A Surveillance Option for Long-Term Operation that Optimizes Future Data Collection Needs

Mark Kirk[1], Yoshinori Hashimoto[1], and Akiyoshi Nomoto[1]

Abstract

Current RPV surveillance programs were originally designed and licensed for a 40-year plant lifetime. As plants consider extended licensing periods the constraints on sample availability, capsule holder location, and so on can make it challenging to maintain adequate monitoring during long-term-operation. Various strategies allow plants to continue surveillance monitoring, including the withdrawal of standby capsules, the optimized use of existing samples (e.g., reconstituted Charpy specimens, or mini-CT specimens), and optimization of the future withdrawal schedule. In this paper we explore the possibility of exploiting the knowledge gained from 60+ years of surveillance data collection to optimize future surveillance capsule withdrawal schedules and testing plans. Specifically, this paper describes a retrospective integrated surveillance program (R-ISP) where not only is future data shared as is done in traditional ISPs, but measurements already obtained from plants having similar materials to the plant of interest can in some cases be credited to fulfilling future surveillance monitoring needs. The information presented herein demonstrates that this approach helps to eliminate low-value repeated measurements while also identifying situations where available data is sparse and greater additional data may be beneficial.

Background and Motivation

The goal of reactor pressure vessel (RPV) surveillance can be expressed as follows:

> Estimate with reasonable accuracy the degree of embrittlement of the steel used to construct the RPV sufficiently in advance of that condition occurring in service that actions to ensure the safe operation of the RPV may be taken proactively.

In the past this goal was achieved through surveillance monitoring coupled with the use of embrittlement trend curves (ETCs) to estimate the value of Charpy transition temperature shift (ΔT_{41J}). In many countries the legal requirements for surveillance monitoring are distinct from the methods for ΔT_{41J} estimation. Nevertheless, the surveillance goal cannot be achieved without both elements because of practical limitations that make it impossible to surveil the embrittlement of all materials.

Surveillance requirements for current light water reactor designs first appear in 1961 [ASTM E185-82]. These evolved considerably over the next two decades, but since the late 1970s the basic requirements have changed little [Kirk 2018]. Generally, the withdrawal of 3-5 capsules occurs over the plant's licensed lifetime, using more capsules for more embrittlement prone materials. By recommendation one to two standby capsules are often included, and archive materials are often retained in storage, but not in all cases for all plants. Surveillance programs were originally designed for a 40-year plant lifetime. The initial design constraints on the samples available to surveil and the locations of the capsule holders make it challenging for

[1] Guest Research Fellow, Research Scientist, and Senior Research Scientist (respectively), Materials Science Division, Energy Transformation Research Laboratory, Central Research Institute of Electric Power Industry, Yokosuka, Kanagawa, Japan. kirk@peaiconsulting.com, yhashi@criepi.denken.or.jp, and a-nomoto@criepi.denken.or.jp.

some plants to continue monitoring during periods of extended operation, which now extends to at least 80-years in the USA.

Various strategies allow plants to meet the surveillance goal during extended operation, including the withdrawal of additional capsules, the optimized use of existing samples (e.g., reconstituted Charpy specimens, using even smaller mini-CT fracture toughness specimens, testing fewer specimens), and optimization of the future withdrawal schedule (e.g., delaying capsule withdrawals while placing more reliance on ETC predictions). In this paper we explore the possibility of exploiting the knowledge gained from 60+ years of surveillance data collection that was recently assembled by ASTM to optimize future surveillance capsule withdrawal schedules and testing plans [ASTM Adjunct, ASTM E900-15].

The next section of this paper summarizes the requirements for initial surveillance program design and its modification to address periods of extended operation. After this the database used and analytical approach is described. Finally, the analytical approach is applied to gain insights about the degree to which existing surveillance data helps inform future surveillance trends for different RPV material conditions. These insights may provide a basis for optimizing the information gained from future surveillance capsule testing.

Surveillance Program Design

Requirements of Initial Design

The first of plants producing electricity using a nuclear steam supply system (NSSS) in Japan and the USA[2] began operation in 1966 and 1957, respectively. In both countries NSSS electricity production preceded the establishment of standards for surveillance monitoring by many years [Hirota 2018, Kirk 2018]. Thus, while this section discusses the surveillance standards *generally* followed in Japan and the USA, exceptions to these statements exist at particular plants due to their date of construction and the requirements at that time.

Most plants now operating have surveillance programs that follow the requirements of JEAC4201-2007 (in Japan) and of ASTM E185-82 as required by Appendix H to 10 CFR Part 50 (in the USA) [JEAC4201-2007, ASTM E185-82, 10CFR50H]. The following paragraphs summarize the requirements of these standards concerning the capsule withdrawal schedule, capsule lead factor, the materials to be monitored, and quantity of archive materials retained.

In both Japan [JEAC4201-2007] and the USA [ASTM E185-82], the **capsule withdrawal schedule** requires more capsules for steels that are more sensitive to embrittlement. In both countries

- A minimum of three capsules are required if the estimated Charpy transition temperature shift (ΔT_{41J}) at the vessel inner diameter (ID) of the most embrittlement prone material being monitored is below 56 °C after a 40-year lifetime.
- A minimum of four capsules are required if the ΔT_{41J} at the vessel ID is between 56-111 °C after a 40-year lifetime.
- A minimum of five capsules are required if the ΔT_{41J} at the vessel ID exceeds 111 °C after a 40-year lifetime.

