ELECTRIC POWER RESEARCH INSTITUTE

Materials Reliability Program: Coordinated PWR Reactor Vessel Surveillance Program (CRVSP) Guidelines (MRP-326)

2011 TECHNICAL REPORT

Materials Reliability Program: Coordinated PWR Reactor Vessel Surveillance Program (CRVSP) Guidelines (MRP-326)

This document does NOT meet the requirements of 10CFR50 Appendix B, 10CFR Part 21, ANSI N45.2-1977 and/or the intent of ISO-9001 (1994)

EPRI Project Manager
T. Hardin

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue
Palo Alto, CA 94304-1338
USA

PO Box 10412
Palo Alto, CA 94303-0813
USA

800.313.3774
650.855.2121

askepri@epri.com

www.epri.com

1022871
Final Report, December 2011

THE FOLLOWING ORGANIZATION(S), UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

AREVA NP Inc.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Acknowledgments

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

AREVA NP Inc.
3315 Old Forest Road
P.O. Box 10935
Lynchburg, VA 24506-0935

Principal Investigators:
R. Hosler
G. Troyer
S. Davidsaver

This report describes research sponsored by EPRI and its MRP participating members.

The contributions of Mr. Dennis Weakland (Ironwood Consulting) in preparation of this report are gratefully acknowledged. The review comments provided by the site Reactor Vessel Program Owners, Westinghouse (S. Byrne, J. Hall *et al*) and the PWR Owners Group were also appreciated.

This publication is a corporate document that should be cited in the literature in the following manner:

Materials Reliability Program: Coordinated PWR Reactor Vessel Surveillance Program (CRVSP) Guidelines (MRP-326). EPRI, Palo Alto, CA: 2011. 1022871.

Product Description

As pressurized water reactors (PWRs) operate to 60 years and potentially beyond, a revised embrittlement trend correlation (ETC) will be used to predict and evaluate irradiation embrittlement of reactor pressure vessel (RPV) materials. A clear need exists to obtain high fluence PWR surveillance data that can inform an ETC applicable for PWRs in the high fluence regime. This document describes a Coordinated Reactor Vessel Surveillance Program (CRVSP) that will provide high fluence test data.

Background

Peak RPV fluence levels as high as $7x10^{19}$ n/cm^2 will be attained as PWRs operate to 60 years and potentially beyond. Therefore, a need exists to obtain high fluence PWR surveillance data to validate or revise an embrittlement trend correlation (ETC) applicable for the high fluence regime. Without the availability of high fluence PWR surveillance data, it may be necessary to use the available high fluence test reactor data to inform future-generation ETCs. Because test reactor data exhibit significantly higher rates of embrittlement than PWR surveillance data, such an ETC would predict significantly higher RPV embrittlement for PWRs, and would significantly constrain plant pressure-temperature (P-T) operating curves, increasing startup and shutdown times and costs. The challenge to the PWR fleet is to generate high-fluence surveillance data, and thereby alleviate the need to apply test reactor rates of embrittlement to PWRs.

Objective

To review the reactor vessel surveillance programs (RVSPs) of the operating U.S. pressurized water reactor (PWR) fleet and to recommend changes to selected RVSP withdrawal schedules in order to increase the amount of high fluence surveillance data within the next ten to fifteen years.

Approach

The project team reviewed the RVSP at each plant to document the contents of the remaining surveillance capsules. These remaining surveillance materials were grouped based on product form and chemical content (key factors in susceptibility to neutron embrittlement). The current RVSP withdrawal schedule for each plant was reviewed, and changes to the existing withdrawal schedules were identified in order to obtain high fluence PWR surveillance data for the full range of materials across the entire industry; to obtain the data within a reasonable time horizon (2025); and to remain consistent with Revision 2 of the Generic Aging Lessons Learned (GALL) report for a 60-year license and compliant with 10CFR50 Appendix H.

Results

For the 69 plants evaluated, approximately 250 capsules have been removed and tested, of which 35 were high fluence (>$3.0x10^{19}$ n/cm^2), and only nine capsules had a fluence greater than $5.0x10^{19}$ n/cm^2. By the year 2025, the existing RVSPs will test 26 more high fluence (>$3.0x10^{19}$ n/cm^2) capsules, of which only one will have a fluence of $8.0x10^{19}$ n/cm^2 or greater. The Coordinated Reactor Vessel Surveillance Program (CRVSP) described in this document will test 30 more high fluence (>$3.0x10^{19}$ n/cm^2) capsules than have been tested to date, and will increase the number of capsules with a fluence greater than $8.0x10^{19}$ n/cm^2 to five, which is a significant improvement over the one capsule of that level that would be tested without the CRVSP.

No additional testing or moving of surveillance capsules beyond the requirements of a 60-year license was recommended for 68 of the 69 U.S. PWRs considered. For the RVSPs of 54 plants, the CRVSP does not recommend making any changes. For 11 plants, the CRVSP recommends deferring withdrawal of the planned 60-year capsule to a later date and higher fluence. For three plants, the CRVSP recommends testing a capsule at an earlier date. Finally, in an effort to optimize the data obtained, and to fill gaps in the surveillance data for important material categories, the CRVSP recommends that one of the 69 plants that has already tested a 60-year capsule should test additional capsules.

Applications, Values, and Use

The Industry has been in discussions with regulators over the past several years on the issue of having appropriate data available for use in the revision and enhancement of the irradiation embrittlement trend curves for power reactors. Limited high fluence data from power reactors is widely recognized as a gap that is hindering development of accurate trend curves that bound PWR license renewal values. The recommended coordinated U.S. PWR RVSP management plan will significantly add to the quantity and quality of high fluence surveillance data by the year 2025 by adding approximately 30 base metal and weld metal transition temperature shift data points to the power reactor surveillance database. The addition of this data will facilitate development of embrittlement trend curves based on PWR data for use in 60 and 80-year RPV embrittlement evaluations. This data is necessary to address concerns of irradiation damage of reactor vessel materials for extended license renewal. Because future embrittlement trend correlations will have direct, significant operational and cost impact on each operating PWR, it is important that all plants with capsules capable of contributing valuable high fluence data participate in this program.

Keywords
Reactor vessel surveillance program
Radiation embrittlement
PWR
Surveillance capsule

Table of Contents

List of Figures

List of Tables

Section 1: Executive Summary

As pressurized water reactors (PWRs) operate to 60 years and potentially beyond, a revised embrittlement trend correlation (ETC) will be used to predict and evaluate irradiation embrittlement of reactor pressure vessel (RPV) materials. Current ETCs (e.g., the correlations used in Regulatory Guide 1.99, Rev. 2 [1], and the Alternative PTS Rule, 10 CFR 50.61a [2]) are based on U.S. light water reactor (LWR) surveillance data which is generally less than $3x10^{19}$ n/cm^2 (E>1.0 MeV); there is a paucity of high fluence data above that level. With projected 60 year PWR peak RPV fluence levels as high as $7x10^{19}$ n/cm^2 (E>1.0 MeV), a clear need exists to obtain high fluence PWR surveillance data that can inform an ETC applicable for PWRs in the high fluence regime. Without high fluence PWR surveillance data, it will be necessary to rely on test reactor data as a substitute. Test reactor data exhibit significantly higher embrittlement rates than PWR surveillance data at current PWR fluence values; a high fluence ETC based on test reactor data would predict significantly higher embrittlement and would significantly impact plants' pressure-temperature (P-T) operating curves. As a result, P-T operating windows would be constrained, increasing plant startup and shutdown times and costs.

Each PWR maintains or participates in a reactor vessel surveillance program (RVSP) that complies with 10 CFR 50 Appendix H [3]. Approximately 25 surveillance capsules remain to be withdrawn and tested to maintain compliance with Appendix H and with applicable license renewal requirements. The current withdrawal schedules for those remaining capsules are based on individual plant compliance with Appendix H without consideration of the PWR fleet's need to obtain high fluence surveillance data. This report defines a Coordinated Reactor Vessel Surveillance Program (CRVSP) for U.S. PWRs that establishes schedule changes (e.g., deferrals and other changes) that will increase the amount of high fluence PWR surveillance data obtained by 2025 while also maintaining individual plant compliance with 10 CFR 50 Appendix H [3] and consistency with the license renewal guidance of NUREG-1801, Rev. 2 [4] (GALL Report).

As a work product of the Electric Power Research Institute (EPRI) Materials Reliability Program (MRP), this guideline is intended to coordinate the withdrawal schedules of selected remaining surveillance capsules so that PWR surveillance data in the high fluence regime is available by 2025. This guideline identifies the need for designated PWRs to request NRC approval to change their RVSP to achieve higher capsule fluence. If a plant's remaining capsule cannot attain $>3 \times 10^{19}$ n/cm^2 by 2025, then no recommendation is made for that plant, and the plant will continue to follow its current schedule. Plants identified for RVSP changes were based on the following factors: (1) the capability of the next scheduled capsule to attain >3 x 10^{19} n/cm^2 by 2025; (2) obtaining high fluence data for the entire spectrum of representative PWR surveillance materials (e.g., product form, chemistry content); and (3) avoiding excessive cost burden on the fleet. A summary of the actions recommended by this program, and the plants affected, is presented in Table 1-1.

The CRVSP is implemented when each designated plant submits a request to the NRC for a change in the plant's Appendix H surveillance capsule program to implement the plant-specific recommendations given in Section 6. Once the NRC reviews and approves the request, the issue is managed within the context of the plant's licensing basis; long term CRVSP program management by the MRP will not be required.

Due to the impact that inadequate high fluence surveillance data will have on the entire PWR fleet and its future operating costs, this guideline contains a Needed recommendation that shall be implemented in accordance with the NEI 03-08 Materials Initiative [5]. Section 7 describes all of the requirements of the guidelines, including an implementation schedule. The requirements contained in this document are applicable to all PWRs currently operating in the United States.

These guidelines do not reduce, alter, or otherwise affect the requirements of 10 CFR 50, Appendix H [3]. Each PWR is responsible for continued compliance with Appendix H requirements.

Table 1-1
Summary of Recommended CRVSP Implementations Actions

Plant	No Change to Current Program	Defer Withdrawal Date of a Scheduled Capsule	Test Additional Capsules Beyond That Required for 60-year License Renewal	Test Same or Different Capsule Earlier Than Planned
ANO-1*	X			
ANO-2	X			
Beaver Valley-1	X			
Beaver Valley-2*			X	
Braidwood-1	X			
Braidwood-2	X			
Byron-1	X			
Byron-2	X			
Callaway-1*	X			
Calvert Cliffs-1	X			

Table 1-1 (continued)
Summary of Recommended CRVSP Implementations Actions

Plant	No Change to Current Program	Defer Withdrawal Date of a Scheduled Capsule	Test Additional Capsules Beyond That Required for 60-year License Renewal	Test Same or Different Capsule Earlier Than Planned
Calvert Cliffs-2	X			
Catawba-1	X			
Catawba-2	X			
Comanche Peak-1*	X			
Comanche Peak-2*	X			
Crystal River-3*	X			
Davis-Besse	X			
DC Cook-1		X		
DC Cook-2	X			
Diablo Canyon-1		X		
Diablo Canyon-2*	X			
Farley-1*	X			
Farley-2*	X			
Fort Calhoun				X
Ginna*	X			
Indian Point-2	X			
Indian Point-3	X			
Kewaunee*	X			
McGuire-1*	X			
McGuire-2*	X			
Millstone-2	X			
Millstone-3*	X			
North Anna-1				X
North Anna-2	X			
Oconee-1*	X			
Oconee-2*	X			
Oconee-3*	X			
Palisades	X			
Palo Verde-1	X			
Palo Verde-2	X			

Table 1-1 (continued)
Summary of Recommended CRVSP Implementations Actions

Plant	No Change to Current Program	Defer Withdrawal Date of a Scheduled Capsule	Test Additional Capsules Beyond That Required for 60-year License Renewal	Test Same or Different Capsule Earlier Than Planned
Palo Verde-3	X			
Point Beach 1	X			
Point Beach 2	X			
Prairie Is 1		X		
Prairie Is 2		X		
Robinson 2		X		
Salem 1*	X			
Salem 2	X			
SONGS-2		X		
SONGS-3		X		
Seabrook		X		
Sequoyah-1	X			
Sequoyah-2	X			
Shearon Harris		X		
South Texas-1*	X			
South Texas-2*	X			
St Lucie-1	X			
St Lucie-2	X			
Surry-1	X			
Surry-2				X
Three Mile Is-1*	X			
Turkey Point-3	X			
Turkey Point-4		X		
VC Summer*	X			
Vogtle-1*	X			
Vogtle-2*	X			
Waterford-3	X			
Watts Bar		X		
Wolf Creek*	X			
Totals	**54**	**11**	**1**	**3**

*Plant has already tested a capsule required for a 60-year license.

Section 2: Introduction

Background

The ability of the large low alloy steel RPV containing the reactor core and the primary coolant to resist fracture constitutes an important factor in ensuring safety in the nuclear industry. The RPV is subjected to significant fast neutron exposure. Low alloy ferritic materials show an increase in hardness and tensile properties and a decrease in ductility and toughness after experiencing neutron irradiation (irradiation embrittlement).

A method for establishing operating procedures for ensuring the integrity of RPVs is codified in "Fracture Toughness Criteria for Protection Against Failure," Appendix G to Section XI of the ASME Boiler and Pressure Vessel Code [6], which is cited by 10CFR50 Appendix G [7]. The method uses fracture mechanics concepts and is based on the reference nil-ductility transition temperature (RT_{NDT}).

All United States (U.S.) nuclear power plants have a reactor vessel surveillance program (RVSP) as required by 10CFR50 Appendix H [3], which cites ASTM E185-82 [8] for post-irradiation evaluation. Surveillance capsules containing encapsulated RPV material specimens are located between the core and the RPV wall. At this location, the environment is very similar to the RPV wall, but the neutron dose rate is higher due to the closer proximity to the core; the ratio of the peak dose rate at the capsule specimens to the peak dose rate at the RPV inside surface is call the "lead factor." Capsules are removed periodically and tested to measure the change in mechanical properties due to the irradiation environment. The PWR surveillance capsules typically contain tensile and Charpy V-notch impact specimens from the vessel beltline base and weld material. The measured shift in the ductile-to-brittle transition temperature (measured at the Charpy 30 ft-lb energy level) is used to monitor the vessel condition by comparing with the empirically based shift prediction using Regulatory Guide (RG) 1.99 Rev. 2 [1]. RG 1.99 Rev. 2 is used to calculate the Adjusted RT_{NDT} (ART), which is then used to set the operating limits for nuclear power plants taking into account the effects of irradiation on the RPV materials.

