Fracture and Deformation Division and a leading expert in fracture mechanics. The study eventually involved 23 staff members from three different Divisions from both the Boulder and Gaithersburg laboratories of NBS.

The investigation that followed was a diagnostic masterpiece pursued with textbook elegance and deliberation. After documenting the history of the vessel prior to its rupture, testing of the vessel segments began with nondestructive evaluation techniques. Magnetic particle inspection was applied to reveal hundreds of cracks confined mainly to the inner surfaces along the welds between Courses 1 and 2 of the vessel and between Courses 2 and 3. Ultrasonic measurements subsequently detected clear indications of delamination damage confined to Course 1. However, thickness measurements, made with a micrometer, showed that Courses 1 and 2 had wall thicknesses well within the prevailing allowances for pressure vessels.

More aggressive measurements were then undertaken to examine the mechanical and chemical characteristics of the initial and replacement components. Test after test showed that all initial and replacement components satisfied the industry standard specifications. The cause of failure did not become clear until metallography results were combined with stress corrosion cracking and hydrogen embrittlement tests, followed by a fracture mechanics analysis. It appeared that a pre-existing crack had extended through more than 90 % of the wall thickness and was about 800 mm in length. Further, it was determined that hydrogen embrittlement had reduced the fracture resistance of the steel by more than half. After approximately 6 months of investigation, the findings were published as NBSIR 86-3049 [1].

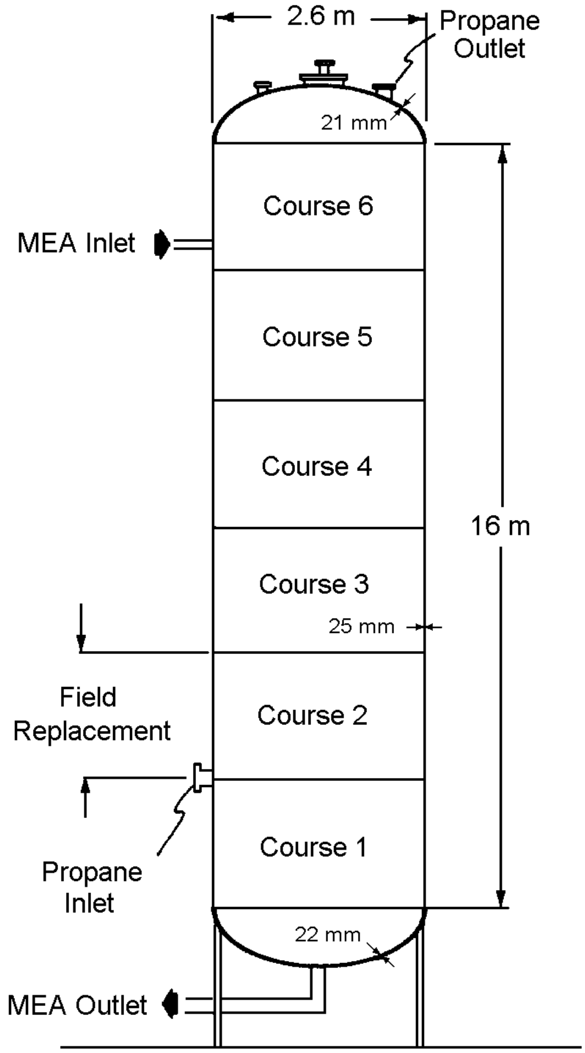

Fig. 1. Schematic of the original pressure vessel consisting of a series of sections know as Courses.

The vessel had been put into service in 1970 and had undergone several repairs and modifications before the July 1984 incident. The failure investigation determined that the vessel fractured along a path that was weakened by extensive cracking adjacent to a repair weld joining a replacement section to the original vessel. These pre-existing cracks initiated in areas of hard microstructure known to be susceptible to hydrogen stress cracking. This hard microstructure formed during the repair welding of the replacement section. The cracks grew through the vessel wall as a result of hydrogen pressure cracking. When the depth of the largest of these pre-existing cracks exceeded 90 % to 95 % of the wall thickness, the remaining thin ligament of steel in the cracked section ruptured and leakage occurred. This crack triggered a complete fracture of the vessel circumference at the operating stress level of only 35 MPa (roughly 10 % of the rated strength of the steel) because the toughness of the vessel steel had been reduced by hydrogen embrittlement.