These minimum number of required capsules were based on the estimated ΔT_{41J} values at the time of plant design, which were based on the information then available and are not necessarily

[2] The surveillance program requirements in Japan and in the United States are discussed here as examples. Requirements in other countries are generally similar but differ in some details.

the same as values that would be estimated today. For all materials, the withdrawal date for the last required capsule occurs when it reaches a fluence between one- and two-times the ID fluence projected to occur at the end of the initial 40-years of licensed operation. The number of calendar years it takes to active this fluence in the capsule depends on the capsule lead factor, which is discussed next.

The **capsule lead factor** expresses the rate at which a capsule accumulates fluence relative to rate of fluence accumulation at the vessel ID. Lead factors above 1.0 are therefore needed to achieve the surveillance program's goal of knowing the embrittlement condition in the RPV wall sufficiently in advance of its occurrence that proactive measures to maintain operating safety can be taken, if needed. The lead factor requirements in Japan and in the USA are similar but have somewhat different histories. [Hirota 2018] explains that JEAC4201 contains no requirements on lead factor, but that industry practice established lead factors from 1-5 in pressurized water reactors (PWRs). In boiling water reactors (BWRs) lead factors are either ≈1 or ≈10. [Kirk 2018] explains that the lead factor requirements of ASTM E185 have been either between 1-5 or 1-3; current limits are 1.5-5.

Capsule lead factors in a particular RPV are established before a plant becomes operational via the selection of capsule holder locations. While additional capsule holders can *in principle* be installed after the plant enters service this would be expensive in terms of both cost and dose; it has not yet been done. Selecting capsule lead factors requires the designer to balance the need to get information about embrittlement trends early in plant life (favoring higher lead factors) versus ensuring that fluence monitoring can continue throughout the plant's licensed lifetime (favoring lower lead factors). Designs that favored the latter constraint can have limited time between a capsule withdrawal and the capsule fluence occurring on the vessel's ID. This combined with the limited number of available capsules means that low lead factor plants will likely spend some part of their licensed life relying on the accuracy of the ETC because the current fluence at the vessel ID will exceed that of the highest surveillance capsule tested to date. However, plant operational limits (Pressure-Temperature, or P-T limits) are always bounded by the highest surveillance capsule fluence, even in low lead factor plants, for a decade or more after each capsule withdrawal because of the lower fluence that occurs at the ¼-T wall position used in P-T limits calculations [MRP-484].

Both JEAC4201 and ASTM E185 require that the **materials monitored** be the base metal and the weld metal most susceptible to neutron irradiation embrittlement; the so-called "limiting materials;" in Japan the heat affected zone (HAZ) is also monitored. Determination of the limiting materials is made during plant design. The increase in the state of knowledge concerning embrittlement causes and trends over the last half century mean that in some cases this design selection was incorrect, which results in the most embrittlement prone materials not being surveilled. In some cases, this has led to the establishment of supplemental surveillance programs [DeVan 2001]. More typically a change of limiting materials leads to an increased reliance on the accuracy of the ETC to estimate ΔT_{41J} for future plant conditions.

Finally, the requirements for **archive materials**, including standby capsules, that could be used if needed has also changed over time. This evolution is summarized in [Kirk 2018] for ASTM E185. The 1982 version of ASTM E185, which is the legal requirement in the USA, requires one standby capsule to be installed in the reactor. As described by [Hirota 2018], industry practice in Japan is to have six capsules installed in PWRs while BWRs have four capsules, one of which is accelerated. Thus, PWRs have between 1-3 capsules that are standby (exceed requirements). BWRs have one more capsule than is required if the accelerated capsule is counted. For archive materials the requirements in Japan and in the USA are the same: a quantity of material sufficient to load two additional capsules should be retained.

Program Modification to Address Extended Operations

Since 2000 plants have sought to extend their operating licenses to 60- or 80-year terms, first in the USA and later in other countries. In the USA regulatory guidance on surveillance requirements for extended operations can be found in the "GALL" reports (GALL = Generic Aging Lessons Learned). [NUREG-1801] addresses the first license extension from 40→60 years while [NUREG-2191] addresses "subsequent" license extension from 60→80 years[3]. [NUREG-1801] imposes no direct requirements for additional capsules beyond emphasizing that the requirements of [10CFR50H] and [ASTM E185-82] remain in force and that the fluence for the EOL capsule and the EOL ΔT_{41J} estimate should be updated to reflect the extended license term. This may or may not produce changes in the surveillance program. For example:

- No change: Following ASTM E185-82 the EOL capsule should be withdrawn between 1- and 2-times the peak EOL fluence. If the plan when EOL was 40 years withdrew this capsule at close to 2-times peak 40-year fluence that same withdrawal schedule may still fall in the window defined by 1-to-2-times peak 60-year fluence.
- Possible change: The ΔT_{41J} at EOL is re-estimated when EOL changes. As discussed previously, the number of required capsules depends on this estimate. In some cases, this increase in ΔT_{41J} estimate at EOL may increase the number of capsules required following ASTM E185-82 guidance.

