Evaluation of pipe failure incidents

R.H.Vollmer
TENERA Master Limited Partnership, Bethesda, Md., USA, formerly USNRC
L.C.Shao & A.Taboada
USNRC, Washington, D.C., USA

ABSTRACT

Catastrophic failures of large pipes have occurred in reheat systems of fossil plants and in a main feedwater line of a nuclear plant. This paper describes the incidents and compares the details of design and operation with those of safety related piping in nuclear plants. Probable failure mechanisms are discussed as is the relevance and implication of such failures to the safety of nuclear plants.

1. Introduction

During 1984 and 1985 the NRC Piping Review Committee performed a comprehensive review of requirements for safety related, nuclear power plant piping. As part of this review the Committee completed in-depth evaluations in the areas of: stress corrosion cracking in piping of boiling water reactors, seismic design, potential for pipe breaks, and other dynamic loads and load combinations.[1] These evaluations resulted in recommendations for appropriate changes to NRC requirement for nuclear power plant piping and for research needed to resolve outstanding piping issues. In part, this review and related NRC research provide a basis to support the leak-before-break concept for certain pipe systems which, when applied would enhance maintainability and permit the removal of massive pipe whip restraints and jet impingement barriers.

Subsequent to this review, catastrophic failures of large welded pipes occurred in reheat systems at two major fossil power plants and in the main feedwater line of a nuclear plant. These pipe failures resulting in damage to the plants as well as injuries and, at two plants, fatalities to personnel. Because of the concerns with pipe breaks, members of the Committee visited these plants to review the incidents, observe the pipe failures and determine any information that might relate to Committee recommendations or be applicable to safe operation of nuclear plants.

This paper describes the incidents and compares details of pipe design and operation with the design, and operating conditions of safety-related pipe in light water reactor nuclear plants. Probable failure mechanisms are discussed, as is the relevance of these failures to the safety of nuclear reactor piping.

2. Pipe Failure at The Mohave Generating Station

On June 9, 1985, a 20-foot section of a 30-inch diameter high pressure steam pipe of the Mohave Generating Station, ruptured without warning, releasing high pressure steam that resulted in the death of six plant personnel and injuries to 10 others. This plant consists of two coal-fired, steam turbine-generator units, each rated at 790 MWe. It was designed in the late 1960's to deliver superheated steam to high pressure turbines at 1000 °F and 3500 psig, and began commercial operation in 1971.

Failure occurred in a "hot reheat" line that operates at 1000 °F with loads of up to 580 psig. The piping system was designed to the ANSI/ASME B31.1 power piping code. The failed pipe was 30-inch in diameter and 1.5-inch thick and was fabricated by seam welding alloy steel plate containing 1¼% chromium and ½% molybdenum.

Pipe rupture occurred in a straight horizontal spool piece along the seam weld which unfortunately was oriented to release escaping steam towards the personnel work area. The fracture was described as a "fish mouth" rupture approximately 20-feet long and approximately 6 feet at its widest point.

A metallurical analysis of the failed pipe reported that the crack initiated in a midwall location, at the seam weld-base metal interface, and apparently grew in size over a period of time along this interface due to the occurrence of creep rupture. During this crack growth period the inner pipe surface was penetrated at several locations exposing the crack surface to steam environment. Final rupture occurred when the crack grew so large that the degraded pipe could no longer contain the pressure loads.

3. Pipe Failure at the Monroe Power Plant

On January 30, 1986 a pipe rupture very similar to the one at the Mohave Power Plant, occurred at the Monroe Power Plant located at Monroe, Michigan injuring several of the plant personnel. This facility is a coal fired plant with four turbine-generator units, each rated at 750 MWe, and has steam conditions at 1000°F and 3600 psig. The plant began commercial operations in June 1971 and had operated for 97,000 hrs. at the time of failure.

The pipe failure at the Monroe Power Plant occurred also in a "hot reheat" line which was designed to operate at 1000°F and 750 psig applying the ANSI/ASME B31.1 power piping code. The failed pipe was a 32-in in diameter and 1.5-inch thick seam welded pipe made of alloy steel plate, containing 2¼% chromium and 1% molybdenum.

As in the Mohave failure the pipe rupture occurred in a straight, horizontal spool piece along the seam weld which although causing significant damage to the plant equipment did not result in serious injuries. The fracture was a "fish mouth" rupture approximately 20 feet long and 6 ft. at its wides point.

A metallurgical analysis of the failed pipe reported numerous cracks initiating on the outside diameter as well as at mid-wall that linked up along the toe of the weld at locations of weld repairs. It appeared, that at the time of failure, a crack pre-existed that was over 10 feet long and as much as 80% through the wall.