A database is maintained of the measured transition temperature shifts from irradiated surveillance data. The database has been used to develop models (embrittlement trend curves) which are used to predict changes in RPV transition temperature shift due to neutron irradiation for a given material chemistry, product form, and actual or projected fluence. However, there is a limited amount of irradiated LWR surveillance data at fluences above ~$3x10^{19}$ n/cm^2. Many existing and next-generation reactors in the U.S. will reach peak RPV fluences greater than this fluence during operation to 60 and 80 years. In 2008, approximately nine operating U.S. PWRs experienced a peak fluence above $3x10^{19}$ n/cm^2. By the end of the initial license (40 years) this number increases to approximately 34 [9]. While there is a significant amount of test reactor data available at these high fluences; there is limited power reactor data available. Some of this test reactor data shows higher embrittlement shifts [10, 11] than power reactor data-based correlations predict at these high fluence levels (e.g., 10CFR50.61, 10CFR50.61a, RG1.99 Rev. 2, and ASTM E900) [12, 2, 1, 13]. This has significant implications for plant operation to 60 years and beyond if the test reactor shift data are used to inform ETCs that are applied to LWRs. The irradiation embrittlement shift model for the RPV steels is foundational to 10CFR50.61 [12] (the pressurized thermal shock rule), 10CFR50.61a (the alternate pressurized thermal shock rule) and 10CFR50 Appendix G [7] (fracture toughness requirements and pressure-temperature limits). It is necessary to obtain more power reactor data in the high fluence range between $3x10^{19}$ n/cm^2 and the peak RPV fluence after 80 years of operation of the U.S. PWRs (~$10x10^{19}$ n/cm^2). Increasing the amount of the surveillance data at fluences in excess of ~$5x10^{19}$ n/cm^2 would facilitate the discrimination of actual trends and provide an empirical basis for assessment of future ETCs used by the regulator for applicability to PWRs.

Scope

This report provides a recommended coordinated reactor vessel surveillance program (CRVSP) capsule management plan for the U.S. pressurized water reactor (PWR) fleet. The objective of the CRVSP is to manage the withdrawal schedules of remaining PWR surveillance capsules to increase the fluence levels of the capsules at withdrawal and to fill the high fluence irradiated Charpy data gaps in the PWR surveillance capsule database (SDB) that is used to develop embrittlement correlations. A surveillance database that is robustly populated with high fluence data generated from the CRVSP will facilitate development of future neutron embrittlement trend curves (ETCs) that are applicable to the PWR operating environment to sixty years and beyond.

The CRVSP recommendations consider capsule withdrawals to obtain irradiation data through 80 years of operation to support a second license renewal and to obtain high fluence data for a broad, representative spectrum of PWR surveillance materials product forms and chemistries. The objective fluence levels are between $3x10^{19}$ and $10x10^{19}$ n/cm^2. The recommendations of the CRVSP are designed so that PWRs remain in compliance with 10 Code of Federal Regulations (CFR) 50 Appendix H [3], and the recommendations are consistent with Revision 2 of the Generic Aging Lessons Learned (GALL) [4] report.

The CRVSP recommendations for each plant provide approximate capsule withdrawal dates and target fluences to attain the objectives of this program. They are for coordinated planning purposes only and each plant remains responsible for its compliance with 10CFR50 Appendix H. Thus, all plants are responsible to verify continued compliance of its surveillance program with 10CFR50 Appendix H and all applicable regulations as part of implementation of any CRVSP recommendation.

Strategy Used for Developing the CRVSP

The basis for the current surveillance capsule withdrawal schedules is ASTM E185 (for each plant, the edition of ASTM E185 that is current on the issue date of the ASME Code to which the reactor vessel was purchased). Plants that have applied for license renewal have used Revision 1 of the GALL report [14] to adjust capsule withdrawal schedules for the extended operating period. Revision 1 of the GALL [14] report states that an acceptable surveillance program will test a capsule at the approximate 60-year peak RPV fluence. Any capsules that are left in the RPV can be used to provide additional meaningful metallurgical data (i.e., the capsule fluence does not significantly exceed the vessel fluence at an equivalent of 60 years). This has led some utilities to withdraw all capsules (e.g., move them to storage pools) when they reach a fluence equivalent to the vessel fluence at 60 years of operation, thus reducing the number of capsules that will be available at higher fluences. The latest revision of the GALL (Revision 2) [4] recommends that the surveillance capsule program be consistent with ASTM E185 [8] and 10CFR50 Appendix H [3] and states that capsule testing is to be performed between once and twice the end of license peak RPV fluence. The CRVSP identifies the remaining PWR capsules with materials that will fill high fluence data gaps and then schedules withdrawal and testing of those capsules consistent with the guidance of GALL Revision 2 [4].

Guidelines Applicability

The guidelines are intended to serve as the primary basis for owner preparation of a revised surveillance capsule withdrawal and test schedule in accordance with the requirement cited in Section 7. Section 6 identifies the plants for which surveillance program changes are recommended; most of the PWRs (54 of the 69 plants) do not have recommended changes. In all cases, compliance with 10 CFR 50 Appendix H and ASTM E-185 remains the responsibility of the owner.

Section 3: Methodology

The development of recommended changes to plant RVSP capsule withdrawal schedules requires that certain assumptions be made regarding future plant operations (e.g., capacity factor), RPV peak fluences, and capsule lead factors and fluences. Therefore, certain assumptions have been made in this report in order to estimate future capsule fluences and the years at which those fluences would be achieved. The project team used the best available data but it is recognized that each plant may have more recent or precise information that may yield slightly different results. Therefore, when changes to a plant's RVSP capsule withdrawal schedule are recommended in Section 6, those recommendations are usually expressed in terms of the plant's peak RPV fluence at some future time in life. For example, a recommendation may be made to defer capsule withdrawal from a planned date of 2016 to a future time when the capsule has attained a fluence equal to that plant's 80 year peak RPV fluence. To implement that recommendation, the plant will determine the appropriate outage (or year) to withdraw the capsule in order to achieve that fluence, using its current fluence and capacity factor projections and the same methodology that would be used to calculate, for example, the appropriate withdrawal date for its 60 year license renewal capsule. Where this report makes projections of withdrawal times and estimates of fluences, the estimates are for coordinated planning purposes within the CRVSP only and are not meant for any other purpose. Final determination of the appropriate capsule withdrawal year that achieves the CRVSP recommendation is the responsibility of the plant, based on data deemed by the plant to be authoritative and appropriate.

The assumptions used throughout this report for future fluence and schedule calculations include the following:

- In all cases for projecting calendar years from effective full power years (EFPY), a capacity factor of 0.95 was assumed. This capacity factor was applied starting at the most recent calendar year-EFPY data point, which was typically the most recent capsule pull.
- It was assumed that the majority of U.S. PWRs will seek a second license renewal.
- When developing a recommendation for revised capsule withdrawal date, it was assumed that all plants will be permitted to follow the RVSP provision of GALL Rev. 2 [4] that allows testing the end of license capsule between once and twice the 60-year peak RPV fluence. It is recognized that most if not all plants currently holding a renewed operating license applied for that

license under GALL Rev. 1. GALL Rev. 1 guidance for testing the license renewal capsule was to test the capsule at no greater than the 60-year peak RPV fluence. GALL Rev. 2 [4] now provides greater flexibility for testing the capsule at substantially higher fluences, and that flexibility was used in developing the revised capsule test schedule of the CRVSP. Discussions with the regulator have indicated that plants which received a renewed license under GALL Rev. 1 will be able to revise capsule withdrawal schedules to be consistent with GALL Rev. 2.

- It was assumed that the RPV capsule materials are of the same material groupings (e.g., SA-533 low Cu and Linde 91 low Cu) as the RPV beltline materials.

Approach

This evaluation considered the RVSPs from all the 69 U.S. PWRs. Forty-eight were designed by Westinghouse, 14 were designed by Combustion Engineering and 7 were designed by Babcock & Wilcox. The seven B&W designed plants have an integrated RVSP with only 2 plants still containing RVSP capsules [15, 16].

The methodology for developing the CRVSP is shown graphically in the flow chart, Figure 3-1. The RVSP at each plant was reviewed to document the contents of the surveillance capsules. The chemical compositions of the capsule specimens (base metal and weld metal) were used to group the materials based on their susceptibility to irradiation induced embrittlement. The primary material properties used in this determination were the product form (forging, plate and weld flux type) and the composition (copper content).

The current site specific RVSP withdrawal schedule was reviewed. The tested capsule fluence values were used to determine the range where irradiated Charpy data from U.S PWRs is available and, by difference, to indicate the fluence range for which new data are required to fill the high fluence gaps. The projected removal dates and fluence projections of the capsules planned for withdrawal and testing show the capability of the existing program to fill the high fluence gaps in the current Charpy data from U.S. PWRs.

Recommended changes to the existing withdrawal schedules at the plant sites were based on obtaining high fluence PWR surveillance data for the full range of RPV materials across the U.S. PWR fleet. The need for getting data on the full range of RPV materials is crucial to establishing a sound basis for updating the ETC for power reactors– that is, obtaining high fluence data on the base and weld materials representing all U.S. PWR RPVs.

The recommended changes to the existing withdrawal schedules were also based on obtaining high fluence surveillance data in a timely manner while remaining consistent with GALL Rev. 2 [4] and 10CFR50 Appendix H [3] for a 60-year license. The target range of capsule fluence is from $3x10^{19}$ n/cm^2 to $10x10^{19}$ n/cm^2. The target fluence range encompasses the highest projected 80 year peak RPV fluence for the U.S. PWR fleet. All remaining RVSP capsules were considered in this effort with the goal of obtaining high fluence Charpy data by the year 2025. Capsules that could not reach the target fluence by the year 2025 were not considered directly for this effort.

Once the plants with capsule materials that have the potential to fill high fluence gaps were identified (e.g., plants with materials of the needed product form and chemistry that could reach the target fluence range by 2025), recommended modifications to the existing RVSPs were made by one of three methods:

- Deferring Withdrawal
  - If the end of license capsule has not yet been removed and tested at the approximate 60-year peak RPV fluence, consideration was given to deferring withdrawal, consistent with GALL Rev. 2 [4], by removing and testing the capsule between once and twice the projected 60-year peak RPV fluence. The preferred objective was to schedule the capsule withdrawal and testing at approximately twice the projected 60-year peak RPV fluence. If this could not be reasonably achieved by the year 2025, then a lower fluence, such as the projected 80-year peak RPV fluence, was recommended.
- Testing a Different Capsule than Planned
  - In some cases, a plant's current RVSP planned to test a capsule that has a lower lead factor than another available capsule. If a higher lead factor capsule is a viable alternative and will attain >$3x10^{19}$ n/cm^2 before 2025, the CRVSP recommends testing the higher lead factor capsule in its place. The recommended test year may also be earlier than the original capsule's test date.
- Optimization
  - If a capsule has already been removed and tested at the approximate 60-year peak RPV fluence, consideration was given to test an additional capsule at a higher fluence (e.g., 80-year or 2x60-year peak RPV fluence). This determination was made based on the value of the test specimens in the capsules to the needs of the fleet for high fluence data in key material categories. The plant asked to test the additional capsule would potentially benefit by obtaining the surveillance data necessary to support a second license renewal, should that be pursued. Section 4 describes the methodology employed to identify high value capsules and the reasons that additional capsule testing was recommended.

The projected EFPY at a given year was calculated using a 0.95 capacity factor beginning at the highest reported EFPY value (EQ3-1).

$$E_X = (Y_X - Y_i) \times 0.95 + E_i \qquad \text{Equation 3-1}$$

Where:

E_X = Projected EFPY at Y_X years,

E_i = Highest reported EFPY value,

Y_X = Years of operation corresponding to E_X EFPY,

Y_i = Years of operation corresponding to E_i EFPY.

Fluence projections at a given EFPY of operation were calculated assuming a linear relationship between RPV fluence and EFPY and using the best available data which included reports on surveillance capsule evaluations, final safety analysis reports (FSAR), pressure-temperature limit reports (PTLR) and license renewal applications. The projection was made using the following relationship (EQ3-2):

$$f_x = f_L + LF_{future} \cdot A \cdot (E_x - E_L)$$

Equation 3-2

Where:

f_x = Projected fluence at E_x EFPY (10^{19} n/cm^2, E > 1.0 MeV),

f_L = Latest known fluence (10^{19} n/cm^2, E > 1.0 MeV),

E_L = Latest known EFPY,

A = Irradiation rate coefficient – solved by regression analysis of peak RPV fluence projections (10^{19} n/cm^2, E > 1.0 MeV / EFPY),

LF_{future} = Future lead factor – the ratio of fluence projected to be received by the surveillance capsule to that projected to be received by the RPV (unitless).

EQ 3-2 is used with LF_{future} = 1 to extrapolate peak RPV fluence.

The lead factors reported in capsule reports are generally cumulative lead factors representing irradiation received by the capsule up to the point of the capsule report (EQ 3-3):

$$LF_{cumulative} = \frac{Capsule\_Fluence}{peak\_RPV\_fluence}$$

Equation 3-3

If the surveillance capsule is not moved to a different location, the future lead factor is assumed to be equivalent to the cumulative lead factor.

However, if a surveillance capsule is moved from its original location to a location receiving a higher rate of fluence, its cumulative lead factor will increase with time. In this case, the future lead factor is greater than the cumulative lead factor reported in a capsule report. The future lead factor is calculated using EQ 3-4 (if data is available from capsule report) or the cumulative lead factor of a surveillance capsule previously removed from the higher lead factor location.

$$LF_{future} = \frac{Projected\_Capsule\_Flux}{Projected\_Peak\_RPV\_Flux}$$

Equation 3-4

The above equations are used to project peak RPV fluences at 60, 80, and 100 years of operation as well as capsule fluence at a given EFPY and year of operation. The results are used to estimate capsule withdrawal year and fluence.

It will be necessary to substantiate the preceding projections to obtain accurate input to the capsule withdrawal date. Actual core operating histories – including power uprates – need to be considered in establishing the most appropriate timing. As previously stated, all recommended withdrawal times and fluences are for coordinated planning purposes only and are not meant for any other analysis. Final determination of the appropriate capsule withdrawal year and fluence is the responsibility of the plant, based on data deemed by the plant to be authoritative and appropriate.