For subsequent license renewal from 60 to 80 years the following language from [NUREG-2191] suggests that testing of one additional capsule may be required for some plants:

> *"If a surveillance capsule was previously identified for withdrawal and testing to address the initial period of extended operation, it is not acceptable to redirect or postpone the withdrawal and testing of that capsule to achieve a higher neutron fluence that meets the neutron fluence criterion for the subsequent period of extended operation"*

[Hirota 2018] describes how in Japan, like in the USA, surveillance capsule requirements for times after the initial licensing period are found within national regulatory guidance, not within the JEA Codes and Standards. The nuclear regulatory authority in Japan (NRA) requires two additional capsules for plants seeking a license for 60 years of operation. The first should be withdrawn and tested as late as possible within the original 40-year license term while the second should be performed after approximately 50 years of operation. Additionally, for PWRs with an ID fluence exceeding 2.4×10^{19} n/cm^2 the NRA states explicitly that operation must stop if the ID fluence reaches the highest capsule fluence. In this specific situation extrapolation of surveillance data using an ETC is not allowed.

Integrated Surveillance Programs

In the USA, [10CFR50H] permits the adoption of an integrated surveillance program (ISP) as an alternative to plant-specific surveillance, stating that "*in an integrated surveillance program, the representative materials chosen for surveillance for a reactor are irradiated in one or more other reactors that have similar design and operating features.*" [10CFR50H] lists the NRC's requirements for an ISP. Two major ISPs have been operating in the USA since the 1990s. One is for Linde 80 welds in PWRs fabricated by Babcock and Wilcox [BAW-1543]; it was undertaken to better address low upper shelf toughness issues for these materials. The other is for the entire BWR fleet designed by General Electric [BWRVIP-78, BWRVIP-86]; it was

[3] There is no explicit legal limit on the licensable lifetime of a nuclear power plant in the USA [10 CFR 54].

undertaken because some early-construction BWRs did not include the plant's limiting material in their surveillance capsules due to the limited state of knowledge when the plants were designed. Finally, a two-unit ISP was approved for Turkey Point Units 3 and 4 [Turkey 2009]. Collectively nearly 50% of RPVs now operating in the USA base their surveillance monitoring on an ISP rather than on a plant-specific program. Recently, the 2021 revision of ASTM E185 includes a nonmandatory appendix on the design of ISPs [ASTM E185-21].

Currently no framework to use an ISP as an alternative to the plant-specific surveillance approach exists in Japan.

Summary

The information in this section can be summarized as follows:

- Number of Capsules: Both Japan and the USA require between 3-5 surveillance capsules for the initial 40-year license term with the number depending on the embrittlement sensitivity of the materials surveilled. For a 20-year license extension to 60 years Japan requires the testing of two additional capsules. In the USA requirements for additional capsules are more implicit and plant specific; in certain cases, additional capsules may be needed.

- Extrapolation: During the initial license term neither country prohibits extrapolation beyond the maximum fluence of the surveillance data, in which case increased reliance is placed on the accuracy of the ETC. Before the first capsule is tested all plants must extrapolate; this can occur for up to 6 EFPY. Also, low lead factor plants will almost invariably extrapolate for some part of their service lifetime at the ID location, which is pertinent to PTS calculations. However, extrapolation when estimating P-T limits curves is unlikely, even for low lead factor plants, because of the lower fluence at the ¼-T wall location that is used in these calculations. During extended licenses the NRC's requirements in the USA remain unchanged, whereas the NRA's requirements in Japan expressly forbid extrapolation for PWR plants having a 60-year ID fluence exceeding 2.4×10^{19} n/cm^2.

- Materials Monitored: Both countries require that the base metal and weld metal predicted to have the highest predicted reference temperature at end of license be surveilled. However, the identification of these "limiting" materials can change over time as the state of knowledge concerning embrittlement changes. If this happens neither Japan nor the USA have an explicit requirement to modify the surveillance program. In this situation some USA plants have performed supplemental surveillance to address this knowledge gap. Other options available in the USA are the use of similar data from so-called "sister plants," or to simply use the standard ΔT_{41J} prediction with a larger margin term.

- Integrated Surveillance Programs: In the USA there is a well-established framework for and experience with ISPs; nearly 50% of units now operating in the USA participate in an ISP. There is currently no recognized framework for an ISP in Japan. Nevertheless, regardless of country some plants that follow a plant-specific surveillance framework are, in some sense, participating in an unrecognized ISP due to situations where operation occurs at fluences exceeding the highest surveillance fluence and for those plants not monitoring their limiting materials. These plants implicitly rely on the data from other plants, either national or international, that informs the ETCs they must use for embrittlement prediction without reference to plant-specific data.

Data Used

This paper uses a collection of ΔT_{41J} data compiled by ASTM Subcommittee E10.02 on the *Behavior and Use of Nuclear Structural Materials* [Adjunct 2015, Kirk 2022a]. This database, referred to as PLOTTER-22, includes 2,048 ΔT_{41J} values collected as part of light water reactor surveillance programs conducted in 13 nations. The data includes only steels used in the fabrication of western-design LWRs; ex-Soviet VVER RPV materials are not included. Of these, 1,697 are from pressurized water reactor (PWR) surveillance while the remaining 351 are from boiling water reactor (BWR) surveillance. **Figure 1** and **Figure 2** illustrate the distribution of these data over the four variables having the greatest influence on embrittlement sensitivity: copper content, nickel content, neutron fluence, and the temperature at which exposure to neutron irradiation occurs. The irregularity of these data across the regressor domain is a direct consequence of the constraints placed on these variables by material specification and by reactor operating characteristics. The data points on **Figure 1** and **Figure 2** are plotted with 90% transparency so darker regions of these figures indicate qualitatively the regions of the database where empirical knowledge is greater.

