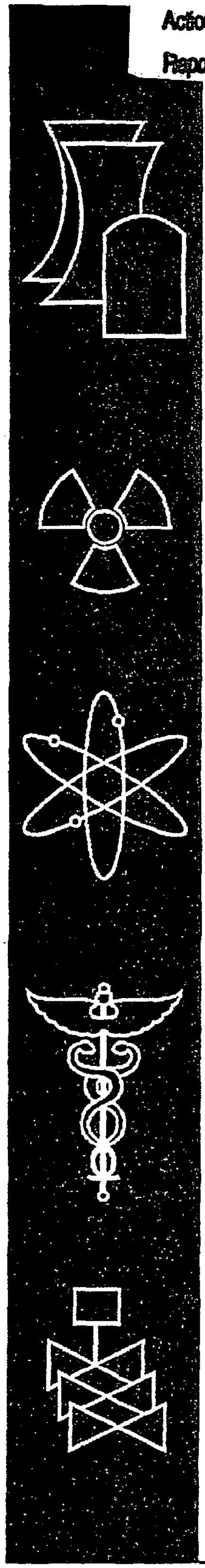
RAS J-51

U.S. NUCLEAR REGULATORY COMMISSION
In the Matter of Entergy (Pilgrim Nuclear Power Station)
Docket No. 50-293-LR Official Exhibit No. 21
OFFERED by: Applicant/Licensee [✓ Inten] PilgrimWatch Ex 8
NRC Staff Other
IDENTIFIED on 4-10-08 Witness/Panel
Action Taken: [✓ ADMITTED] REJECTED WITHDRAWN
Reporter/Clerk Thibault

NUREG/CR-6876
BNL-NUREG-74000-2005



Risk-Informed Assessment of Degraded Buried Piping Systems in Nuclear Power Plants

DOCKETED
USNRC
April 15, 2008 (10:00am)
OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

Brookhaven National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

Temp = SECY-028

DS03

3.1.1 Aging Mechanisms

The primary aging mechanisms that directly affect buried metallic/steel piping are described below. Aging mechanisms affecting polymer piping are not discussed because polymer buried piping are rarely used at NPPs. Aging mechanisms of concrete pipe are also not discussed because buried concrete pipe is primarily used at NPPs for large diameter lines due to their significant weight. These large diameter lines provide the ability for personnel to gain access and perform periodic inspections. Therefore, the focus of this research study is limited to buried metallic pipe. Information for aging mechanisms and effects of concrete pipe would be similar to those already described for concrete members in NUREG/CR-6715.

General Corrosion

General corrosion is a degradation of the pipe surface that results in loss of material over a region without appreciable localized attack. Corrosion is caused by a direct current that flows from a metal such as a buried pipe to an electrolyte such as the soil material. Corrosion occurs at the location where the current exits the pipeline to enter the soil. Corrosion depends on the electrical resistance and potential of the electric circuit that is developed. Corrosion varies with the moisture content of the soil. If the soil is dry, very little corrosion is expected to occur, while in soils with higher moisture content, the resistivity drops and higher rates of corrosion would occur.

Corrosion is also a function of the level of oxygen in the soil. Where oxygen is more plentiful, the rate of corrosion is initially high and then is slowed by the corrosion products that remain adhered to the pipe surface. Corrosion products however cannot be relied upon to prevent corrosion because they do not adhere tightly to the pipe, may be thin, and may not exist throughout the pipe.

General corrosion rates vary depending on many design and environmental parameters. A discussion of general corrosion rates in steel pipe is provided in Section 3.4

Because of the poor corrosion resistance of carbon steel pipes, they are often lined or coated on the inside with bonded polymeric coatings, cement-mortar, or elastomers. On the outside, buried pipes are usually protected by coal tar epoxy coatings and wrappings. Buried piping is also protected at many plants by a cathodic protection system which is described in Section 4.1 of this report.

Pitting Corrosion

Pitting corrosion is a localized form of corrosion that forms cavities or holes in the material. Pitting corrosion occurs when chemical attack breaks through the passive film that protects the metal surface. Once a pit penetrates the passive film, an electrochemical (galvanic) reaction develops. The metal in the pit becomes anodic while the surface outside the pit is cathodic. The exposed surface outside the pit is cathodically protected and can lead to a large cathode to anode ratio which can accelerate the anodic reaction in the pit. The reaction in the pit leads to a reduction in the pH and an increase in the chloride ion concentration. The acidic chloride environment is aggressive to most metals and thereby propagates the pit growth. It is possible for most of a pipe section to show little corrosion while some deep pits may develop.

indicated that there was internal coating degradation of buried piping at three of the six plants visited. Remedial action was taken by the licensees after the degradation resulted in inadequate flow conditions or unacceptable water quality.