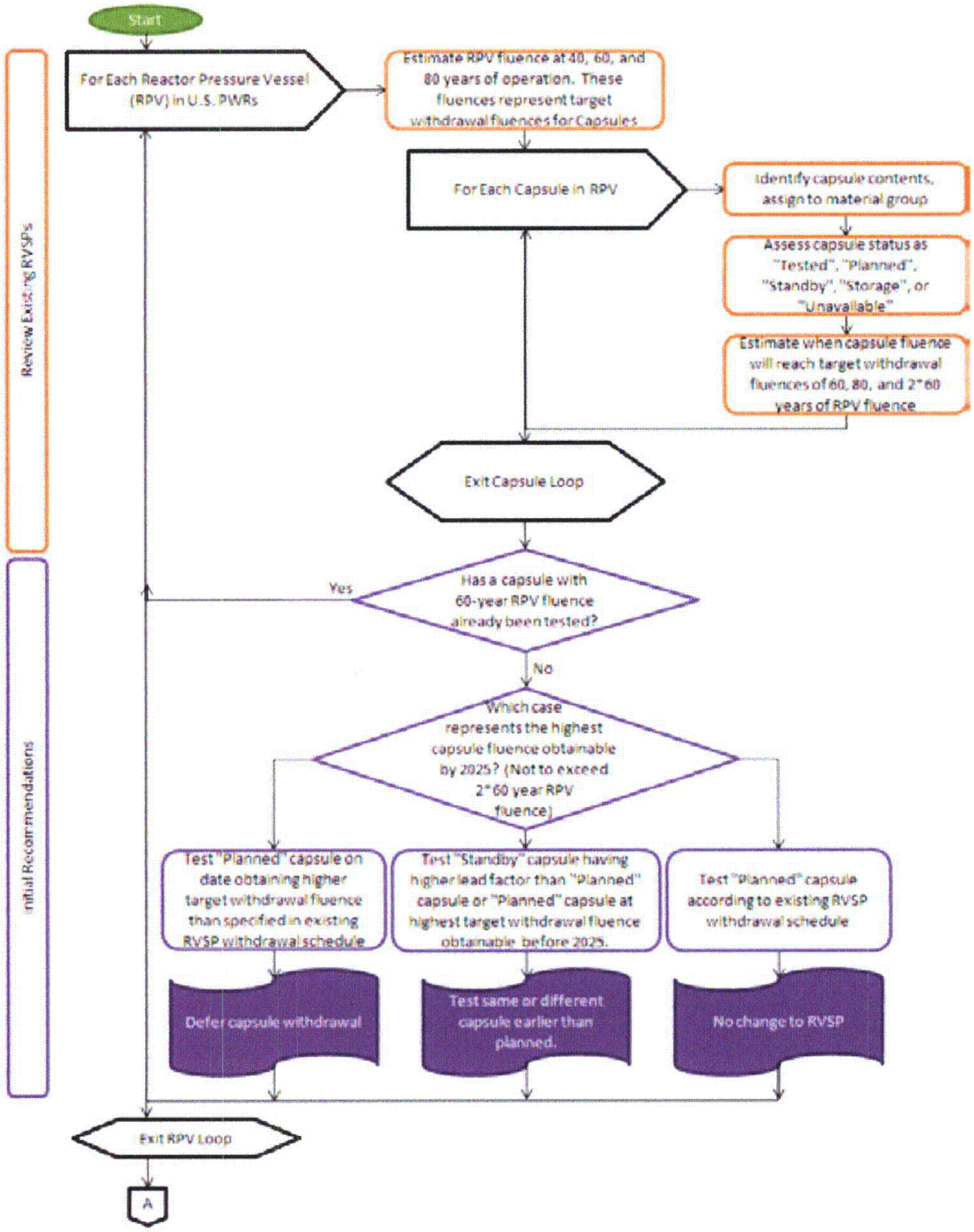


Figure 3-1
CRVSP Development Methodology Flow Chart

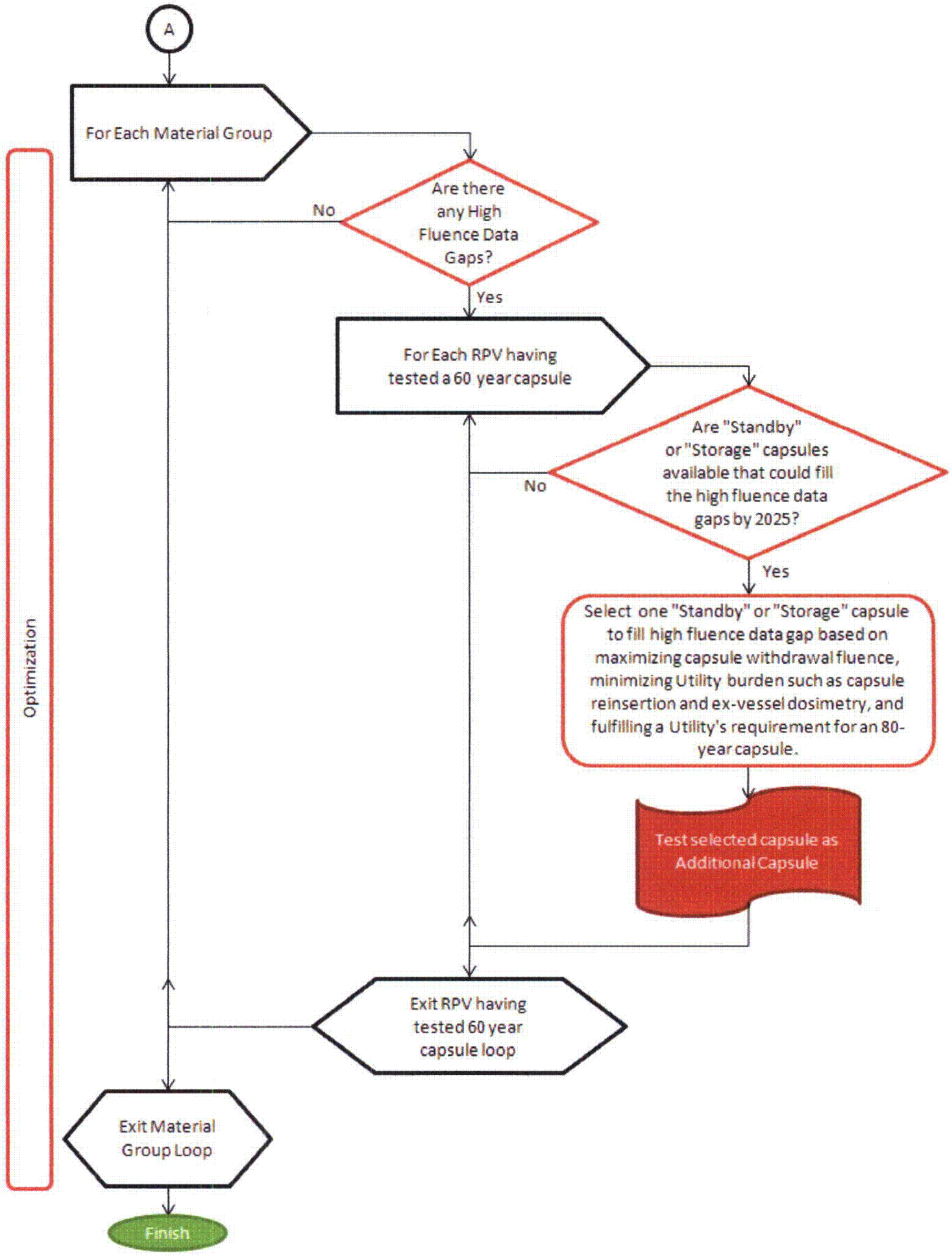


Figure 3-1 (continued)
CRVSP Development Methodology Flow Chart

Section 4: Optimization

The current RVSP at each plant was considered to determine the optimal method of obtaining high fluence data expeditiously while meeting the needs of the plant and CRVSP without creating an undue burden on the plant. Each plant RVSP fell into one of two categories:

1. No additional testing or moving of capsules recommended beyond the requirements for a 60-year license,
2. Recommend testing an additional capsule after the 60-year capsule has already been tested, which is not required for a 60-year license but would need to support 80 years of operation.

For the purpose of developing the CRVSP, it is assumed that all plants will be permitted to follow the provisions of GALL Rev. 2 [4] that allow testing of the end of license capsule for a 60-year license at a fluence between once and twice the end of license peak RPV fluence. This is consistent with the surveillance capsule withdrawal guidance in ASTM E 185-10 [17] and E 2215-10 [18] which addresses monitoring over a 60- and 80-year operating period.

No additional testing or moving of surveillance capsules beyond the requirements of a 60-year license was recommended for 68 of the 69 U.S. PWRs considered. For 54 plants, this program does not recommend making any changes to their RVSP. Common reasons that changes were not recommended for those plants include: 1) the plant has already tested all of their capsules, 2) testing of the 60-year capsule is already planned and the lead factor is too low for the capsule to reach the 80-year peak RPV fluence by 2025, 3) the 2x60-year peak RPV fluence is at or below ~$3x10^{19}$ n/cm^2, or 4) the 60-year capsule has already been tested and the materials in the remaining capsules do not provide sufficient value to the to the CRVSP to warrant additional testing ("value" will be discussed later in this section). For 14 of the remaining 15 plants, the CRVSP recommends RVSP modifications such as: 1) testing the planned 60-year capsule at a later date and with a higher fluence (e.g., 80 or 2x60-year); 2) testing a different, higher-lead-factor capsule earlier than the original capsule was scheduled; and 3) testing the same capsule as currently planned, but earlier than originally scheduled.

The CRVSP recommends that one of the 69 plants test an additional capsule beyond the requirements of a 60-year license, noting that such a test would be required to support an 80-year license. This capsule was selected based on the optimization process described below.

A total of 25 of the operating U.S. PWRs have already tested their 60-year capsule. Many of these plants do not have remaining capsules of value to this program for a variety of reasons. Farley Units 1 and 2 and Oconee Units 1, 2 and 3 do not have any remaining capsules. Crystal River Unit 3 already plans on testing additional capsules, but not within the time interval of this program. The McGuire Unit 1 and 2 test materials have been removed from the capsules so it is not available for further irradiation. At Salem Unit 1, moving the remaining capsule to a higher lead factor location would not produce high fluence data in the planning horizon of this program. Vogtle Unit 1 and 2 have already tested their 80-year capsules.

The remaining capsule at Kewaunee contains material that could be of potential use to the CRVSP. Kewaunee plans to test an additional capsule beyond the requirements of their 60-year license. The plant will test either capsule N or a supplemental capsule that will be inserted in the near future. Due to these circumstances, the CRVSP makes no specific recommendation regarding the Kewaunee capsules.

Of the 25 plants that have already tested their 60-year capsule, 13 plants have capsules remaining that may be useful for this program. Of these 13 plants, one plant was selected because the test specimen materials will fill significant high fluence data gaps.

The relative value of the capsule materials at these 13 remaining plants was determined based on two factors: 1) how well the base metal and weld flux material categories will be populated with high fluence data by the CRVSP and 2) the divergence of the embrittlement trend curves at the projected withdrawal fluences.

Evaluation of High Fluence Data Gaps

The 13 plants identified as having capsules of potential value to this program were organized by capsule material group and evaluated to determine the most appropriate additional capsule(s) to be tested to meet the needs of the CRVSP.

For the purposes of optimization of the CRVSP, "high fluence data gap" is defined as follows:

- An 80-year peak RPV fluence bin is occupied by at least one vessel, and
- The corresponding surveillance capsule recommended fluence bin is unoccupied, and
- The surveillance capsule recommended fluence bins higher than the unoccupied bin identified above are also unoccupied.

The testing of one surveillance capsule can fill a maximum of two high fluence data gaps.

For each of the capsules containing the material group listed below, the following factors were considered when selecting capsules to fill high fluence data gaps: the potential capsule fluence at withdrawal, the 60-year and 80-year peak RPV fluence, and the additional burden on the plant (i.e., capsule re-insertion and/or installing external vessel dosimetry).

SA-533 Grade B Class 1 Plate (low copper)

Table 4-1 includes all plants that have already tested their 60-year capsule and have a reactor vessel fabricated from SA-533 Grade B Class 1 plate with copper less than or equal to 0.10 wt%. Note that Vogtle Units 1 and 2 are not included in Table 4-1 because they have already tested their 80-year capsule.

The CRVSP recommended plan for capsules containing low copper SA-533 Grade B Class 1 is shown in Figure 4-1. The capsules shown in red (Recommended) represent the capsules that were selected for testing prior to optimization and will be referred to as "Recommended" capsules. The capsule shown in green was selected using the optimization methodology discussed above; this is the "Rec Optimized" capsule. It was selected from the list of available capsules listed in Table 4-1. This selection was performed by comparing the data in Figure 4-1 (before the "Rec Optimized" capsule was added) to the distribution of the 80-year peak RPV fluence for all plants with reactor vessels fabricated from low copper SA-533 Grade B Class 1 plate, Figure 4-2.

Based on the definition of a "high fluence data gap" given above, a gap exists in the 7-8x10^{19} n/cm^2 fluence bin.

The following capsules could fill the 7-8x10^{19} n/cm^2 fluence gap: BV2-Y, STP1-X, STP2-X and VCSum-Y, as shown in Table 4-1. Capsule VCSum-Y has the highest potential recommended withdrawal fluence, but this capsule is currently in storage and therefore would require re-insertion. Capsule BV2-Y was selected to fill the 7-8x10^{19} n/cm^2 fluence gap because it has the next highest fluence and additional burdens such as re-insertion are not required. As discussed below, the testing of capsule BV2-Y is also required to fill a high fluence data gap for the low copper Linde 91 weld metal material group. Note that the current plant specific RVSP already plans on testing BV2-Y (or a similar capsule) between the projected 80-year and 2x60-year peak RPV fluence.

Table 4-1
Remaining Capsules with SA-533 Grade B Class 1 with Low Copper

Plant-Capsule	Would Reinsertion Be Required?	Add External Dosimetry Required?	Potential Recommended Withdrawal Fluence (n/cm²)	Potential Recommended Withdrawal Year	60-year peak RPV Fluence (n/cm²)	80-year Peak RPV Fluence (n/cm²)
BV2-Y	No	No	$8.5x10^{19}$	2018	$5.2x10^{19}$	$6.9x10^{19}$
Call-W	No	Yes	$6.1x10^{19}$	2013	$3.1x10^{19}$	$4.1x10^{19}$
CP1-Z	Yes	No	$4.5x10^{19}$	2020	$3.3x10^{19}$	$4.5x10^{19}$
CP2-Z	Yes	No	$5.5x10^{19}$	2025	$3.4x10^{19}$	$4.5x10^{19}$
MS3-Z	No	Yes	$5.9x10^{19}$	2017	$3.0x10^{19}$	$4.0x10^{19}$
STP1-X	No	No	$7.6x10^{19}$	2025	$3.9x10^{19}$	$5.2x10^{19}$
STP2-X	No	No	$7.0x10^{19}$	2025	$3.7x10^{19}$	$5.0x10^{19}$
VCSum-Y	Yes	No	$8.8x10^{19}$	2020	$6.6x10^{19}$	$8.8x10^{19}$
WC-X	Yes	No	$6.5x10^{19}$	2025	$3.5x10^{19}$	$4.8x10^{19}$

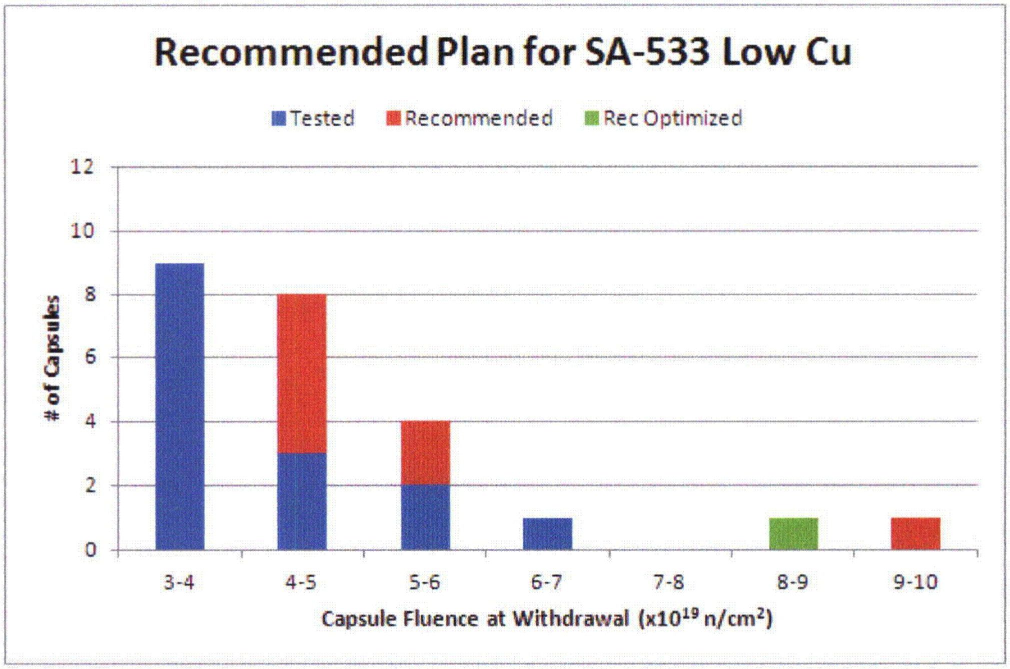


Figure 4-1
Recommended plan for capsules containing SA-533 Grade B Class 1 with low copper.