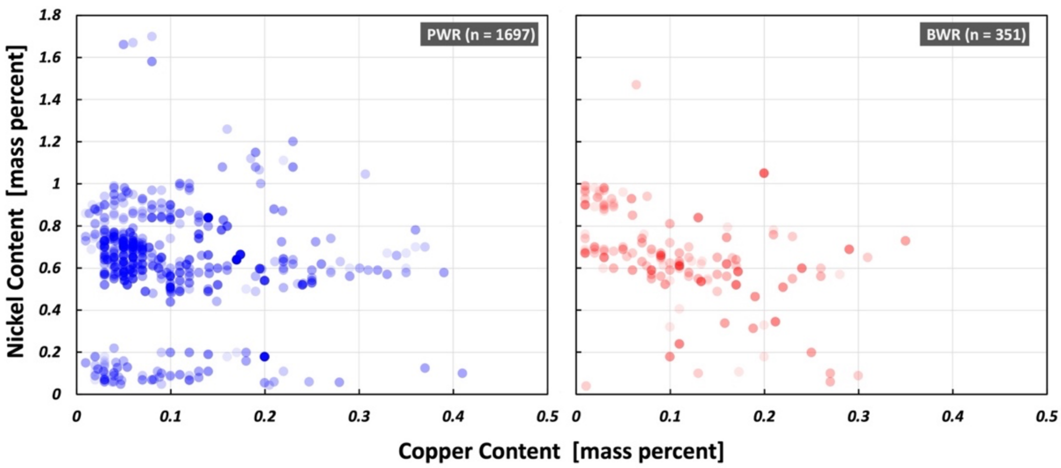

Figure 1. The copper and nickel content of the various RPV steels in the PLOTTER-22 database [Kirk 2022a]. Data points are plotted with 90% transparency, so darker regions of these plots correspond qualitatively to conditions for which there is more numerical evidence.

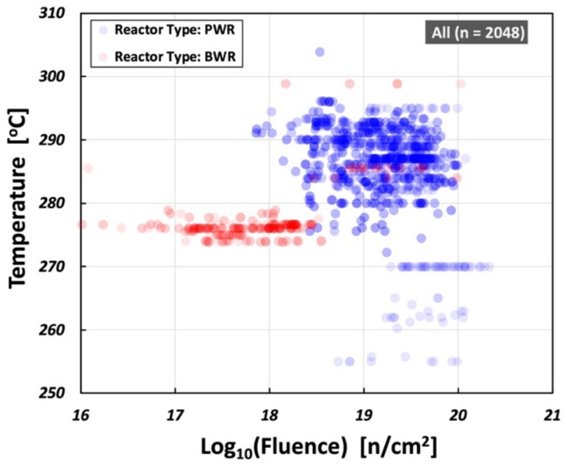

Figure 2. The temperature and fluence conditions to which the various RPV steels in the PLOTTER-22 database were exposed [Kirk 2022a]. Data points are plotted with 90% transparency, so darker regions of these plots correspond qualitatively to conditions for which there is more numerical evidence.

Analytical Approach

To quantify the similarity of embrittlement conditions between specific plant materials and the worldwide surveillance database an approach described in [Kirk 2022b] based on "k Nearest Neighbors (kNN)," a machine learning technique, was adopted [Chen 2022, Fiori 2020]. This approach uses the three variables that most affect embrittlement sensitivity (copper, nickel, and irradiation temperature) to quantify the similarity of embrittlement sensitivity between a condition of interest (e.g., the plate and weld in a future surveillance capsule withdrawal) and the data in the ASTM PLOTTER-22 surveillance database. **Figure *3*** illustrates this approach conceptually. The plant condition of interest (blue square) can be thought of as defining a point in a (Cu, Ni, T) space. The kNN approach distinguishes between data being sufficiently close in (Cu, Ni, T) space to a condition of interest that they are judged to be similar (red squares lying inside the orange-colored sphere) and dissimilar data lying further away (grey squares). [Kirk 2022b] provides a quantitative method to distinguish similar data from dissimilar data based on the measurement accuracy on copper. These authors cite Japanese Industrial Standard JIS G 0321:2017, which requires a measurement accuracy of ±0.03 weight percent [JIS G 0321]. In general, values of copper in the ASTM PLOTTER-22 surveillance database are not known to better than this accuracy. Consequently, within ±0.03 weight percent different steels can be expected to exhibit a similar response to neutron irradiation embrittlement provided other important variables, nickel and temperature, also remain reasonably similar.

