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Failure Mechanisms and Effects Laboratory
The Impact of Failure Analysis on Engineering Practice

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In a taped interview with Dr. John H. Smith of the Metallurgy Division, National Institute of Standards and Technology, Gaithersburg, Maryland, Dr. Smith discusses how failure analysis in the field often impacts Engineering Standards. Using slides Dr. Smith discusses and illustrates two specific cases where this has happened. The first of these cases involved the failure of an oil storage tank that was relocated from Cleveland to Pittsburgh. The other case involved the failure of a compressed natural gas trailer tube in Litchfield, Kentucky. In each of these cases, compliance with existing construction and/or building codes failed to prevent failures that ultimately resulted in serious consequences.

Objective: The objective of studying and analyzing cases like this is threefold. First there is the objective of preventing future failures. The second objective is to identify corrective action(s), and the third is to advance engineering practice. Some would even add a fourth objective of "to find fault."

Background: The background for the oil storage tank failure is as follows: the tank involved was a four million gallon circular tank that was built in 1940 for Ashland Oil Company in Cleveland, Ohio. Beginning in 1940, the tank was operated for many years in what was believed to have been heated oil service. It is unclear as to how many years the tank was not used, but in 1986 it was disassembled by cutting it apart into sections. Using oxy-acetylene torches the "old welds" were left in place as the tank was cut apart and the sections were moved to an Ashland Oil facility near Pittsburgh, Pennsylvania. Using shielded metal arc welding, the tank was reassembled in 1987 and placed in a tank farm with many other similar tanks near the Monongahela River. When reassembled, the tank joints were x-rayed and leak tested. Test results indicated that none of the welds required rework. The reassembled tank was 50 feet high and approximately 120 feet in diameter. A dike was built around the tank that would hold 150 percent of the tank capacity.

The tank was partially filled with diesel fuel in August 1987. On January 2, 1988, during its initial filling to capacity after reconstruction, the tank failed catastrophically creating a tidal wave of oil that sent nearly 500,000 gallons of diesel fuel into the Monongahela River causing a major environmental problem. The problem was so severe that the entire water supply for all of South Pittsburgh had to be shutdown for two weeks. In addition to spilling thousands of gallons of oil in the river, the tidal wave of oil from the tank damaged other nearby tanks and structures as well. "A small, uncemented cinderblock shed about 120 feet distant had its walls literally swept away… leaving its roof lying neatly on the slab floor."

Eyewitness accounts of the failure indicated that there were no warnings. At the time of failure the tank was nearly full. There was no explosion. An operator was on the roof of the tank to verify that it was nearly full just five minutes before the tank ruptured. Sounds like thunder were described as emanating from the tank for about 30 seconds at the time of the failure. Observations of the failure site revealed that the tank had moved about 120 feet. The roof of the tank was still attached to portions of the tank wall. The bottom of the failed tank remained intact. Collateral damage included a fifty feet high adjoining tank that had oil on its roof and another tank some distance away that had oil all over it and was physically damaged.

Description of the experiment or process: In a failure of this type, several failure hypotheses immediately come to mind and are investigated. The investigative team involved in this failure consisted of Dr. Smith and other experts. They concluded that the failure possibilities were some external event, an operational failure, a foundation failure, a structural failure, and/or a material failure. To test for these type failures, many tests were called for and performed. They included stress analysis, finite element analysis, and thermal analysis to determine both the metal temperature and oil temperature at the time of failure. Also, Foundation Evaluation studies were performed to see if some form of settling had created stresses in the vessel walls. Materials Characterization analyses were performed to identify the materials and properties of the tank metal and welds. Structural analysis and fracture analysis was performed to evaluate the base metal and the weld metal. Finally, hardness, strength, Charpy v-notch tests to determine brittleness, nil ductility, fracture toughness, and tensile strength tests were performed to determine the physical characteristics of the tanks metallurgical microstructure.

Data to be expected: It was expected that the results of the tests and analysis outlined above would reveal the cause of failure as well as its origin. This proved to be true as the failure was found to begin with a brittle fracture in the base metal alongside old welds with the origin of failure being an undetected flaw in the base metal that was present prior to tank's original construction in 1940. Repeated heating and cooling of the weld process exacerbated this flaw. Ambient conditions (below the ductile to brittle transition temperature of the tank metal) as well as the pressure from the filled tank caused this flaw to yield catastrophically.

Potential analysis of the expected data: Analysis of the expected data produced the desired result. It led to the discovery of the root cause(s) of the failure and highlighted deficiencies or shortcomings in engineering standards. It is unfortunate that failures of this magnitude and the inconveniences it produced had to happen; but, at present, this is often the only way that deficiencies in standards can be detected.

Discussion: "Just past five o'clock p.m. on January 2, 1988, a large aboveground fuel storage tank located in Floreffe, Allegheny County, Pennsylvania suddenly and without warning collapsed as its shell rent completely from base to roof. The tank collapse unleashed a tsunami of petroleum product as almost 3.9 million gallons of diesel fuel surged out of the failed structure. The crest of this wave washed over nearby earthen dikes, whose intended design for containing a gradual release of petroleum products left them pitifully inadequate to confront the force of this catastrophe."

The above paragraph describes eloquently and with emotion how the local press viewed this incident. The original article describes with even more emotion how much diesel fuel flowed into the river and how much damage was done to the ecosystem, to the tank, the structural steel that supported it, and to other nearby structures. The same article, taken off the Internet, while commending them for their attitude and cooperation after the incident, is very critical of Ashland Oil, its management and employees, and its contractors for allowing this disaster to occur.