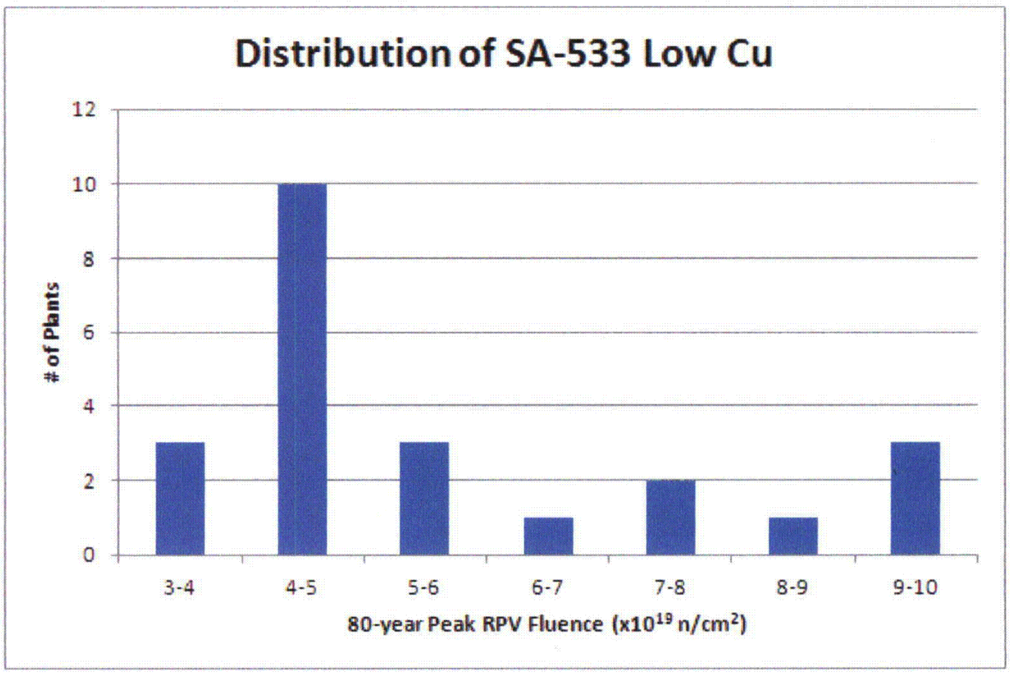


Figure 4-2
Distribution of 80-year peak RPV fluence for plants with vessels fabricated from low copper SA-533 Grade B Class 1 plate.

SA-533 Grade B Class 1 and SA-302 Modified Plate (high copper)

Table 4-2 includes all plants that have already tested their 60-year capsule and have a reactor vessel fabricated from SA-533 Grade B Class 1 plate or SA-302 Modified with copper greater than 0.10 wt%. Note that McGuire Unit 1 is not included in Table 4-2 because the only remaining capsule was removed and disassembled so the test specimens are not readily available for reinsertion.

The CRVSP recommended plan for capsules containing high copper SA-533 Grade B Class 1 or SA-302 Modified is shown in Figure 4-3. A comparison was performed between the data in Figure 4-1 to the distribution of the 80-year peak RPV fluence for all plants with reactor vessels fabricated from SA-533 Grade B Class 1 plate or SA-302 Modified with high copper, Figure 4-4.

Based on the definition of a "high fluence data gap" given above, no gaps are present so testing an optimization capsule is not recommended.

Table 4-2
Remaining Capsules with SA-533 and SA-302M High Copper

Plant-Capsule	Would Reinsertion Be Required?	Add External Dosimetry Required?	Potential Recommended Withdrawal Fluence (n/cm2)	Potential Recommended Withdrawal Year	60-year Peak RPV Fluence (n/cm2)	80-year Peak RPV Fluence (n/cm2)
DC2-Z	Yes	No	4.7x1019	2025	2.3x1019	3.1x1019

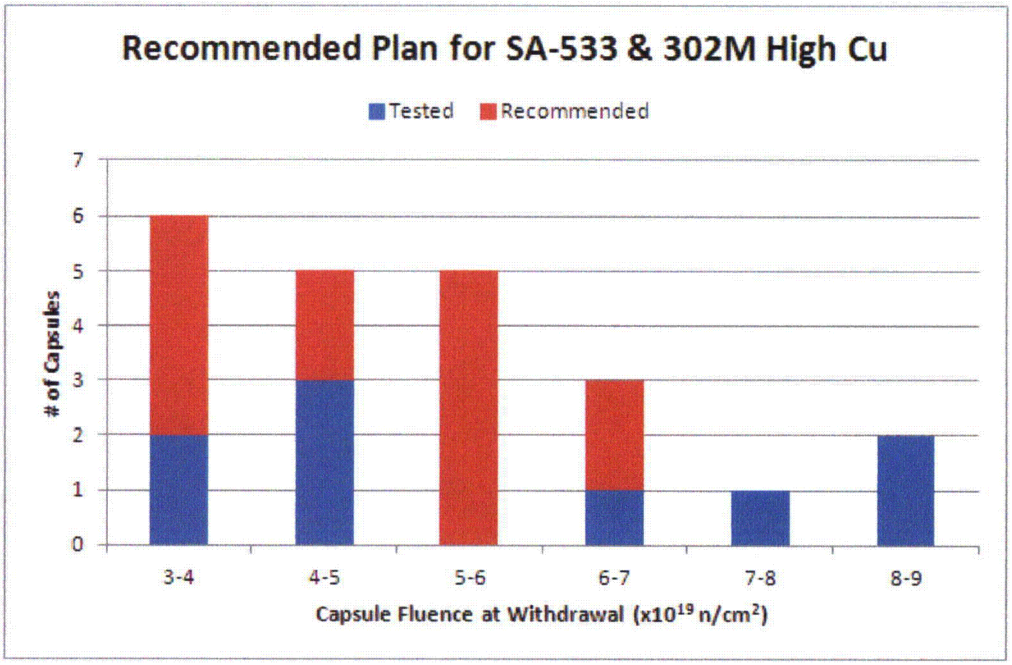


Figure 4-3
Recommended plan for capsules containing SA-533 Grade B Class 1 and SA-302 Modified with high copper.

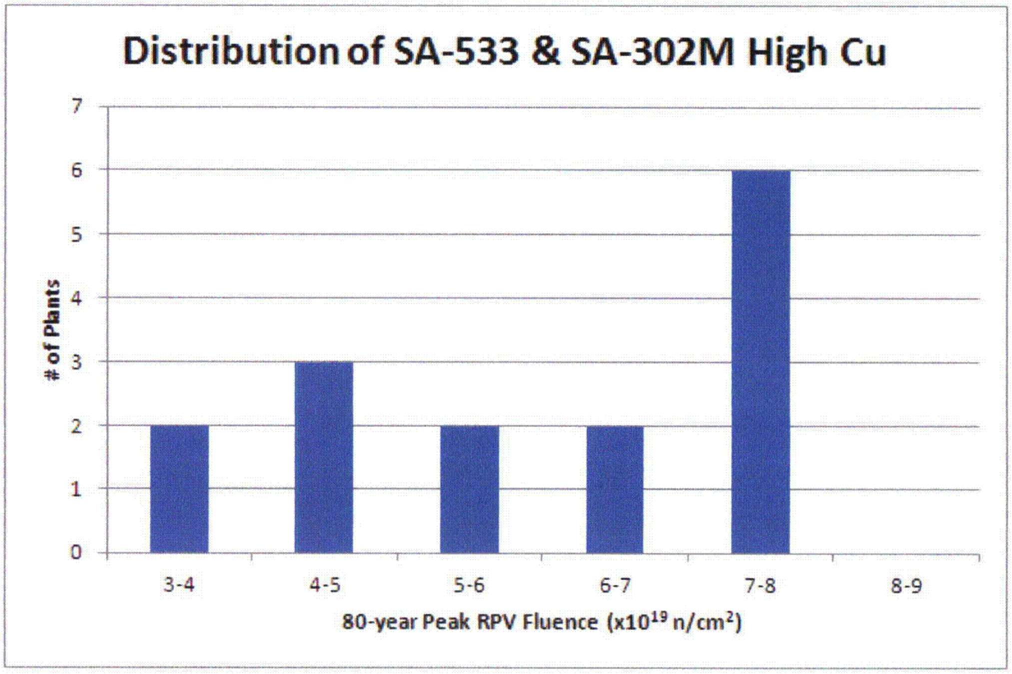


Figure 4-4
Distribution of 80-year peak RPV fluence for plants with vessels fabricated from high copper SA-533 Grade B Class 1 or SA-302 Modified plate.

SA-302 Grade B (all high copper)

No plants which have a reactor vessel fabricated from SA-302 Grade B plate with copper greater than 0.10 wt% have tested 60-year capsules. However, the 60-year capsule for Point Beach Unit 1 is part of the B&W MIRVP integrated program so the withdrawal cannot be modified without affecting other plants. Therefore Point Beach Unit 1 will be treated as if it had already tested its 60-year capsule because testing additional capsules is not required for the 60-year license. The possibility of testing an additional Point Beach Unit 1 capsule is considered, as shown in Table 4-3.

The CRVSP recommended plan for capsules containing SA-302 Grade B is shown in Figure 4-5. The data in Figure 4-5 was compared to the distribution of the 80-year peak RPV fluence for all plants with reactor vessels fabricated from SA-302 Grade B plate, Figure 4-6.

Based on the definition of a "high fluence data gap" given above, the CRVSP will remove all gaps for this material group without testing an optimization capsule.

Table 4-3
Remaining Capsules with SA-302 Grade B High Copper

Plant-Capsule	Would Reinsertion Be Required?	Add External Dosimetry Required?	Potential Recommended Withdrawal Fluence (n/cm^2)	Potential Recommended Withdrawal Year	60-year Peak RPV Fluence (n/cm^2)	80-year Peak RPV Fluence (n/cm^2)
PB1-N	No	Yes	7.1×10^{19}	2016	5.1×10^{19}	7.1×10^{19}

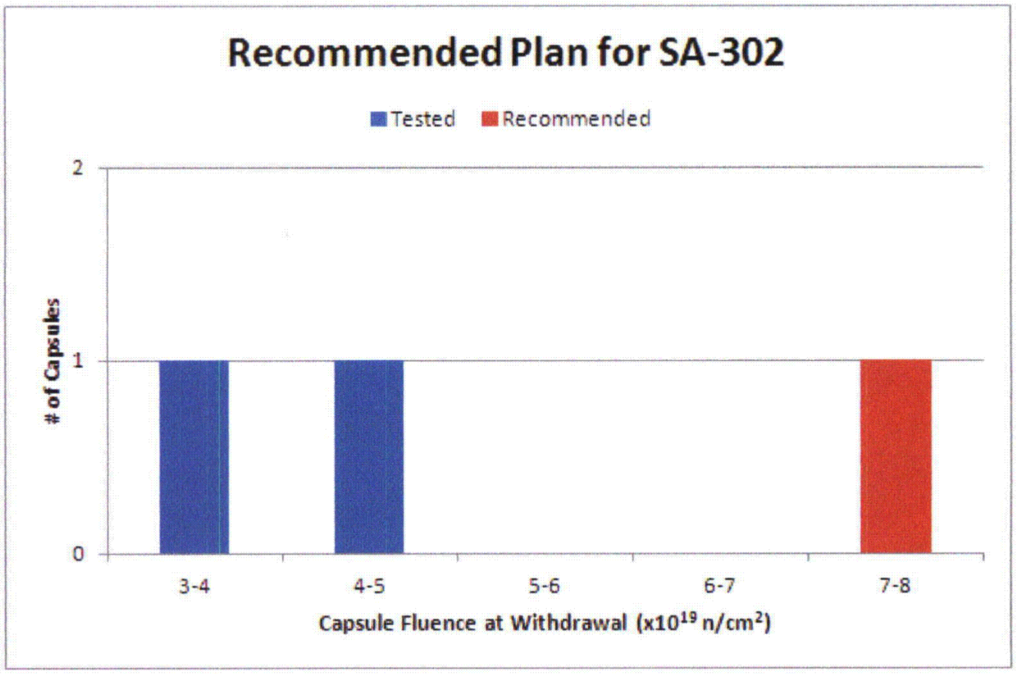


Figure 4-5
Recommended plan for capsules containing SA-302 Grade B.

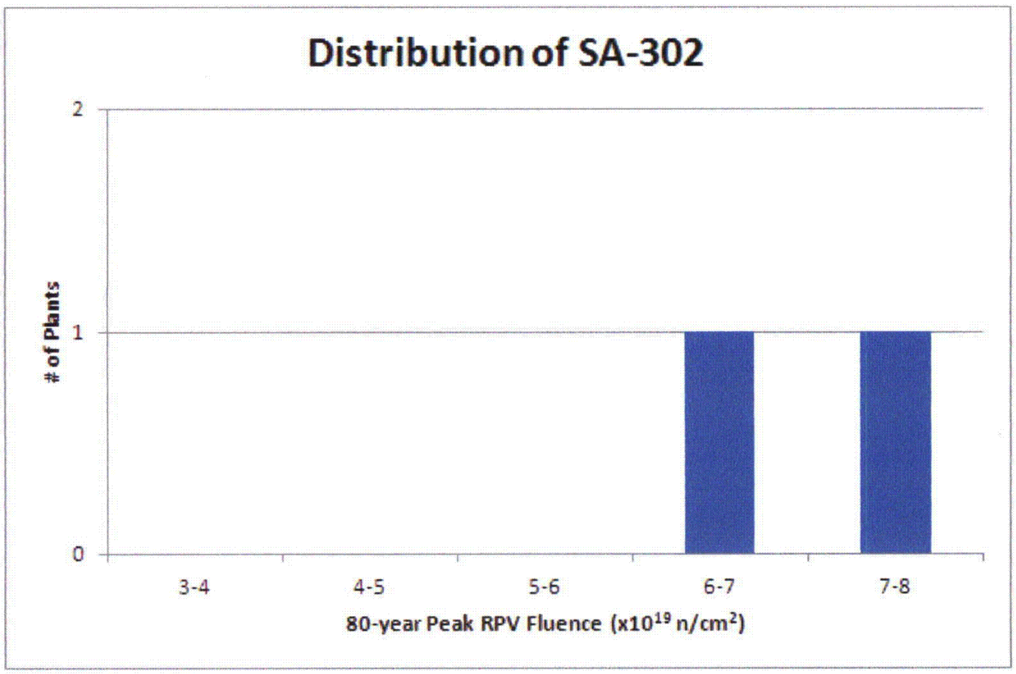


Figure 4-6
Distribution of 80-year peak RPV fluence for plants with vessels fabricated from SA-302 Grade B plate.