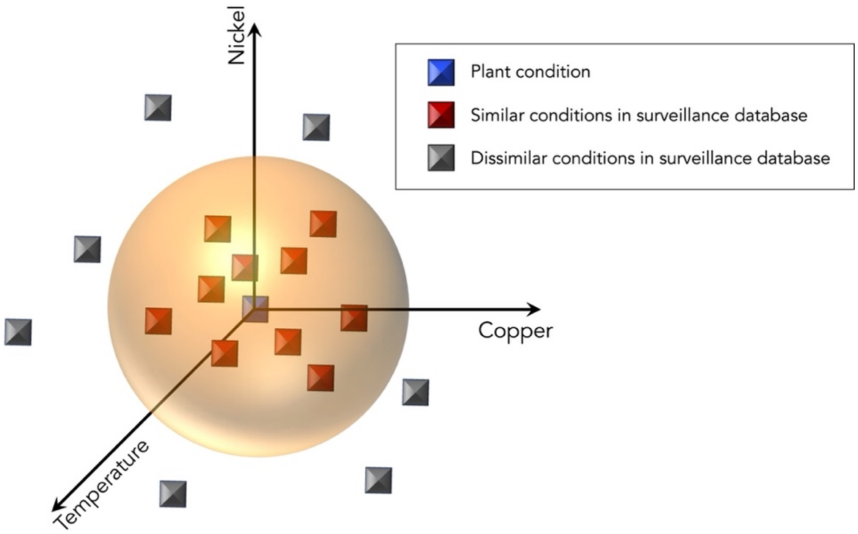

Figure 3 Illustration of kNN approach for defining similar data, based on information from [Kirk 2022b].

The following procedure is used to define the dimensions of the orange sphere in **Figure 3**, this being used to differentiate similar from dissimilar data:

Step 1. The condition of interest and its (Cu, Ni, T) are identified.

Step 2. The (Cu, Ni, T) distance of every datum in the database from the condition of interest is calculated. These distances are normalized to ensure that variables having different numeric ranges have the same effect on the distance, see [Kirk 2022b] for details.

Step 3. Rank order the Step 2 distances from smallest to largest.

Step 4. Beginning with the smallest distance, evaluate each datum to determine if its copper value lies within the interval [Cu-0.03, Cu+0.03] from the copper value associated with the condition interest. All data are considered "similar" to the condition of interest until the first time a datum falls outside the interval [Cu-0.03, Cu+0.03]. The distance of the last qualifying datum defines the radius of the sphere in Figure 3. All remaining data have distances exceeding this radius and are considered dissimilar to the condition of interest.

[Kirk 2022b] provides a detailed evaluation of this approach, demonstrating that due to the topology of the database additional restrictions on nickel and temperature are not needed, and that product form distinctions do not improve the prediction accuracy. Since this method produces an ETC fit to data having similar embrittlement sensitivity to the specific plant conditions of interest, this method provides predictions of ΔT_{41J} of slightly greater accuracy than does the more conventional approach of fitting an ETC to all available data as adopted, for example, by ASTM E900.

Results and Discussion

Inspection of **Figure 1** and **Figure 2** reveal that the density of surveillance data collected to date is not uniform across all conditions. Nevertheless, except in unusual cases application of the kNN-inspired method described in [Kirk 2022b] will identify many more ΔT_{41J} data similar to a plant-specific condition of interest than the 5-7 values long required and considered adequate for the purposed of for plant-specific surveillance.

Figure 4 and **Figure 5** illustrate four sets of similar data identified by the kNN-inspired method, two for PWRs and two for BWRs. Each figure shows one condition from a higher (but not highest) data density region and one condition from a lower (but not lowest) data density region. These examples illustrate the considerably greater evidence made available for any particular condition using the kNN-inspired method than has traditionally been available on a plant-specific basis. It is interesting to note in **Figure 5** that some BWR conditions get a particular benefit from this approach because of some low-temperature PWRs in the PLOTTER-22 data; these expand considerably the range of fluences available for certain BWR conditions. **Figure 6** illustrates the distribution of all kNN-identified similar data set sizes for the PLOTTER-22 database. Only 3.4% of data have 7 or fewer similar values, these being the conditions for which the kNN-inspired method identifies no similar data beyond that collected in a particular plant-specific program. The kNN-inspired method provides a systematic, quantitative, and repeatable means to identify similar data based on a modern understanding of the factors most important to irradiation sensitivity in RPV steels. This method builds upon the related but mostly *ad hoc* methods employed by current ISP programs.

A benefit of ISPs is that they enable a planning of capsule withdrawals to maximize the value of future data collected. Since existing ISPs were established two or more decades ago there was then a greater need for future testing since ΔT_{41J} data was more limited than it is today. However today, as illustrated in **Figure 4** and **Figure 5**, considerable data is already available at lower fluences, making questionable from a technical point-of-view[4] the benefit of repeating such measurements in future testing.

Figure 7 illustrates three regions (A, B, C) where different actions are warranted based on how the fluence of the planned withdrawal fluence for the next capsule compares with available similar data:

Region (A) If the next capsule fluence exceeds the highest fluence in the set of similar data identified by the kNN-inspired method then capsule withdrawal and testing

[4] This paper does not address licensing concerns, which currently mandate the repeated collection of lower fluence data irrespective of the state of knowledge as collected in the PLOTTER-22 database.

should proceed as planned. Obtaining new data in this region helps ensure that RPV integrity and operational limits calculations to not extrapolate beyond available data.

Region (B) This is a lower data density region at higher fluences, but not beyond the maximum fluence of kNN-identified similar data. In this region it may be prudent to either proceed with capsule withdrawal and testing as planned or consider deferring withdrawal to a higher fluence so as to obtain more valuable data.

Region (C) This is a higher data density region at lower fluences. Here ample data exists, making it questionable if obtaining additional data in adds significant value. Capsules with target fluences in this region should have their withdrawal deferred to a higher fluence to obtain more valuable data.