3.3 Important Aging Effects for Use in this Study

Although there are numerous aging mechanisms possible for buried piping, the analysis described in this report is based on the aging effect or manifestation of the degradation, not what causes the degradation. This approach is taken because to achieve the objective of developing degradation acceptance criteria (DAC), the degradation criteria will need to be developed in terms of observable levels of degradation which normally correspond to aging effects such as loss of material in the pipe wall. Based on Table 3.3, the primary aging effects that are caused by almost all aging mechanisms are thinning of the pipe wall over a region and localized loss of material/pitting in the pipe wall. The remaining aging effect of loss/reduction in flow is not addressed because this aging effect can be monitored by measuring performance parameters of the system such as flow rates, pressure, and sampling of the fluid.

Degradation to the internal or external coatings as reported in Table 2.2 for some plants is not considered because the coating is a protective material whose deterioration can lead to wall thinning or pitting of the pipe wall at some time in the future, only if no action is taken. As long as degradation of the steel pipe has not occurred, degradation of the coating does not affect overall plant risk. The purpose of this study is to develop DAC on degraded buried piping and not acceptance criteria on the coating material. It is expected that any degradation identified with the interior or exterior coating of buried piping will be repaired unless otherwise justified.

3.4 Degradation Rates For Corrosion and Localized Loss of Material/Pitting

The rate of degradation of steel buried piping is a function of environmental variables, metallurgical variables, and hydrodynamic variables. Environmental variables that can affect the degradation rates occur on the exterior surface of the buried pipe and inside surface of the pipe. For the external surface of the pipe, the rate of degradation is a function of parameters such as aggressive chemicals, oxygen, pH level, and stray currents that may exist in the soil material and groundwater (if present). The rate of degradation on the interior pipe surface is a function of fluid parameters such as fluid velocity, temperature, aggressive chemicals, pH level, dissolved oxygen, and biological elements. Metallurgical variables consist of the chemical composition of various elements in the pipe material such as the weight percentage of chromium, molybdenum, and copper in the steel, which may affect the degradation rate. Hydrodynamic variables such as fluid velocity, piping configuration, and roughness of the pipe inner surface also affect the degradation rate.

Other variables that may affect the degradation rate are: time, type of corrosion/degradation, and whether the piping is pressurized. Depending on the conditions and time period of interest, the degradation rate may not be constant with respect to time. The two types of aging effects which are evaluated in this study (general wall thinning and localized loss of material/pitting) may have some effect on the degradation rate of the buried pipe. In addition, the degradation rate is also expected to be affected by piping that is normally operating and thus "continuously" subject to internal pressure, and by piping that is normally in standby and thus is not subject to internal pressure at all times.

Based on the above discussion, it is evident that predicting an accurate degradation rate for buried piping systems is difficult to achieve, and beyond the scope of this research program.

Therefore, a literature search was performed to determine what are typical degradation rates for buried piping systems that might be appropriate for use in nuclear power plants. Based on EPRI Report TR-103403 (1993), general corrosion rates vary from 1 to >10 mils/year (1 mil per year = 0.0254 mm per year (0.001 in. per year)) for carbon steel and low alloy steels in fresh water at temperatures of 1.67°C to 40.6°C (35°F to 105°F). Assuming 3 mils/year and a 40 year life, this results in a loss of thickness equal to approximately 0.318 cm (1/8 in.), which should have been considered as corrosion allowance in the original design of buried pipe. Corrosion rates of stainless steels, nickel based alloys, and copper alloys have much lower corrosion rates, often less than 1 mil per year. These materials would be used in buried piping subjected to more aggressive environments such as seawater or brackish waters, or where safety concerns require more corrosion-resistant material.

Since there wasn't much more information that could be identified specifically for buried piping, data on degradation rates for above ground piping systems were also searched. Degradation occurrences reported in NRC Information Notices were identified and reviewed. Information Notices that provided quantitative data on degradation rates are IN 2001-09; IN 86-106, Supplement 3; IN 87-36; IN 91-18; and IN 92-35. A review of these Information Notices indicates that the degradation rates for the reported occurrences generally went as high as 60 mils per year, with one case for localized thinning at 90 mils per year. It should be noted that most of these cases occurred in high energy lines such as feedwater systems and it could be argued that their degradation rates are more severe than what would be expected in buried piping systems operating at lower pressures, temperatures, and fluid velocities. On the other hand, these above ground piping systems are not subjected to the external environment that buried piping may be exposed to. Often this external environment in buried piping is mitigated by means of external coatings on the pipe or sometimes by the use of cathodic protection systems. The information provide by these Information Notices do give a measure of perhaps the upper bound of what might be expected in buried piping systems.