SA-508 Class 2 Forging (low copper)

Ginna is the only plant with a reactor vessel fabricated from SA-508 Class 2 forgings with copper less than or equal to 0.10 wt% that has already tested its 60-year capsule. However, Point Beach Unit 2 was also considered in Table 4-4 even though the 60-year capsule has not yet been tested. The 60-year capsule for Point Beach Unit 2 is part of the B&W MIRVP integrated program so the withdrawal cannot be modified without affecting other plants. Therefore, Point Beach Unit 2 is being treated as if it had already tested its 60-year capsule because testing additional capsules is not required for the 60-year license.

The CRVSP recommended plan for capsules containing low copper SA-508 Class 2 is shown in Figure 4-7. The data in Figure 4-7 was compared to the distribution of the 80-year peak RPV fluence for all plants with reactor vessels fabricated from low copper SA-508 Class 2 forgings, Figure 4-8.

Based on the definition of a "high fluence data gap" given above, the CRVSP will remove all gaps for this material group without testing an optimization capsule.

Table 4-4
Remaining Capsules with SA-508 Class 2 Low Copper

Plant-Capsule	Would Reinsertion Be Required?	Add External Dosimetry Required?	Potential Recommended Withdrawal Fluence (n/cm2)	Potential Recommended Withdrawal Year	60-year Peak RPV Fluence (n/cm2)	80-year Peak RPV Fluence (n/cm2)
Ginna-P	No	Yes	9.1x1019	2025	5.7x1019	7.6x1019
PB2-N	No	Yes	8.6x1019	2025	5.1x1019	6.9x1019

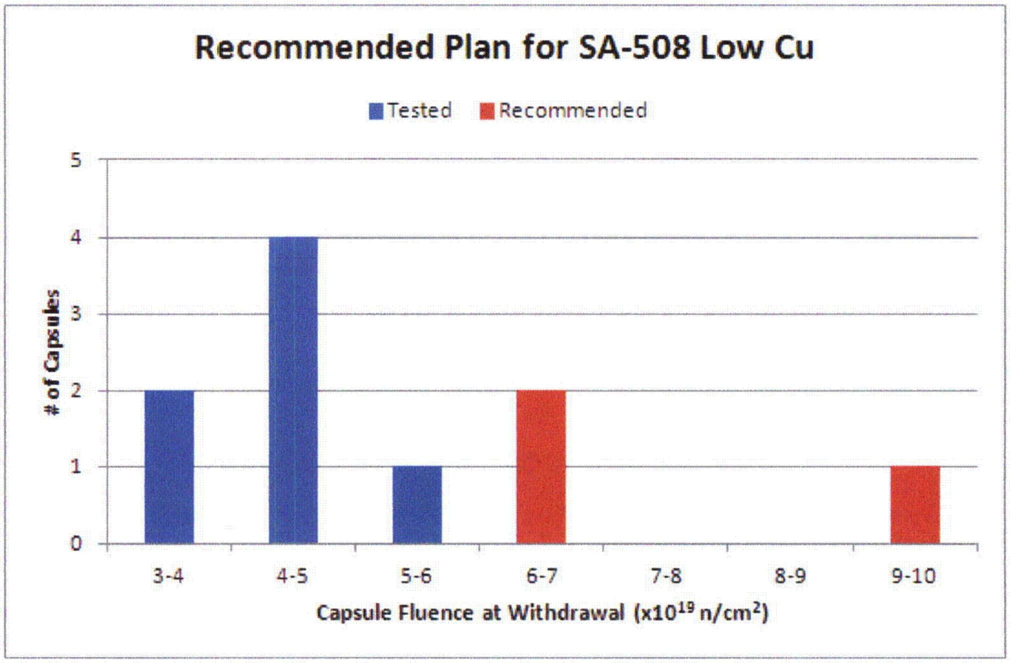


Figure 4-7
Recommended plan for capsules containing SA-508 Class 2 low copper.

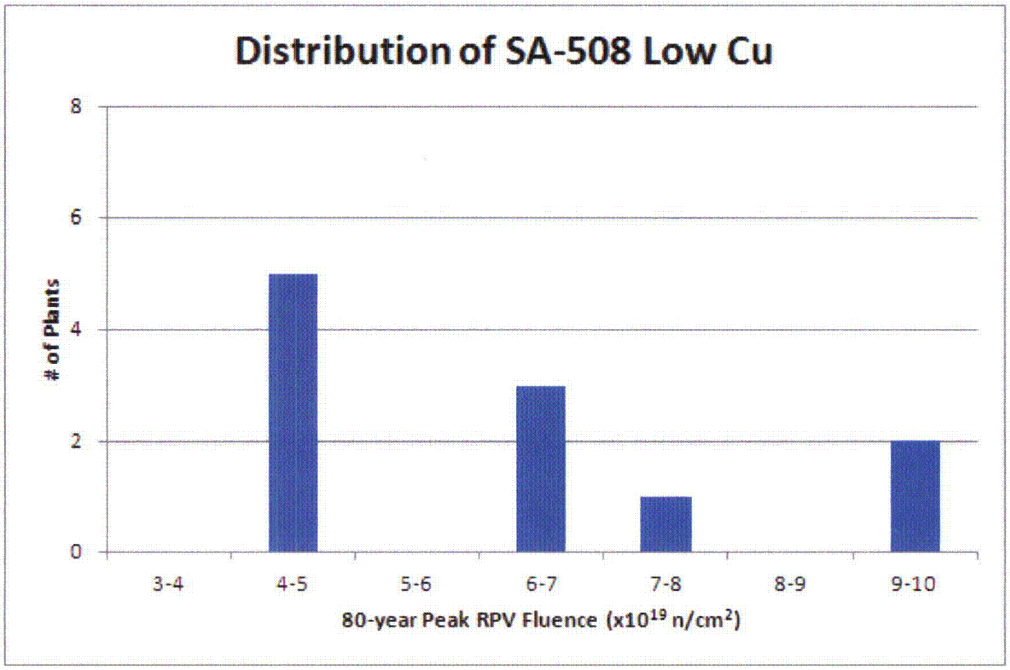


Figure 4-8
Distribution of 80-year peak RPV fluence for plants with vessels fabricated from SA-508 Class 2 low copper.

SA-508 Class 2 Forging (high copper)

The only plant that has already tested their 60-year capsule and has a reactor vessel fabricated from SA-508 Class 2 forgings with copper greater to 0.10 wt% is McGuire Unit 2. However, the McGuire Unit 2 test materials have been removed from the capsules and are not available for further irradiation.

Linde 91 Weld (low copper)

Table 4-5 includes all plants that have already tested their 60-year capsule and have a reactor vessel fabricated with Linde 91 weld metal containing copper less than or equal to 0.10 wt%.

The CRVSP recommended plan for capsules containing low copper Linde 91 is shown in Figure 4-9. The capsules shown in red are labeled as "Recommended" and represent the capsules that were selected for testing prior to optimization. The capsule shown in green (Rec Optimized) was selected from the list of available capsules listed in Table 4-5. This selection was performed by comparing the pre-optimized data in Figure 4-9 to the distribution of the 80-year peak RPV fluence for all plants with reactor vessels fabricated with low copper Linde 91 weld metal, Figure 4-10.

Based on the definition of a "high fluence data gap" given above, gaps exist in the 7-8, 8-9 and 9-10x10^{19} n/cm^2 fluence bins.

Capsule BV2-Y was selected to fill the 8-9x10^{19} n/cm^2 fluence gap because it is the only available capsule in the necessary fluence range. As discussed above, the testing of capsule BV2-Y is also required to fill a high fluence data gap for the low copper SA-533 plate material group. Based on the definition of high fluence data gap, testing capsule BV2-Y will also remove the 7-8x10^{19} n/cm^2 fluence gap. Note that the current plant specific RVSP already plans on testing BV2-Y (or a similar capsule) between the projected 80-year and 2x60-year peak RPV fluence.

No capsules are available in this material group to fill the 9-10x10^{19} n/cm^2 fluence gap by the year 2025. This will be discussed later in the report.

Table 4-5
Remaining Capsules with Linde 91 Low Copper

Plant-Capsule	Would Reinsertion Be Required?	Add External Dosimetry Required?	Potential Recommended Withdrawal Fluence (n/cm^2)	Potential Recommended Withdrawal Year	60-year Peak RPV Fluence (n/cm^2)	80-year Peak RPV Fluence (n/cm^2)
BV2-Y	No	No	$8.5x10^{19}$	2018	$5.2x10^{19}$	$6.9x10^{19}$
CP1-Z	Yes	No	$4.5x10^{19}$	2020	$3.3x10^{19}$	$4.5x10^{19}$
MS3-Z	No	Yes	$5.9x10^{19}$	2017	$3.0x10^{19}$	$4.0x10^{19}$

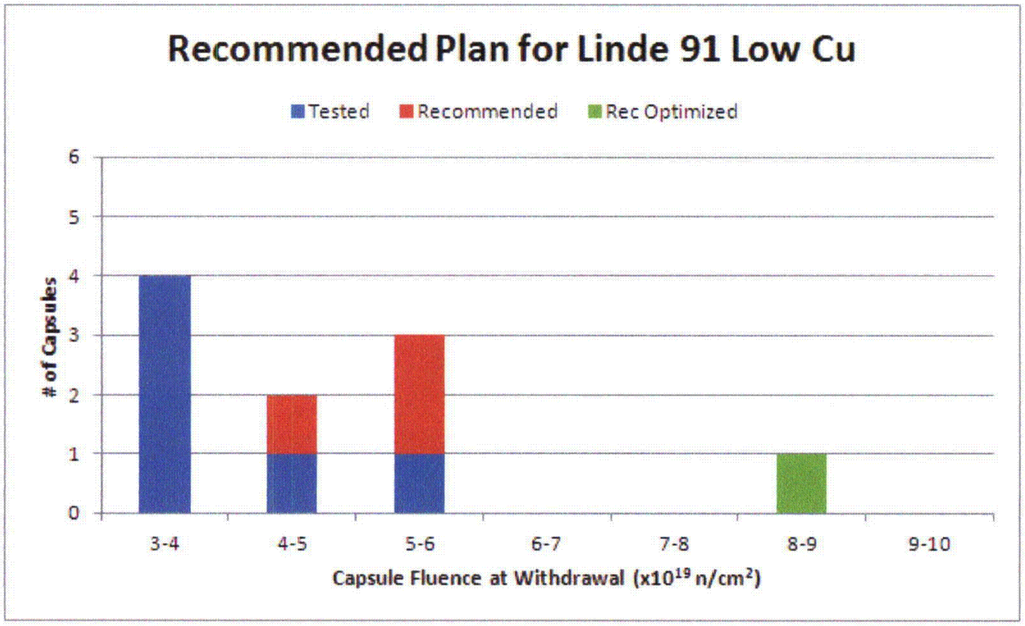


Figure 4-9
Recommended plan for capsules containing Linde 91 with low copper.

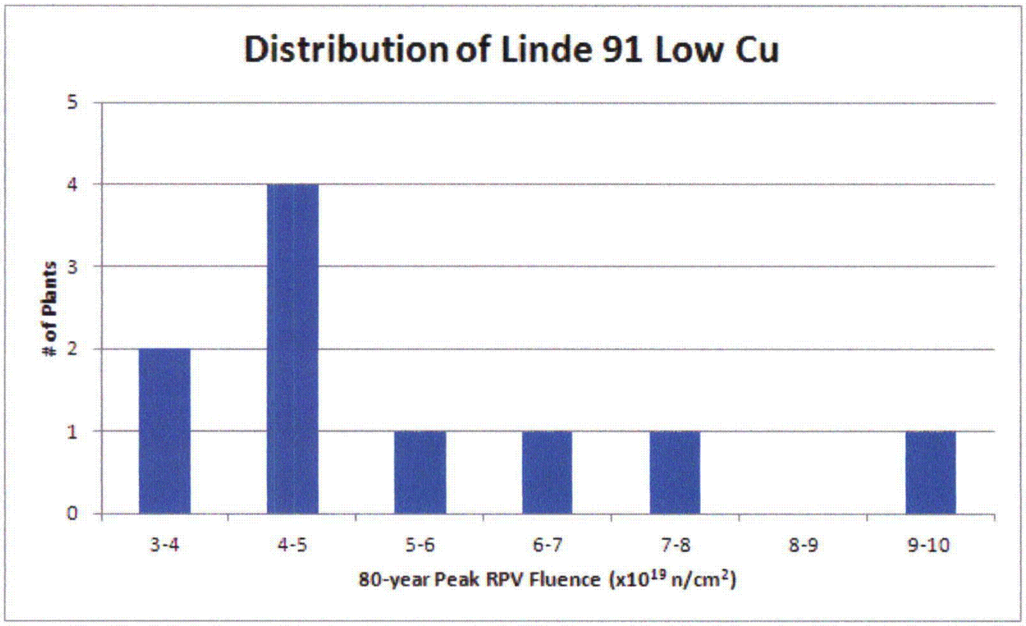


Figure 4-10
Distribution of 80-year peak RPV fluence for plants with vessels fabricated with Linde 91 with low copper.

Linde 124 Weld (all low copper)

Table 4-6 includes all plants that have already tested their 60-year capsule and have a reactor vessel fabricated with Linde 124 weld metal. Note that Vogtle Unit 2 is not included in Table 4-6 because the 80-year capsule has already been tested.

The CRVSP recommended plan for capsules containing Linde 124 is shown in Figure 4-11. The data in Figure 4-11 was compared to the distribution of the 80-year peak RPV fluence for all plants with reactor vessels fabricated with Linde 124 weld metal, Figure 4-12.

Based on the definition of a "high fluence data gap" given above, the CRVSP will remove all gaps for this material group without testing an optimization capsule.