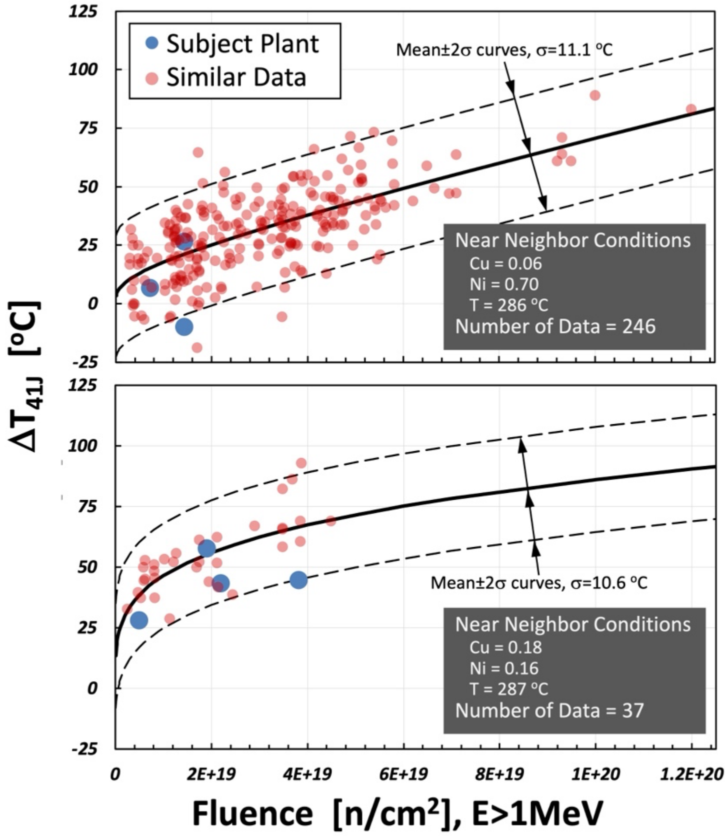

Figure 4 Examples of similar data sets identified by kNN inspired method for PWR conditions. The curves are fit to the data shown.

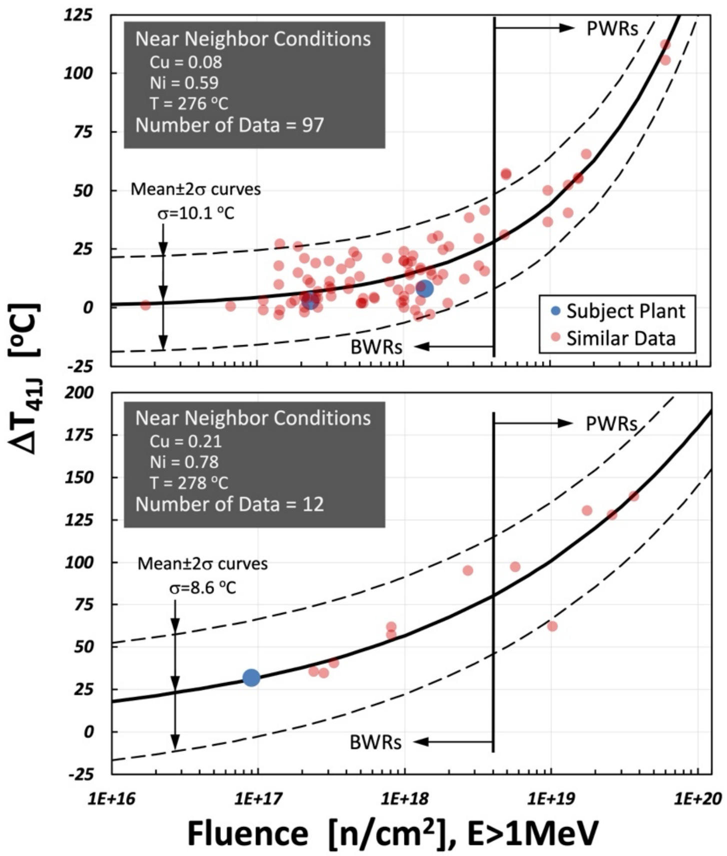

Figure 5 **Examples of similar data sets identified by kNN-inspired method for BWR conditions. The curves are fit to the data shown.**

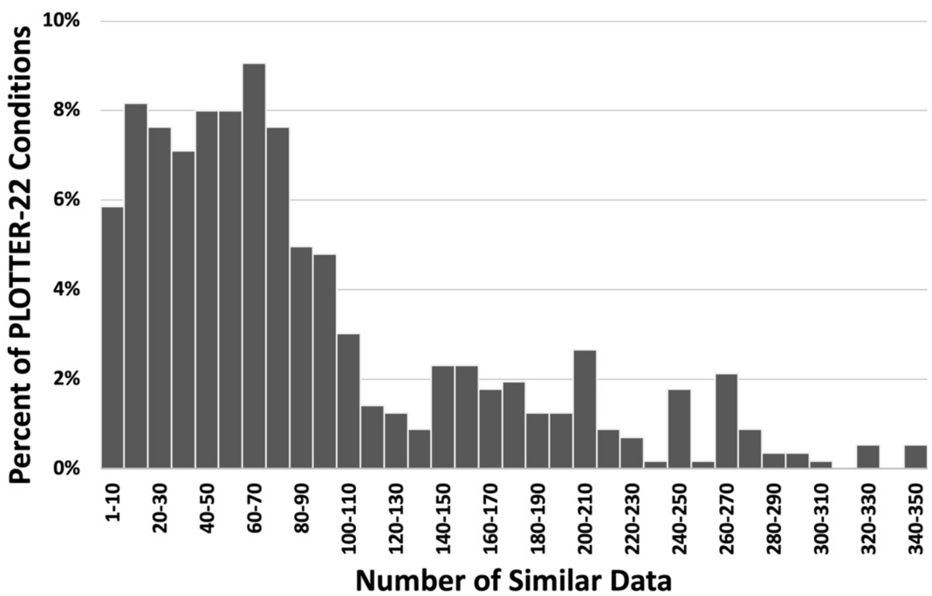

Figure 6 **Set sizes of similar data identified using the kNN-inspired method of [Kirk 2022b] along with the ASTM PLOTTER-22 database.**