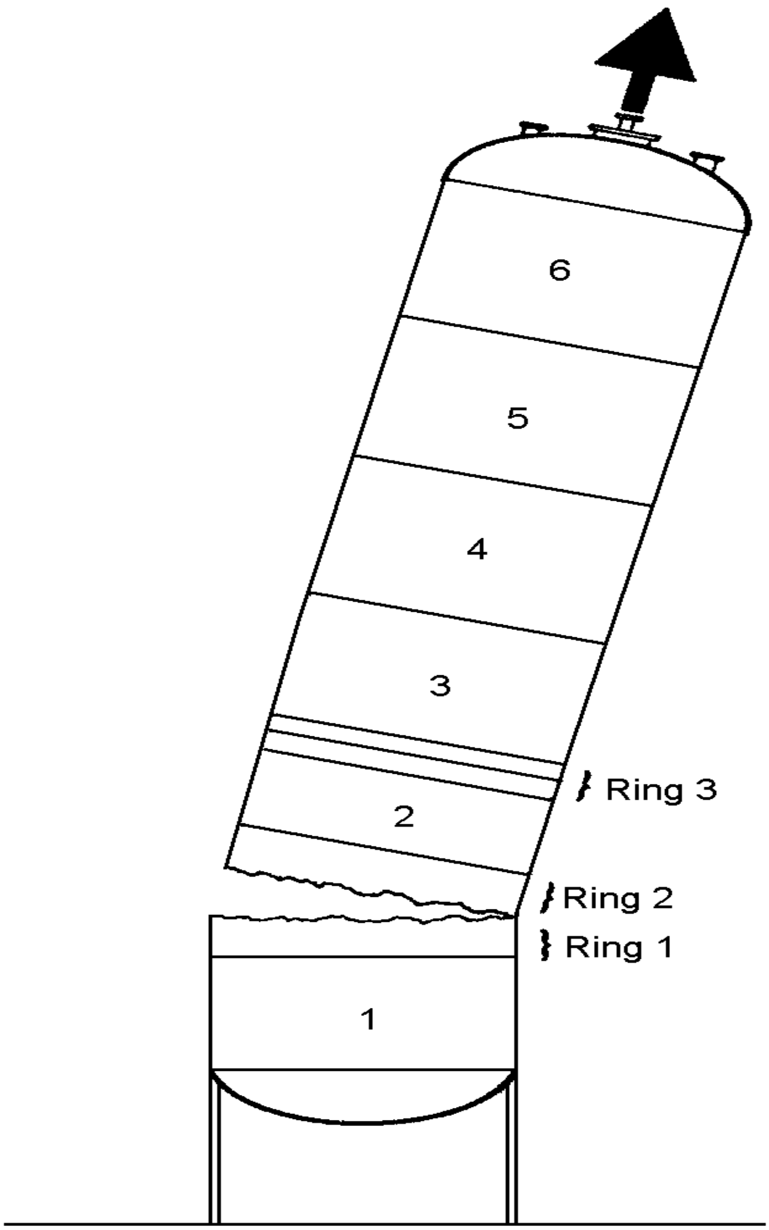

Fig. 2. The pressure vessel ruptured adjacent to the repair weld joining Courses 1 and 2.

The NBS publication pointed out previously unrecognized interactions between pressure vessel steel, the thermal cycles that occur during repair welds, and hydrogen-containing environments. Rapid dissemination of this information was important because many other vessels in the petrochemical and chemical processing industries might have had histories with a similar combination of these factors, and so might also be at risk of a similar catastrophic failure. In late 1986, the findings of the report were summarized in articles published in *Corrosion Science* [2] and *Materials Performance* [3], journals which were widely read by industrial process engineers and safety officials in these industries.

OSHA recognized the technical complexities involved in assessing the mechanical integrity of the various items of equipment used in process industries such as petroleum refineries and petrochemical manufacturing. To provide the OSHA inspectors and regulators with necessary technical information regarding the design and construction and related factors affecting the integrity of process equipment, OSHA engaged NIST to perform two additional tasks:

(1) Prepare an information document titled: "Guidelines for Pressure Vessel Safety Assessment" for distribution within OSHA, and

(2) Organize and conduct a training course (Course 340, Hazard Analysis in the Chemical Processing Industries) for OSHA inspectors, with informative lectures concerning pressurized equipment. The first course was taught at NBS (Boulder) in 1988.

The publication of the findings in *Corrosion Science* [2] and *Materials Performance* [3] allowed industrial process engineers and inspection personnel to update the inspection plans for plants under their control. Now that they were aware of the conditions found in this study, the inspection personnel could search for similar problems (such as hydrogen blisters and cracks) during the next annual or biennial shutdowns of processing plants under their control, and inspection intervals could be adjusted accordingly.

Several years following the failure incident and the NBS/NIST report, OSHA issued a final rule titled "Process Safety Management of Highly Hazardous Chemicals, Explosives and Blasting Agents." This rule was published as 29CFR Part 1910 in the Federal Register on February 24, 1991, and became effective on May 26, 1992. The rules have had a major impact on the process industry, particularly those parts that indicated, for example, that inspection and testing procedures to assess the mechanical integrity of process equipment shall follow recognized and generally good engineering practices. These rules have prompted cooperatively funded activities in the process and allied industry sectors which focus on the preparation of technical documents that describe and define methodology, procedures, and techniques that constitutes "recognized and good engineering practices." The first document developed in this activity was expected to be completed and available in early 2000.

Meanwhile, the OSHA training center has continued to offer the NBS-developed training course on hazard analysis to its inspectors. So far, the course has been held 11 times, and about 230 inspectors have attended it.

Harry McHenry retired in 1999 as the Chief of the Materials Reliability Division (the successor to the Fracture and Deformation Division). Bob Shives retired from the Metallurgy Division in 1992, but continues as a Guest Researcher, working on hardness standards. David Read continues as a Physicist in the Materials Reliability Division and is now studying the mechanical behavior of thin films. David McColskey continues as a Physical Scientist in the Materials Reliability Division and is now studying acoustic emission and the behavior of thin films. Charles Brady retired from the Metallurgy Division in 1988, and Patrick Purtscher left NIST in 1999 to become an Engineer with the Portsmouth Naval Yard in Portsmouth, New Hampshire.

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Bibliography

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[3] H. I. McHenry, D. T. Read, and T. R. Shives, Failure Analysis of an Amine-Absorber Pressure Vessel, *Mater. Perform.* **26** (8), 18-24 (1987).