Table 4-6
Remaining Capsules with Linde 124

Plant-Capsule	Would Reinsertion Be Required?	Add External Dosimetry Required?	Potential Recommended Withdrawal Fluence (n/cm^2)	Potential Recommended Withdrawal Year	60-year Peak RPV Fluence (n/cm^2)	80-year Peak RPV Fluence (n/cm^2)
Call-W	No	Yes	$6.1x10^{19}$	2013	$3.1x10^{19}$	$4.1x10^{19}$
CP2-Z	Yes	No	$5.5x10^{19}$	2025	$3.4x10^{19}$	$4.5x10^{19}$
STP1-X	No	No	$7.6x10^{19}$	2025	$3.9x10^{19}$	$5.2x10^{19}$
STP2-X	No	No	$7.0x10^{19}$	2025	$3.7x10^{19}$	$5.0x10^{19}$
VCSum-Y	Yes	No	$8.8x10^{19}$	2020	$6.6x10^{19}$	$8.8x10^{19}$
WC-W	Yes	No	$6.5x10^{19}$	2025	$3.5x10^{19}$	$4.8x10^{19}$

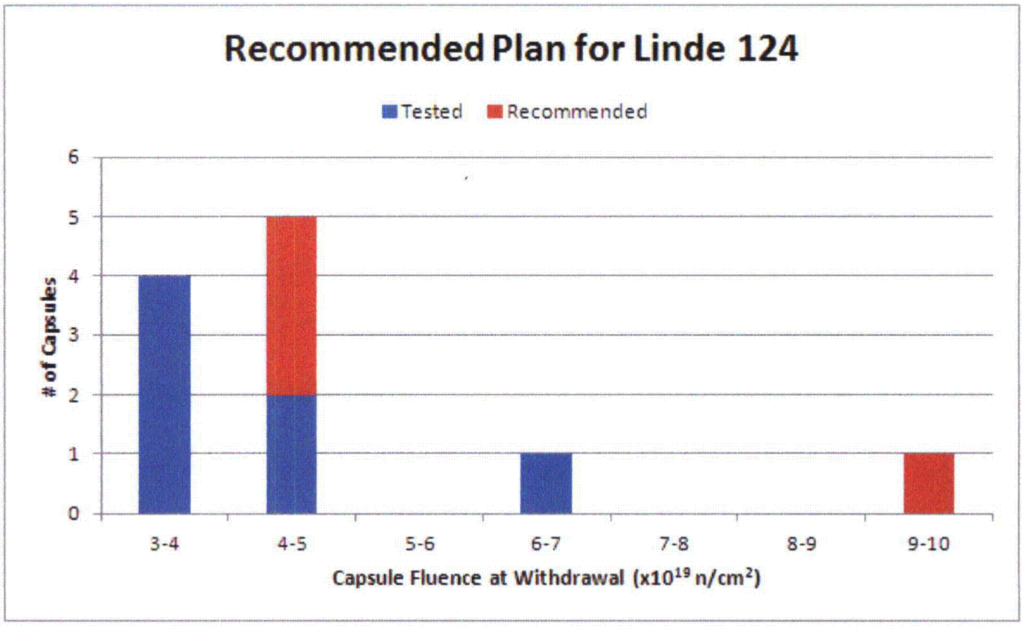


Figure 4-11
Recommended plan for capsules containing Linde 124.

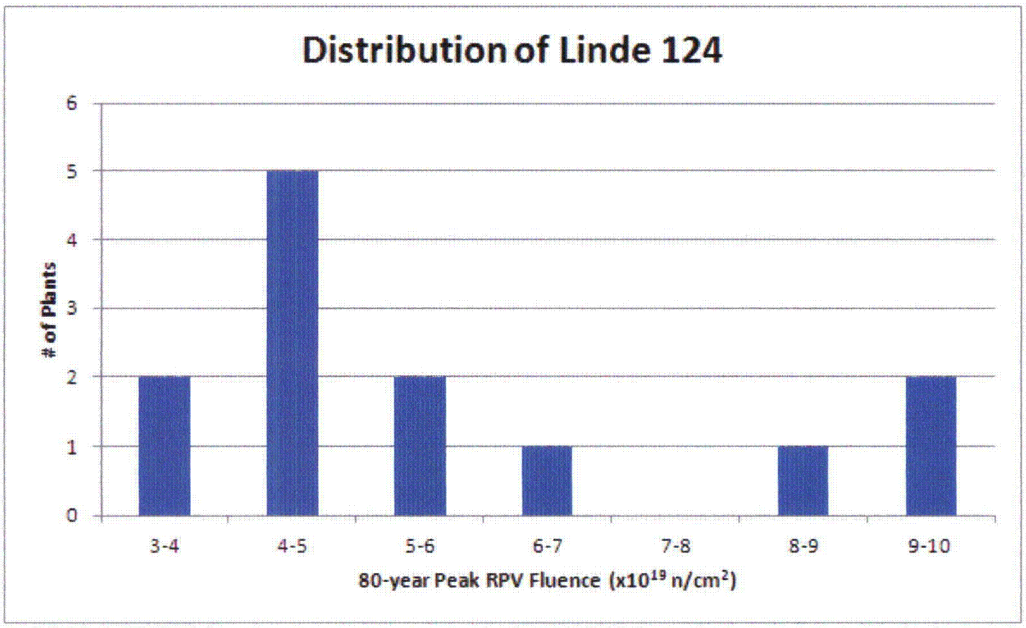


Figure 4-12
Distribution of 80-year peak RPV fluence for plants with vessels fabricated with Linde 124.

Linde 1092 Weld (all high copper)

Table 4-7 includes all plants that have already tested their 60-year capsule and have a reactor vessel fabricated with Linde 1092 weld metal. Note that Kewaunee, McGuire Unit 1 and Salem Unit 1 were not included in Table 4-7 for reasons given at the beginning of the "Optimization" section of this report.

The CRVSP recommended plan for capsules containing Linde 1092 is shown in Figure 4-13. The data in Figure 4-13 was compared to the distribution of the 80-year peak RPV fluence for all plants with reactor vessels fabricated with Linde 1092 weld metal, Figure 4-14.

Based on the definition of a "high fluence data gap" given above, a gap exists in the 7-8x10^{19} n/cm^2 fluence bin.

Capsule BV2-A was selected to fill the 7-8x10^{19} n/cm^2 fluence gap because it is the only available capsule in the necessary fluence range. Note that Linde 1092 weld metal in capsule A that is of interest to the CRVSP was previous irradiated in BV1-Y. The 9.1x10^{19} n/cm^2 fluence stated below refers to the BV1-Y material cumulative fluence at the time of capsule A withdrawal. Testing additional BV1 surveillance material is not required for the BV1 60-year license, but it could support a potential BV1 license renewal to 80 years.

Table 4-7
Remaining Capsules with Linde 1092

Plant-Capsule	Would Reinsertion Be Required?	Add External Dosimetry Required?	Potential Recommended Withdrawal Fluence (n/cm^2)	Potential Recommended Withdrawal Year	60-year Peak RPV Fluence (n/cm^2)	80-year Peak RPV Fluence (n/cm^2)
BV2-A	No	No	9.1x10^{19}	2021	5.2x10^{19}	6.9x10^{19}
DC2-Z	Yes	No	4.7x10^{19}	2025	2.3x10^{19}	3.1x10^{19}

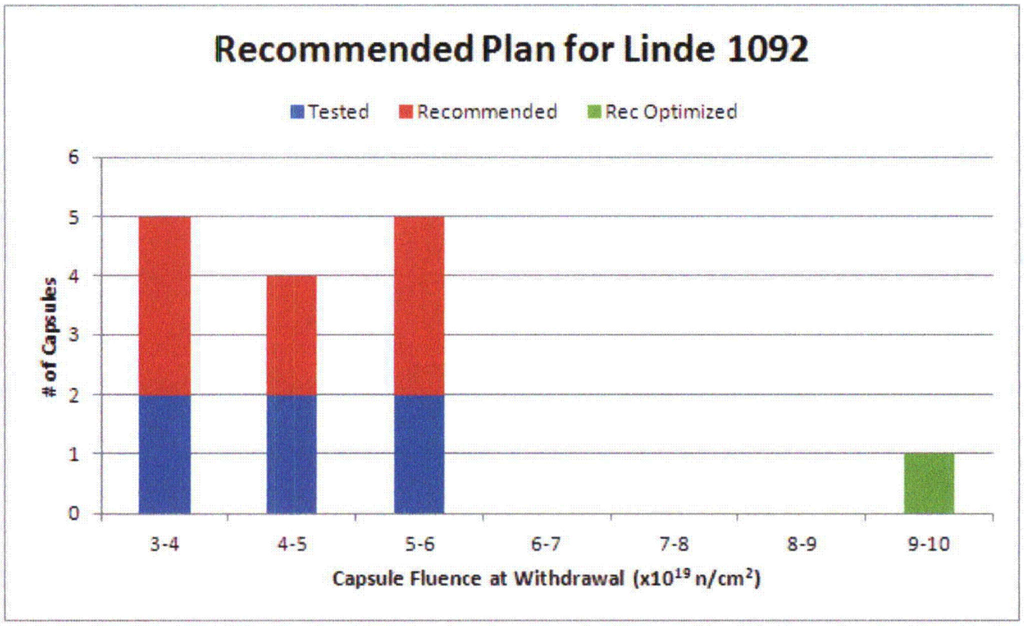


Figure 4-13
Recommended plan for capsules containing Linde 1092

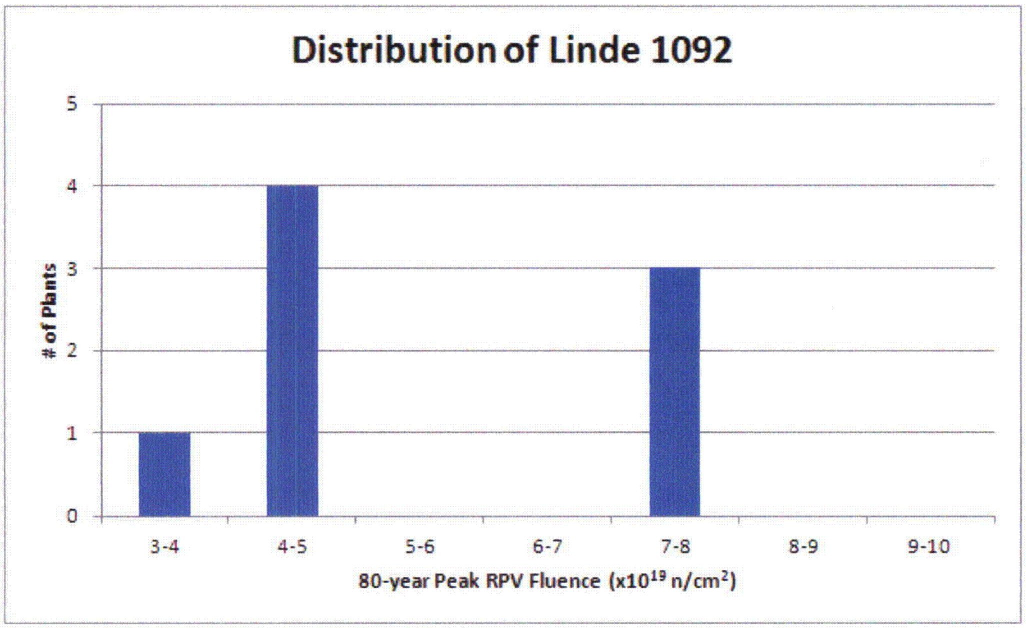


Figure 4-14
Distribution of 80-year peak RPV fluence for plants with vessels fabricated with Linde 1092.

Linde 80 (high copper)

Table 4-8 includes all plants that have already tested 60-year capsules and have a reactor vessel fabricated with Linde 80 weld metal containing copper greater than 0.10 wt%. Point Beach Units 1 and 2 are included even though they have not yet tested their 60-year capsules. This was done because both units are part of the B&W MIRVP Integrated Program and withdrawal of each unit's 60-year capsule cannot be modified without affecting other plants. Therefore, the remaining capsules at each plant were considered in the optimization process and treated as additional beyond the requirements of a 60-year license.

The CRVSP recommended plan for capsules containing high copper Linde 80 is shown in Figure 4-15. The data in Figure 4-15 was compared to the distribution of the 80-year peak RPV fluence for all plants with reactor vessels fabricated with high copper Linde 80 weld metal, Figure 4-16.

Based on the definition of a "high fluence data gap" given above, the CRVSP will remove all gaps for this material group without testing an optimization capsule.

Table 4-8
Remaining Capsules with Linde 80 High Copper

Plant-Capsule	Would Reinsertion Be Required?	Add External Dosimetry Required?	Potential Recommended Withdrawal Fluence (n/cm^2)	Potential Recommended Withdrawal Year	60-year Peak RPV Fluence (n/cm^2)	80-year Peak RPV Fluence (n/cm^2)
Ginna-P	No	Yes	9.1×10^{19}	2025	5.7×10^{19}	7.6×10^{19}
PB1-N	No	Yes	7.1×10^{19}	2016	5.1×10^{19}	6.9×10^{19}
PB2-N	No	Yes	8.6×10^{19}	2025	5.1×10^{19}	6.9×10^{19}

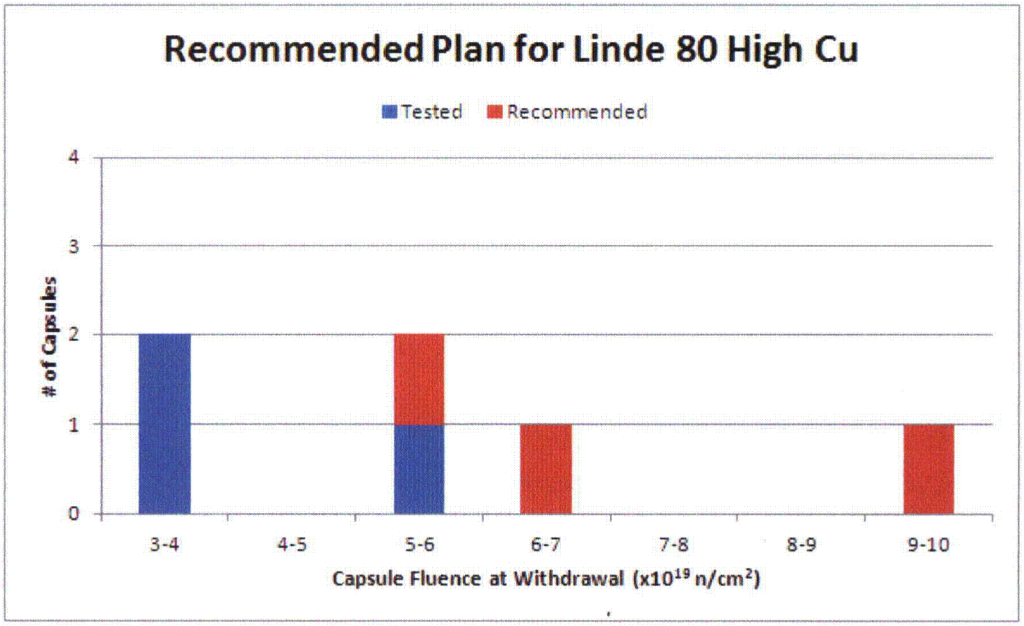


Figure 4-15
Recommended plan for capsules containing Linde 80 with high copper

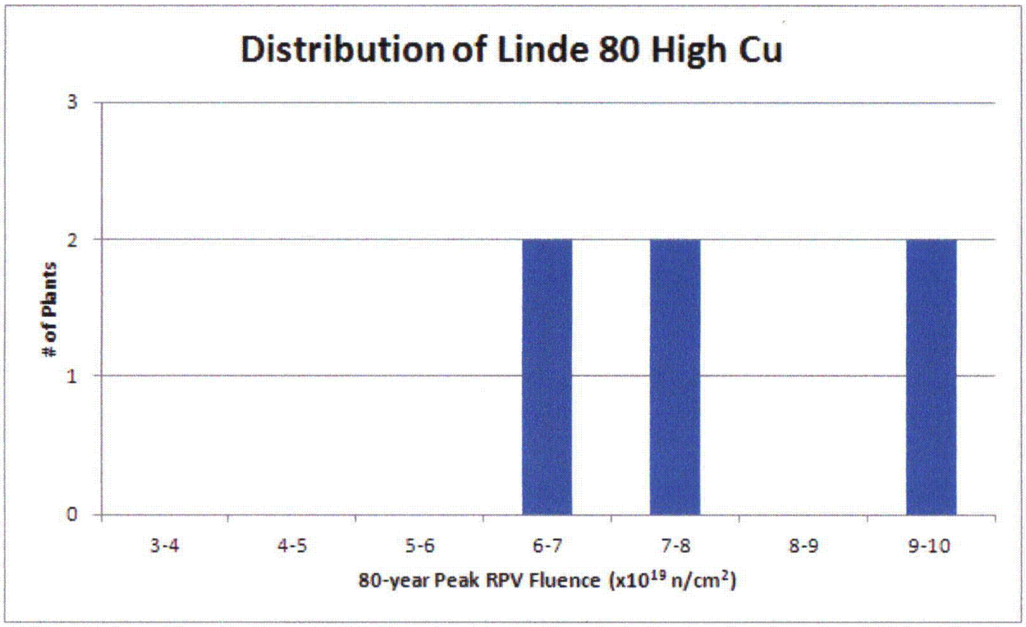


Figure 4-16
Distribution of 80-year peak RPV fluence for plants with vessels fabricated with Linde 80 with high copper