A key point, which must be based on judgement, is where the boundary should lie between regions (B) and (C), or if region (B) should exist at all. The traditional approaches of both ASTM E185 and JEAC4201 suggest that region (B) need not exist at all. Both standards accept a low data density (3-5 measurements spread over a 60-year operating lifetime) relative to what is now achievable using similar data. Also, in the great majority of situations the next surveillance datum in a plant-specific program is obtained at a fluence that exceeds all previously collected data (that is, in Region (A)).

The need for the (B)-(C) division and a basis for it can be usefully discussed within applicable codes and standards bodies such as JEA and ASTM, and with applicable regulatory authorities. Reasonable criteria for the (B)-(C) division that could be considered as a starting point for discussion include the following:

- The division between regions (B) and (C) occurs at the fluence corresponding to the x^{th} highest fluence in the similar data set, where "x" is a number like 2^{nd} or 3^{rd}.
- The division between regions (B) and (C) occurs at the fluence corresponding to the y^{th} percentile fluence of the similar data set, where "y" is a number like the 95^{th} or 98^{th} percentile.

If region (B) is retained, it would make the resultant R-ISP *more conservative* than the plant-specific programs that have served the industry well for over half a century because capsule testing would be performed before the peak fluence of data pertinent to the situation of interest has been exceeded. Even so, adopting a (B)-(C) division along the lines suggested above provides considerable opportunity for optimization of future surveillance data collection by permitting the deferral of low fluence capsules until they reach higher fluences where they can provide more valuable data to inform structural integrity and operating limits decisions for periods of extended operation.

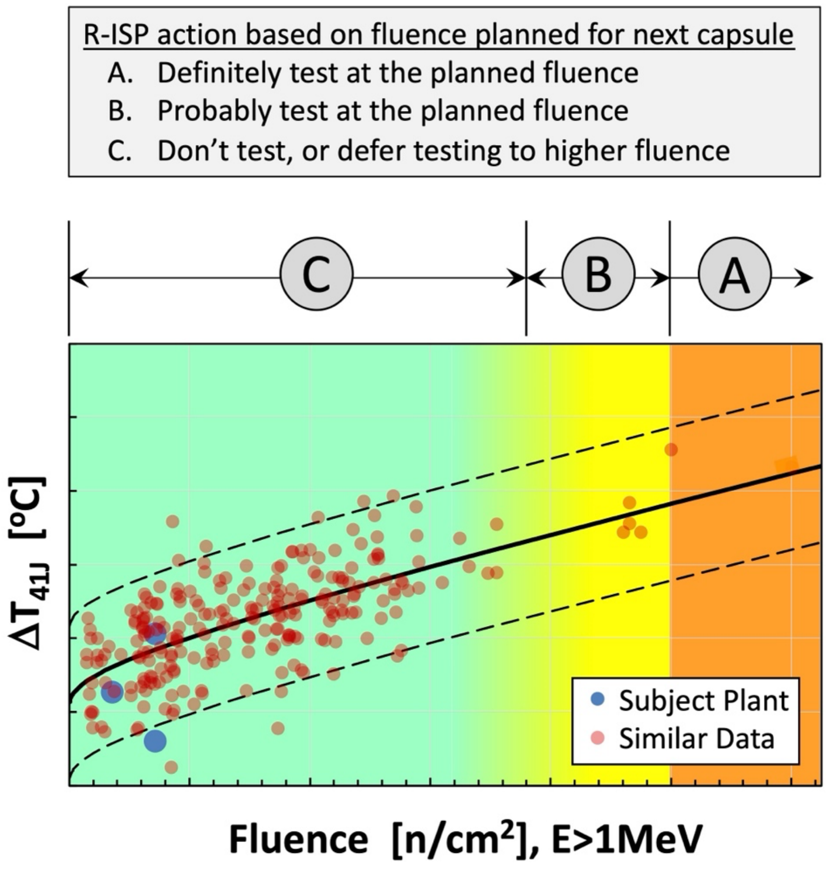

Figure 7 Possible R-ISP testing guidance.

Conclusions

Current RPV surveillance programs were originally designed and licensed for a 40-year plant lifetime. As plants consider extended licensing periods the constraints on sample availability, capsule holder location, and so on can make it challenging to maintain adequate monitoring during long-term-operation. Various strategies allow plants to continue surveillance monitoring, including the withdrawal of standby capsules, the optimized use of existing samples (e.g., reconstituted Charpy specimens, or mini-CT specimens), and optimization of the future withdrawal schedule. In this paper we explore the possibility of exploiting the knowledge gained from 60+ years of surveillance data collection to optimize future surveillance capsule withdrawal schedules and testing plans. Specifically, this paper describes a retrospective integrated surveillance program (R-ISP) where not only is future data shared as is done in traditional ISPs, but measurements already obtained could be credited to fulfilling future surveillance monitoring needs. This is achieved by a method inspired by the machine learning technique called k-Nearest Neighbors (kNN). A kNN inspired technique is used to identify already tested surveillance data from steels of similar embrittlement sensitivity to conditions of interest in service. Examples are provided for both PWR and BWR conditions, as are suggestions for R-ISP testing guidance. Depending on the quantity of similar data available and the fluence values at which previous measurements were made there may be future planned capsule withdrawals that can be eliminated using already measured data. Such an approach can eliminate low-value repeated measurements while also identifying situations where available data is sparse and greater additional data may be beneficial.