Based on the above discussion, it appears that a reasonable range of degradation rates for buried piping would be between 1 and 100 mils per year. This information is only provided as guidance on typical values that have been reported. The selection of an appropriate degradation rate is the responsibility of the individual performing the assessment, based on the conditions that exist for a particular buried piping system.

4 DETECTION OF AGE-RELATED DEGRADATION AND CONDITION ASSESSMENT

4.1 Inspection Methods

Inspection methods for the degradation of buried piping can be based on visual, non-destructive, or destructive methods. Since degradation mechanisms can cause aging effects on the interior and/or exterior of buried piping systems, information about the condition of the inside and outside surface of buried piping is important. Large diameter lines such as portions of the service water system usually can be examined by manual visual inspection provided there is access to the line. Smaller diameter lines however, are not easily accessible and require other techniques which have been improved significantly over recent years. The methods that can be used to inspect the condition of buried piping are described below. The use of a particular method depends on the size of the line, access to the interior or exterior surface, pipe material, aging effect of interest, and cost.

Visual Inspection

This is the most common form of inspection of the condition of the interior or exterior buried piping. For interior examination of large diameter lines, inspections are usually performed during plant outages where a trained individual (inspector) enters the pipeline to examine the condition of the pipe surfaces, coatings (if applicable), welds, and mechanical joints. If the water in the line is not drained, inspections can still be performed using trained divers. The inspector can identify any fouling of the pipe, loss of wall thickness, degradation of coating, and identify the extent of any other degradation. Loss of wall thickness can be identified using a pit gauge to measure pit depth, ultrasonic test (UT) meter to measure general loss of material, and tape measure to record the area of the corroded region. Inspection for coating degradation would include examination for cracking, blistering, debonding, peeling, erosion, and general loss of coating material. During the inspection the inspector can collect any built-up material due to fouling or corrosion by-products for subsequent analysis. In addition, the inspector can insert and remove coupons which can be evaluated for degradation of the pipe material.

Sometimes, an indication of the condition of the interior surface for buried piping can be determined by examining accessible entry points where the buried piping rises above the ground surface or enters into buildings. This may not be reliable though if conditions of the buried piping section are different than the accessible portions of pipe above ground or within the buildings. This may be due, as an example, to stagnant water in the buried piping section which may not exist in the other regions being examined.

Visual inspections from inside the pipe cannot identify degradation on the outside surface of the pipe unless corrosion or pitting penetrates the thickness of the pipe. Therefore, to obtain complete knowledge of the condition of a buried pipe, examination of the inside and outside surface is recommended. The same visual inspection methods described above can be used to examine the exterior surface of the pipe; however, excavation would be needed to gain access to the exterior pipe surface.

Cameras

Cameras can be used for visual inspection of buried pipes. These cameras provide visual type information without the need for direct personnel inspection or excavation to gain access to buried pipe. These cameras are useful for smaller diameter lines where direct visual inspection by personnel is not possible. Presently, these cameras are tethered and may be difficult to

6 RISK EVALUATION OF DEGRADED BURIED PIPING SYSTEMS

Buried piping systems at a nuclear power plant (NPP) can degrade, as described in the previous sections. Such deterioration potentially could impair the operation of the system that contains the buried piping, and thus impact the overall risk of an NPP.

Currently, buried piping is not systematically inspected. Accordingly, a failure of a buried pipe is "discovered" because the failure is self-revealing[1], or a failure or degradation of a buried pipe is "discovered" because of another event, such as excavation that is performed for unrelated items. If the "discovery" indicates that the pipe has failed, then a repair[2] has to be completed to return it to normal condition. If the "discovery" indicates that the pipe has not failed, but it has degraded, the regulatory question that arises is: "does the pipe have to be repaired immediately, or is it acceptable for the plant to continue operating?[3]" In essence, the methods and criteria described in this report provide guidance to the NRC staff to assist them in answering this question.

These methods assess the increase in projected risk as a function of time from the time of inspection to answer the question in the previous paragraph. In this way, they estimate the number of years before the plant risk becomes unacceptable. The expression "projected risk" means that the risk is evaluated at some time after the time of inspection.

The increase in projected risk is assessed from the time of inspection because it is known that the pipe has not failed at this time, and the objective of the evaluation is to assess whether continued operation of the pipe (plant) from this time leads to "unacceptable" risk. Figure 6.1 depicts relevant events as a function of time from the start of life of a buried pipe.