Embrittlement Trend Curves

The three embrittlement trend curves (ETCs) of interest are from Regulatory Guide 1.99 Revision 2 [1] (the current requirement), 10 CFR 50.61a [2] (the likely basis for Regulatory Guide 1.99 Revision 3 currently being developed) and an ETC partially based on test reactor data [11], which is indicative of the type of correlation that could become the basis for a future Revision 4 of Regulatory Guide 1.99 if high fluence commercial LWR data is not obtained. The important variables are those that most affect the transition temperature shift (TTS) at high fluence (Cu, Ni, P, Mn, irradiation temperature, neutron flux, product form and manufacturer).

A comparison of the three ETCs was performed for the materials contained in the capsules recommended for testing (i.e., BV2-A and BV2-Y). The purpose of this comparison was to confirm that there is a sufficient divergence between the ETCs at the recommended capsule withdrawal fluence to facilitate determination of the applicability of the test reactor data to power reactors.

The comparisons of ETCs for the weld metal in BV2-A from BV1-Y and the base metal and the weld metal contained in capsule BV2-Y are shown in Figure 4-17 and Figure 4-18, respectively. At the recommended capsule withdrawal fluences, the divergence in TTS between the Regulatory Guide 1.99 Revision 2 and the test reactor based ETCs are approximately 30°F for BV2-A and 80°F for the base metal and 25°F for the weld metal in BV2-Y. These divergences are sufficient for the stated goal.

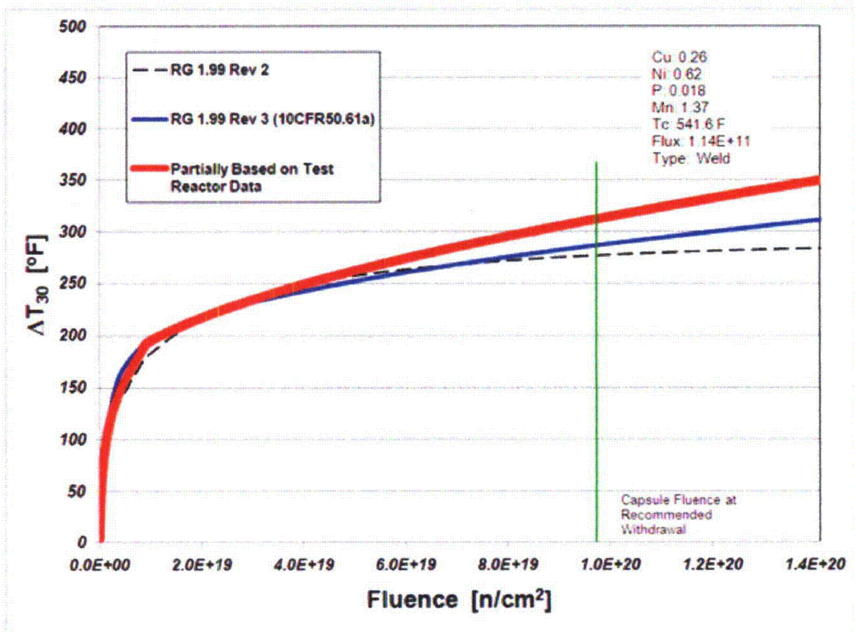
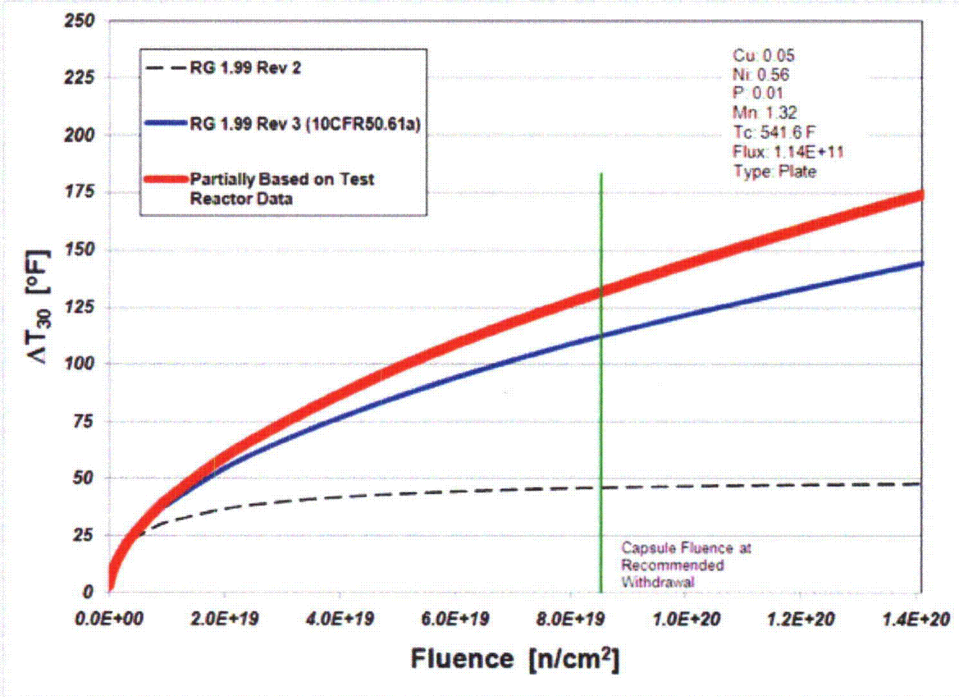


Figure 4-17
ETC comparisons for Beaver Valley Unit 2 capsule A Linde 1092 material from BV1-Y



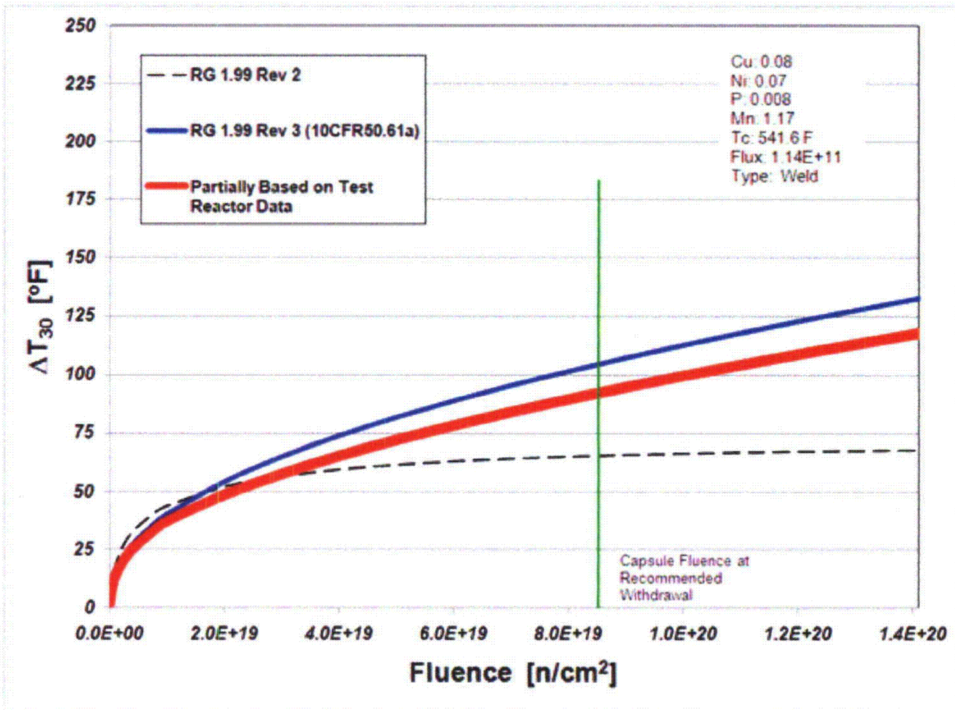


Figure 4-18
ETC comparisons for Beaver Valley Unit 2 capsule Y materials low copper SA-533 (top) and low copper Linde 91 (bottom).

Optimization Results

In summary, the BV2-A and BV2-Y capsules were selected to be tested beyond the 60-year license requirements, as shown in Table 4-9. These capsules were selected based on the evaluation of high fluence data gaps and the ETC comparison. Testing the BV1-Y Linde 1092 weld metal in capsule BV2-A is not required for the BV1 60-year license, but it could support a potential license extension to 80 years. Regarding either capsule, the CRVSP's recommendation to test these post-60 year capsules at BV2 does not cause any additional burden on the plant owner in this case; the plant informed the CRVSP team that testing of these two capsules is planned in order to achieve plant-specific objectives.

Table 4-9
Recommended Capsules to be Tested Beyond 60-year License Requirements

Plant-Capsule	Base Metal	Weld Metal	Withdrawal Fluence (E+19 n/cm^2)	High Fluence Data Gap Figures	Capsule Material ETC Figures
BV2-A	N/A	Linde 1092 from BV1-Y	9.72	Figure 4-13	Figure 4-17
BV2-Y	SA-533 low Cu	Linde 91 low Cu	8.5	Figure 4-1 Figure 4-9	Figure 4-18

Section 5: Results

Data Summary

The CRVSP recommends the following changes to plant specific RVSPs at the 69 U.S. PWRs:

- 54 units: no recommended changes
- 11 units: defer a scheduled capsule withdrawal
- 1 unit: test additional capsules beyond the 60-year commitments, and
- 3 units: test a capsule earlier than currently planned.

The actions described above will entail changes to existing surveillance capsule withdrawal schedules at 15 of the 69 U.S. PWRs.

In some cases the CRVSP recommends testing a different capsule than planned and at a sooner date. At these plants, the current plant specific RVSPs planned to remove a test a capsule while another capsule was available with a higher lead factor. It was recommended that the high lead factor capsule be tested in place of the planned capsule in order to obtain high fluence data expeditiously.

The final type of change is the recommendation that one plant test additional capsules (BV2-Y and BV2-A) after the 60-year capsule has been tested. This recommendation was based on the criteria discussed in Section 4. Testing capsule BV2-Y would normally present an extra cost burden to a plant, in this case the plant's current RVSP already plans to test this capsule. Also, testing of the recommended capsule will be of direct benefit to the plant for obtaining a future license extension to 80 years. The testing of capsule BV2-A is recommended to fill high fluence data gaps for the CRVSP; it can also be used to support potential license extension to 80 years for Beaver Valley Unit 1.

From the 69 PWR plants evaluated, approximately 250 capsules have been removed and tested (see Appendix A, Table A-1). Thirty-five of the tested capsules were high fluence ($>3.0 \times 10^{19}$ n/cm^2) but only nine had a fluence greater than 5.0×10^{19} n/cm^2. By the year 2025, the current RVSP schedules will test 26 more high fluence ($>3.0 \times 10^{19}$ n/cm^2) capsules (Table A-2). Of these 26 planned capsules, only one will have a fluence of 8.0×10^{19} n/cm^2 or greater.

By contrast, the recommended CRVSP provided in this document will test 30 more high fluence (>$3.0x10^{19}$ n/cm^2) capsules by 2025 than have been tested to date (Table A-3). Of these, five will have a fluence ≥$8.0x10^{19}$ n/cm^2, compared to only one that would be tested with the current plan. The additional capsules to be tested from now to 2025 for the existing programs compared to the CRVSP are summarized in Table 5-1.

Table 5-1
Additional Capsules to Be Tested by 2025

Fluence (n/cm^2)	Current Plan	Recommended Plan
≥ $3.0x10^{19}$	26	30
≥ $6.0x10^{19}$	6	11
≥ $8.0x10^{19}$	1	5
≥ $9.0x10^{19}$	0	3

Figure 5-1 shows the distribution of capsules (total number of capsules at each discreet fluence level above $3x10^{19}$ n/cm^2) that would be tested by 2025 under the current RVSPs (top half of figure) versus the distribution achieved through the same period by the CRVSP (bottom figure). The CRVSP will effectively shift remaining capsule tests to higher fluences.