References

10CFR50H — Reactor Vessel Material Surveillance Program Requirements, https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-apph.html.

10 CFR 54 — Requirements for Renewal of Operating Licenses for Nuclear Power Plants, https://www.nrc.gov/reading-rm/doc-collections/cfr/part054/index.html

ASTM E185-82 — ASTM E185-82, Standard Practice for Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels, ASTM International, 1982,

ASTM E185-21 — ASTM E185-21, Standard Practice for Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels, ASTM International, 2021, https://www.astm.org/e0185-21.html

ASTM E900-15 — E900-15, Standard Guide for Predicting Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials, ASTM International, West Conshohocken, Pennsylvania, USA (revised 2015)

ASTM Adjunct — Adjunct for E900-15 Technical Basis for the Equation Used to Predict Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials, https://www.astm.org/adje090015-ea.html

BAW-1543 — BAW-1543, Revision 4, Supplement 7, "Supplement to the Master Integrated Reactor Vessel Surveillance Program," AREVA, December 2014.

BWRVIP-78 BWR Vessel and Internals Project: BWR Integrated Surveillance Program Plan (BWRVIP-78NP), EPRI, Palo Alto, CA and BWRVIP: 1999, TR-114228

BWRVIP-86 BWRVIP-86NP, Revision J-A: BWR Vessel and Internals Project, Updated BWR Integrated Surveillance Program (ISP) Implementation Plan, EPRI, Palo Alto, CA: 2008. 1016575.

Chen 2022 George H. Chen and Devavrat Shah (2018), “Explaining the Success of Nearest Neighbor Methods in Prediction”, https://devavrat.mit.edu/wp-content/ uploads/2018/03/nn_survey.pdf.

DeVan 2001 DeVan, M.J., “Test Results of Capsule SA-60-1, Consumers Energy, Palisades Nuclear Plant, Reactor Vessel Material Surveillance Program,” BAW-2341, Revision 2, May 2021.

Fiori 2020 https://medium.com/@luigi.fiori.lf0303/distance-metrics-and-k-nearest-neighbor-knn-1b840969c0f4

Hirota 2018 Hirota, T., Hirano, T., Uchihashi, M., Toyoda, T., Takamoto, S., and Soneda, N., “Surveillance Program for Irradiation Embrittlement of Reactor Pressure Vessels in Japan,” *International Review of Nuclear Reactor Pressure Vessel Surveillance Programs, ASTM STP1603,* W. L. Server and M. Brumovský, Eds., ASTM International, West Conshohocken, PA, 2018, pp. 202–218, http://dx.doi.org/10.1520/STP160320170144

JEAC-4201-2013 Japan Electric Association Code, “Method of Surveillance Tests for Structural Materials of Nuclear Reactors,” JEAC 4201 -2007, (2013 addenda).

JIS G 0321 JIS G 0321:2017, “Product analysis and its tolerance for wrought steel,” Japanese Industrial Standard, 2017.

Kirk 2018 M. Kirk, R. Hardies, and M. Gordon, “Historical Review of the Development of ASTM Standard Practices E185 and E2215 from the 1960s to 2015,” *International Review of Nuclear Reactor Pressure Vessel Surveillance Programs, ASTM STP1603,* W. L. Server and M. Brumovsky, Eds., ASTM International, 2018, pp. 9–53, https://www.astm.org/stp160320170006.html.

Kirk 2022a M. Kirk, D. Ferreño, and J. Guerra, “Evaluation of the ASTM E900 ΔT_{41J} Prediction Equation in Light of New Data,” ASTM Symposium on Radiation Embrittlement Trend Curves and Equations and Their Use for RPV Integrity Evaluations, ASTM STP-1647, W. Server, M. Brumovsky, and M. Kirk, Eds., in publication.

Kirk 2022b M. Kirk, Y. Hashimoto, and A. Nomoto, “Application of a Machine Learning Approach Based on Nearest Neighbors to Extract Embrittlement Trends from RPV Surveillance Data,” *Journal of Nuclear Materials*, Volume 568, 2022, https://doi.org/10.1016/j.jnucmat.2022.153886.

MRP-484 *Materials Reliability Program: Guidance on Timing for Technical Specification Revision Following Surveillance Capsule Testing (MRP-484):* in publication, EPRI, Palo Alto, CA: 2023

NUREG-1801	NUREG-1801 Revision 2, "Generic Aging Lessons Learned (GALL) Report," December 2010, NRC ADAMS Number ML103490041.
NUREG-2191	NUREG-2191, "Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) Report," July 2017, NRC ADAMS Numbers ML17187A031 and ML17187A204
Turkey 2009	Florida Power and Light, Update to NRC Reactor Vessel Integrity Database and Exemption Request for Alternate Material Property Bases, 18th March 2009, NRC ADAMS ML090920408.