To estimate the effect of buried piping degradation on plant risk, five nuclear plant sites having buried piping systems were selected. Section 6.1 describes the process used to select the five nuclear plant sites with buried piping systems. Each site may have one or more NPPs; to simplify the discussion, this report refers to one site simply as an NPP or a plant.

To develop degradation acceptance criteria, which is one of the stated goals of this research, a quantitative measure of "acceptable risk" is needed. Section 6.2 defines what is considered to be acceptable risk, the conditions for which it is applicable in this study, and the quantitative risk acceptance criteria.

The evaluation of the risk associated with degrading buried piping depends on the type of system that contains this piping. Section 6.3 discusses some top-level considerations for developing methods for estimating this risk, including a classification of the plant's systems for the purpose of assessing this risk. Section 6.3 concludes that all the systems with buried piping of the five nuclear plants selected fall into two categories:

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[1] A failure of a buried pipe is self-revealing, for example, when a system that is normally operating fails in such a way that the failure becomes visible to plant personnel.

[2] In this section the term "repair" is used in a very broad sense, including replacement. In other words, when a "repair" is carried out, it is considered that the pipe is returned to a condition that meets the plant's current licensing basis.

[3] If the buried pipe is degraded but not failed, the licensee is still expected to evaluate the degraded condition to determine if any corrective action needs to be taken depending on the evaluation findings and the level of degradation. Although future inspections are an option, there is no requirement to do so.

The ED provides the amount, in percentage terms, that was lost from the required wall thickness for pressure and other loads. Now the existing DAC table corresponding to a pipe with a thickness equal to (t_r) and percent wall loss equal to ED can be used to determine the number of years to reach a level of degradation that would potentially have a significant effect on plant risk. Therefore, the recommended approach for Case B, when OL > CA, is to use the existing Table 7.3 for DAC and reading off the number of years at the row corresponding to the equivalent observed wall loss percentage (ED) as defined above. An example of how to apply this approach to a pipe that is degraded beyond the corrosion allowance is provided in Section 7.3.

7.3 Guidance on the Use of Degradation Acceptance Criteria

If buried pipe degradation is identified at an NPP, it may not be evident whether the pipe still complies with the plant licensing commitments or whether the degradation potentially has an immediate significant effect on plant risk. Normally, the licensee performs an evaluation of the degraded condition which may include further inspections, testing, calculation/design review, and other actions to determine the severity of the condition, risk implications, and whether an immediate repair is needed. Since these steps may take time, often beyond a week, the methodology and DAC developed in this report provides guidance to the NRC staff for making an assessment in a timely manner whether the degraded condition potentially has an immediate significant effect on plant risk. This knowledge is important in order to provide input that can help determine whether immediate repairs are warranted, or whether the appropriate investigation, inspection, aging management, or other actions can be determined in the normal course of evaluating the condition. The methodology and DAC can not be used by the industry to justify existing degraded conditions; licensees are still required to meet their commitments regarding the plant's current licensing basis.

This section provides the guidelines for using the DAC. It describes what the DAC are, how to use them, the acceptable range of conditions permitting their use, and recommendations if the DAC cannot be satisfied. More specifically, the DAC provides the number of years required for the buried pipe to reach a degradation level that would potentially have a significant effect on plant risk. To utilize the DAC, developed in Section 7.2, there were a number of variables and parameters that were used in the various stages of the research study. Therefore, a number of conditions must be satisfied to permit the use of the DAC. These conditions are described in this section of the report.

It should be noted that the analyses were performed for SA-106 Grade B carbon steel pipe. The results are considered applicable to stainless steel pipe as well because, most stainless steel buried piping systems use 304 and 316 type stainless steel material which have higher ultimate strength values and are more ductile than SA-106 Grade B carbon steel pipe.

The research described in this report developed DAC for general wall thinning and localized loss of material/pitting in buried piping. The types of buried piping systems, configurations, materials, and other conditions that must be satisfied to use the DAC have also been developed and presented below.

The results obtained are based on the service conditions that buried piping is designed for (e.g., pressure induced stresses less than ¼ of the minimum ultimate strength of the material and relatively low temperatures) and recognizing that seismic induced stresses in buried piping are self-limiting since deformations or strains are limited by seismic motions of the surrounding media. In addition, the DAC presented below arose from a probabilistic risk assessment which

8 CONCLUSIONS AND RECOMMENDATIONS

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To achieve the objectives of this study, fragility modeling procedures for degraded buried piping have been developed and the effect of degradation on fragility and plant risk has been determined. The effects of degradation over time were also included in the methodology. The analytical approach provides the technical basis for evaluating degraded buried piping at NPPs and provides guidelines for assessing the effects of degraded conditions on plant risk. The guidelines, which are identified as degradation acceptance criteria (DAC), are presented in tabular form for ease of use.