4. General Observations

The pipe failures at Monroe and Mohave had several similarities. Both failures occurred explosively in large diameter horizontal reheat lines after long term operation at 1000°F and relatively similar pressures (750 psig and 580 psig). Both failures occurred primarily along a seam weld and opened up fish mouth fractures that were approximately 20 feet long and 6 feet wide. Both failed pipes were of the same vintage, made to similar material specification and designed to ASME/ANSI B31.1. However, the Mohave pipe was made of 1¼ Cr-½ Mo material and the Monroe pipe was made of improved 2¼ Cr-1Mo material. Although, as yet, no formal failure report on either incident has been released by the utilities, it is generally understood that the failures were brought on by creep rupture in the fusion zone of weldment at locations containing manufacturing flaws. As a result of these findings the power industry has instituted periodic inspections to mitigate this problem.

5. Comparisons with Safety Related Piping in Nuclear Reactors

The failed Mohave and Monroe piping and their operating conditions are not typical of the safety related piping in light water reactor nuclear systems reviewed by the NRC

Piping Review Committee. In particular, the 1000°F operating temperature is significantly higher and makes the alloy steel material susceptable to creep rupture and creep fatigue problems as well as to further metallurgical changes not expected at the lower operating temperatures of light water reactors. The Chromium, molybdenum materials used in the reheat lines are not used in safety-related systems of light water reactors.

In safety-related systems, light water reactors use austenitic stainless steel and carbon steel for piping materials which tend to be tougher and more weldable than to alloy steels. In addition to material and operating temperature differences, there are other factors which mitigate, against such a failure in nuclear piping. These include:

- Improved design and analysis
- Improved welder qualification
- Better control of pre- and post-weld heat treatments

- A higher quality nondestructive examination during construction
- Inservice inspection--now being instituted in fossil plants
- Leak detection requirements
- Generally more and improved quality assurance

6. Pipe Failure at Surry Power Station

On December 9, 1986, an 18-inch pipe of the nonnuclear part of the Surry Power Station, Surry County, Virginia, failed catastrophically releasing high pressure steam and resulted in burn injuries to eight plant personnel that proved fatal in four cases. The Surry Power Station is a two-unit plant, each of which is a three-loop pressurized water reactor rated at 775 MWe. The plant began commercial operation in

1972 and has operated for approximately 76,000 hours.

Failure occurred as a complete separation of a carbon steel suction line to a main feedwater pump in an elbow at a transition to a 24-inch condensate supply header pipe. In addition to the double ended break, pipe whip reactions twisted and rotated the pipe causing distortion and buckling away from the break and displacing the broken pipe end about 10 feet. As a result, a large fragment was ripped off of the broken pipe end and thrown a distance of approximately 20 feet.

The primary cause of the pipe failure was reported to be gross thinning of the pipe wall over a large area caused by erosion/corrosion. The pipe thickness had decreased from 0.5-inch to as thin as 0.04-inch, making the pipe unable to withstand minor pressure surges.

The rapid wastage of carbon steel pipe by an erosion/corrosion mechanism has been well documented by several European investigators.[2][3][4] Based on the data reported, it is apparent that a combination of the turbulance inducing pipe design, and fluid conditions were ideal for erosion/corrosion to take place in the carbon steel pipe at Surry.

A comprehensive inspection of the remainder of the piping in the Surry plant found significant wall thinning in other pipes at both Surry Units indicating the potential for a generic problem. As a result the NRC and the nuclear industry have initiated programs to evaluate (1) the extent of the problem, (2) the safety significance and risk aspects and (3) the existing state of knowledge on the erosion/corrosion mechanisms and variables that influence this mechanism. The results of these programs should result in guidelines and possible changes to code rules and safety requirements to avoid such an occurrance in the future.

7. References

(1) NUREG-1061, Volumes 1-5, Report of the U.S. Nuclear Regulatory Commission Piping Review Committee, April 1985.

(2) G.J. Bignold et al., Erosion-corrosion in nuclear steam generators, in Proceedings of the Second Meeting on Water Chemistry of Nuclear Reactors, British Nuclear Engineering Society, 1980.

(3) H.G. Heitmann and P. Schub, Initial experience gained with a high pH value in the secondary system of PWRs, in Proceedings of the Second Meeting on Water Chemistry of Nuclear Reactors, British Nuclear Engineering Society, 1980.

(4) Berge, Ph., Ducreaux, J., Saint-Paul, P., "Effects of Chemistry on Erosion-Corrosion of Steels in Water and Wet Steam," pg. 19, Water Chemistry of Nuclear Reactor Systems 2, British Nuclear Energy Society, London, 1980.