It is amid all of this emotion and fault finding that the failure analyst must operate, divorcing himself from the emotion and chaos and focusing on the facts to determine the true cause of the failure. In this case, as in most cases, the true cause of the failure lay in all the wreckage and debris of the failed oil tank.

To the author(s) of the above-mentioned report, Ashland Oil Company was at fault for not following existing industry and government standards for the construction and operation the failed tank. But as Dr. Smith pointed out in his talk, there are two sets of standards. The ones applicable to "oil storage" are those of the American Petroleum Institute (API). The two that apply in this situation are API 650 and 653. API 650 covers new construction only for "Welded Steel Tanks for Oil Storage." API 653 covers the reconstruction, repairs, and modification of existing tanks. It was generally felt that this particular tank was covered under API 653. Of course, as was also pointed out by Dr. Smith, compliance with the standards is voluntary except in certain cases where they are mandatory by law. For example, the Clean Water Act requires compliance with standards in certain cases.

API Standard 650 for new construction requires that 15 foot-pound Charpy energy at +5ºF "semi killed" steel be used, and a that full hydrostatic test be performed. If reconstruction of the failed tank had followed this standard, in all likelihood the failure would have been averted. However, it was rebuilt to the less stringent API

653. After the failure and subsequent investigation the failure did serve as a vehicle for bringing about changes in the API 653 standards.

The new API Recommended Practice 653, (1990) "Tank Inspection and Repair" which covers maintenance, inspection, repair, alteration, and relocation of storage tanks now provides a procedure to assess risk of brittle fracture. It is based on API standard 650 and the "Assessment" is based on a decision tree to determine the risk of brittle fracture. When this practice is followed, failures like the one discussed in this paper will no longer happen and engineering practice will have been advanced.

As discussed by Dr. Smith, any failure in service is an engineering design failure, and we should learn from it. When we learn from the failure, engineering practice is advanced and if necessary the appropriate Engineering Codes and Standards like SAE, API, AGA, ASTM, and ASME are changed to reflect the lessons learned. The lessons learned from the Liberty Ship failures of World War II created a whole new discipline of engineering - Fracture Mechanics. Fracture Mechanics has been in practice for more than 50 years and has advanced our knowledge of materials failures and how to prevent them tremendously.

Finally, since there are literally thousands of tanks just like or similar to the one that failed in Pittsburgh scattered all across the United States along the rivers near major cities, the API conducted a survey of existing tank owners. The API wanted to compile a list of failure data and material toughness data to review their toughness standards. They found that they were able to gather data on 54 failed tanks of welded and riveted construction. The tanks were built between 1897 and 1979 and had a capacity ranging from 55,000 to 186,000 barrels. The age at failure ranged from 0 to 51 years, and the temperature at which they failed ranged from 0ºF to 51ºF. Most of the tanks failed after a repair or modification. This data was used to develop the decision tree for tank assessment that was incorporated in the API standards. Both API standards 650 and 653 were modified based on the oil tank failure investigation and the survey data.

The other failure discussed by Dr. Smith was the failure of a Compressed Natural Gas Trailer Tube. This failure occurred in October 1997 in Litchfield, Kentucky during the filling of the tube from a natural gas well. The tube was a DOT Type 3T (2725-psi) 22-inch diameter, approximately 40-feet long seamless steel tube for CNG service. It was made from A-372, Class 5, quenched and tempered steel with a tensile strength of 160-170 ksi. It had been in use for approximately one week. The failure involved the complete rupture of the tube.

The failure investigation showed that the tube had failed from environmentally assisted cracking due to about 550 parts per million water and hydrogen sulfide in the gas. The fix for this problem actually required the use of a lesser quality steel. The Department of Transportation (Dot) issued Exemption E-8009 for tube steel used in Compressed Natural Gas service. The exemption specified the following:

- Limit CNG to 3AAX tubes
- Maximum tensile strength 126 ksi
- Tubes be marked "CNG"
- 1800 -2800 psi pressure
- Gas purity requirements of 0.5 lb./million water, and 0.1 gr./100 cu. ft. hydrogen sulfide.

Present System for Changing Engineering Practices: The present system for changing engineering practices is done on an "Ad Hoc" basis. This is very inefficient and should be changed. For example, maybe Engineering Data Centers could be established at the various code and standards organizations like API, SAE, ASTM, ASME, etc. to act as a clearinghouse for suggested code changes based on valid failure analyses findings from professional engineers across the country. The need exists for something like this because of our decreased tolerance for failures and the potential environmental impact and increased liability of certain failures. Also, there is an increased public perception about the significance of failures and the concern for worker safety throughout the country. Fortunately, no one was killed or seriously injured in the oil tank failure discussed in this paper, but the potential for those type consequences was certainly there.

References: References for this paper are:

1. A taped interview on *"The Impact of Failure Analysis on Engineering Practice"* with Dr. John H. Smith, Metallurgy Division, National Institute of Standards and Technology, Gaithersburg, Maryland.

2. Failure Mechanisms and Effects Laboratory, ENRE674, Module 3, The Impact of Failure Analysis on Engineering Practice, pages 3-1 through 3-7

3. Storage Tank Collapse Sends 500,000 Gallons Of Diesel Fuel into Monongahela River, Pennsylvania's Environmental Heritage, June 1988, http://www.dep.state.pa.us./dep/pa_env-her/ashland.htm

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