The effects of degradation over time were considered in developing the DAC in a manner that provides the number of years required for the buried pipe to reach a degradation level that would potentially have a significant effect on plant risk. If the degraded condition exceeds the criteria, then immediate repair would be required unless otherwise justified. If the degradation level is less than the criteria, then it is expected that the licensee will still evaluate the conditions that led to the degradation and may need to repair the degraded pipe based on the evaluation findings, the level of degradation, and the plant's current licensing basis.

8.1 Conclusions

8.1.1 Understanding of the Degradation of Buried Piping

The types of buried piping systems, material and design parameters, and analysis and design methods that can be used for buried piping at NPPs have been collected and evaluated. Based on a survey and review of license renewal applications, there are many different buried piping systems used at NPPs; however, the most predominant types are the service water, diesel fuel, fire protection, and emergency feedwater systems. The materials used for buried piping are primarily carbon steel and to a lesser extent stainless steel. Other materials which are not as common are low-alloy steel, galvanized steel, cast iron, fiberglass, copper nickel, ductile iron and Yoloy. Methods for the structural analysis and design of buried piping are available in the general literature and in various industry codes, standards, and guides.

The predominant aging effects and associated aging mechanisms for buried piping have been identified and summarized in this report. The predominant aging effects are loss of material and fouling/biofouling. Most occurrences of loss of material are manifested as either general wall thinning or localized loss of material/pitting. A number of occurrences of degraded buried piping wall becomes thinner, the pressure induced stress increases, thereby increasing the probability of a pipe rupture failure.

Using the properties of buried carbon steel pipe, a methodology for developing buried piping fragility curves to predict probability of failure versus internal pressure was developed. Based on allowable variations in material and dimensional properties, it was shown that the tensile strength was the most significant random variable affecting the probability of failure. By using the minimum strength properties allowed by the material specification and by making reasonable assumptions on mean and upper limit strength values, a normal distribution of material strength was developed. Using this material strength distribution, pipe stress equations, and the assumption of uniform wall thinning, a series of fragility curves were analytically developed for undegraded pipes and for degraded pipes with different levels of percentage wall loss. In addition, a statistical evaluation of available test data on pressure tests of degraded pipes removed from service was performed to confirm the conservatism of these fragility curves and to demonstrate that the curves are applicable to piping with localized or pitting corrosion as well as uniform wall thinning.

Using the same methodology, a series of fragility curves were developed for carbon steel pipe ranging in size from 5.08 to 107 cm (2 in. to 42 in.) in diameter. These curves were developed for both undegraded and degraded pipes. Finally, by assuming that the internal pipe pressure is equal to the design pressure allowed by Code rules, plots of probability of failure versus percent wall loss were generated. These curves were combined on a single graph and showed that under design pressure, the variability of the probability of failure of degraded pipe at different percentage wall losses is within a factor of about 5.

8.1.5 Risk Evaluation of Degraded Buried Piping Systems

Buried piping systems at an NPP can degrade, as described in the previous sections of this report. Such deterioration potentially could impair the operation of the system that contains the buried piping, and thus impact the overall risk of an NPP. To develop a methodology that can estimate the effect of degraded buried piping on plant risk, a definition of the criterion to be used as a measure of significant risk was needed. For this study, the measure of significant plant risk was based on a change in core damage frequency (ΔCDF) of 1.0×10^{-6} per year. This was selected based on the guidelines provided in NRC RG 1.174, Rev. 1.

To determine the effects of buried piping degradation on plant risk, five NPP (sites) were selected for evaluation. The plants selected consist of McGuire 1 and 2; North Anna 1 and 2; Oconee 1, 2, and 3; Surry 1 & 2; and Hatch 1 & 2. These plants were selected because they contain many different buried piping systems and they have different attributes consisting of: reactor types, NSSS suppliers, containment types, architect/engineers, and locations in the United States. In addition, they contain both "frontline" and "support" systems with buried piping.

For the purpose of evaluating the contribution of the degradation of a buried piping system to plant risk, the systems in any NPP can be classified into several categories depending on whether the system's failure causes an initiating event, whether the system is normally operating, and other criteria. A review of the buried piping systems at these five plants determined that they fell into two categories. Analytical time-dependent methods were developed for these two categories to estimate the increase in plant risk due to degraded buried piping. Some parameters required by these methods were obtained by using the Standardized Plant Analysis Risk (SPAR) version 3 models of the five selected plants. A SPAR model is a level-1 probabilistic risk assessment (PRA) model of internal events during full-power operation.