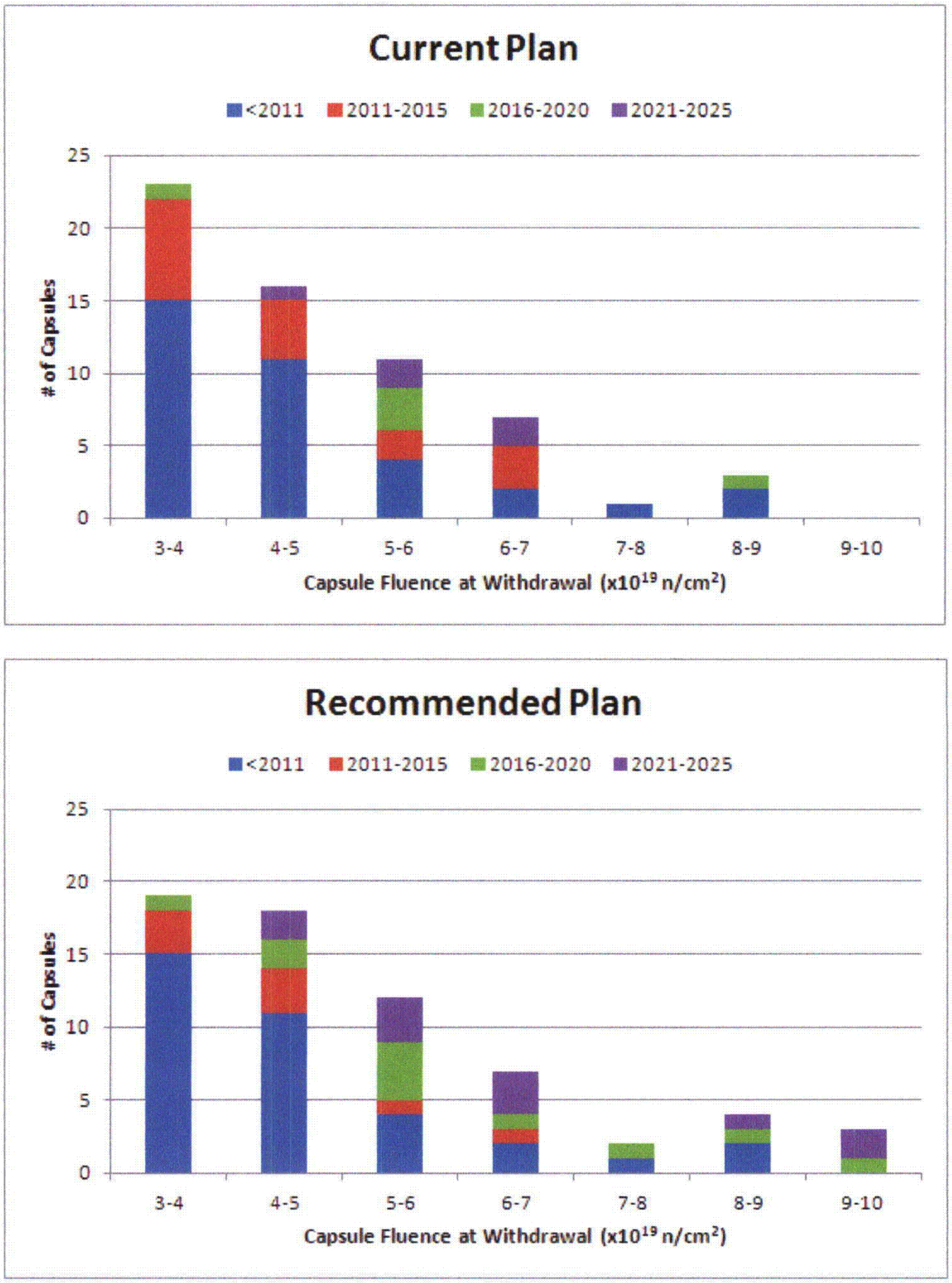


Figure 5-1
Comparison of Existing RVSP Capsule Tests >$3x10^{19}$ n/cm^2 Through 2025 (top) to Capsule Tests by CRVSP (bottom)

Another key objective of the CRVSP is to obtain data for the full range of PWR reactor vessel beltline materials. As noted previously, obtaining data on a full range of materials is key to establishing a sound basis for updating the power reactor data-based correlations. Embrittlement may differ by material type – that is, a high fluence embrittlement mechanism may be unique to a single weld or base metal type – so it is important to characterize embrittlement for all materials to provide assurance for the accuracy of embrittlement predictions.

In order to accomplish this second objective, the data from Figure 5-1 were grouped based on product form, weld flux type and Cu content to identify the gaps in high fluence Charpy V-notch data. This facilitated assessment of how well each material category is represented by high fluence data. For each material grouping, Figures 5-2 through 5-14 compare the results of the current RVSP capsule test schedules (in terms of number of capsules tested at discreet fluence levels, through 2025) to the corresponding results achieved by the CRVSP.

For plates, the groupings are as follows:

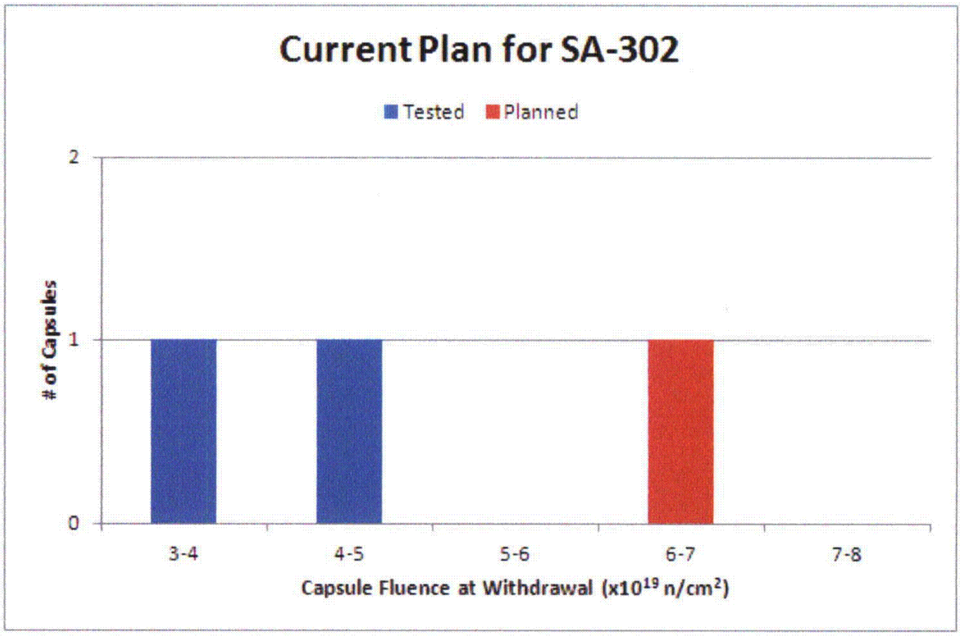
- SA-302 Grade B, Figure 5-2 (all contain more than 0.10 wt% Cu),
- SA-533 Grade B Class 1 and SA-302 Grade B Modified containing more than 0.10 wt% Cu, Figure 5-3,
- SA-533 Grade B Class 1 containing less than or equal to 0.10 wt% Cu, Figure 5-4.

For forgings, the groupings are as follows:

- SA-508 Class 2 and Class 3 containing less than or equal to 0.10 wt% Cu, Figure 5-5,
- SA-508 Class 2 and Class 3 containing more than 0.10 wt% Cu, Figure 5-6.

For welds, the groupings are as follows:

- Linde 80 with more than 0.10 wt% Cu, Figure 5-7,
- Linde 80 containing less than or equal to 0.10 wt% Cu, Figure 5-8,
- Linde 1092 (all contain more than 0.10 wt% Cu), Figure 5-9,
- Linde 91 with more than 0.10 wt% Cu, Figure 5-10,
- Linde 91 containing less than or equal to 0.10 wt% Cu, Figure 5-11,
- Linde 0124, Figure 5-12 (all contain less than 0.10 wt% Cu),
- SMIT 89 and UM 89, Figure 5-13,
- Grau Lo LW320, Figure 5-14.



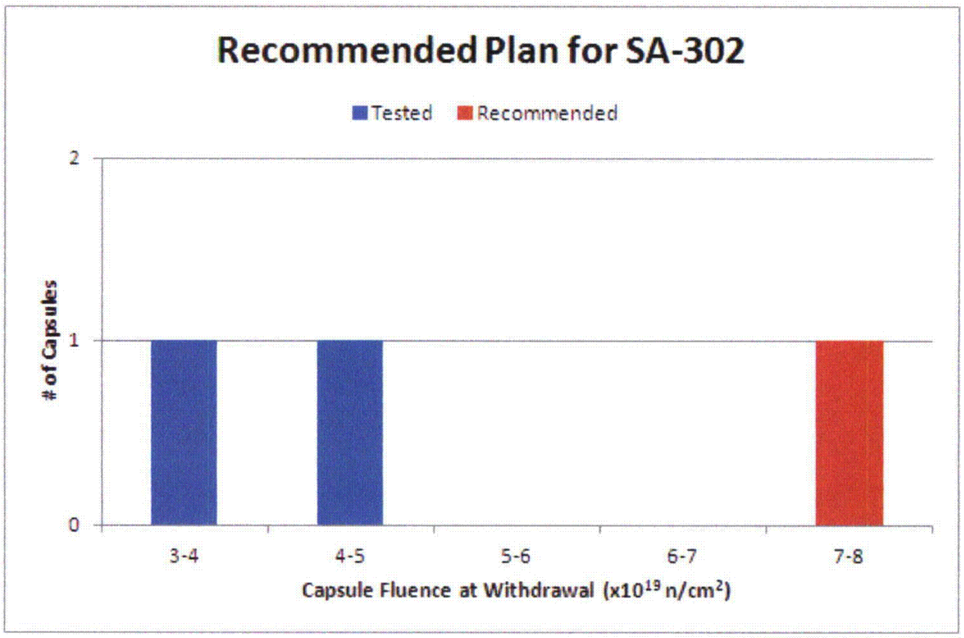
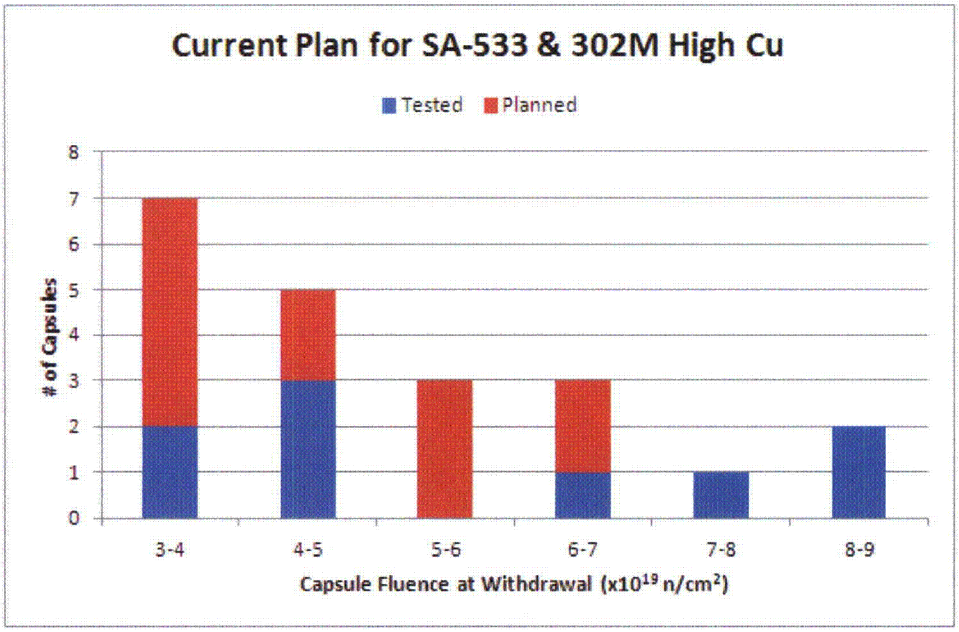


Figure 5-2
High Fluence Data Distribution for SA-302 Grade B Plates (all Cu > 0.10 wt%).



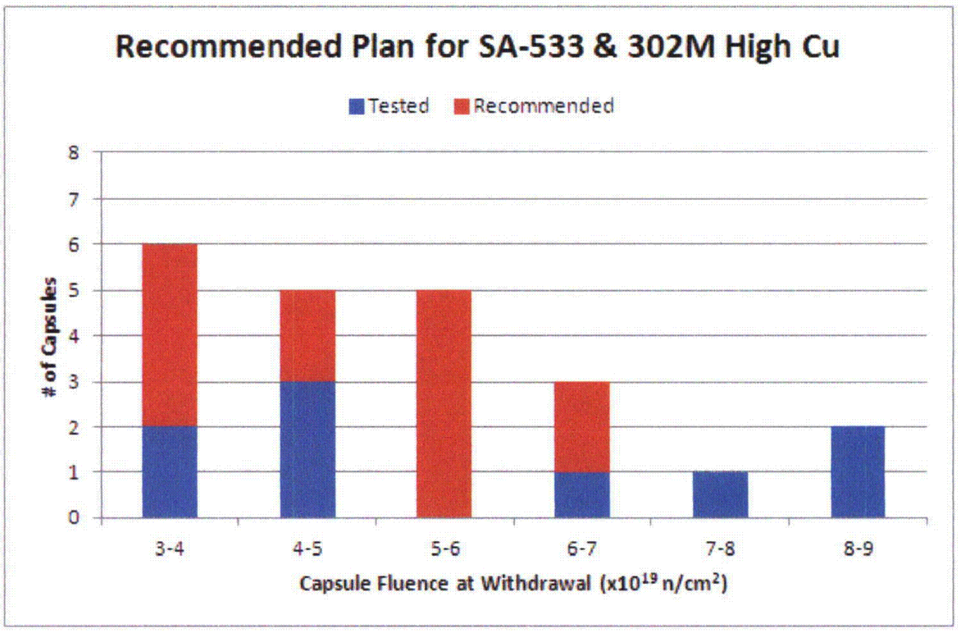
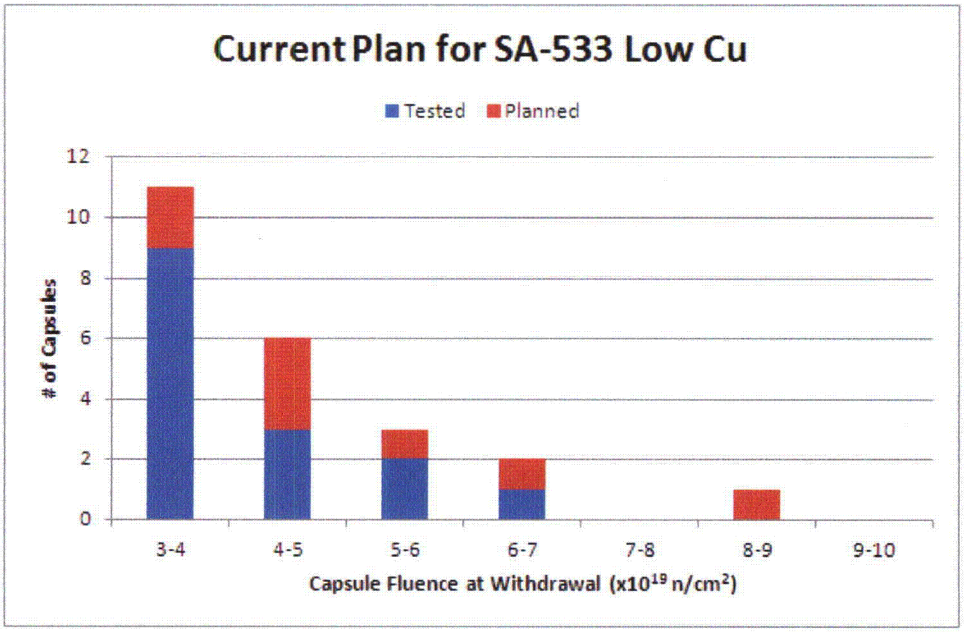


Figure 5-3
High Fluence Data Distribution for SA-533 Grade B Class 1 and SA-302 Grade B Modified Plates with Cu > 0.10 wt%.



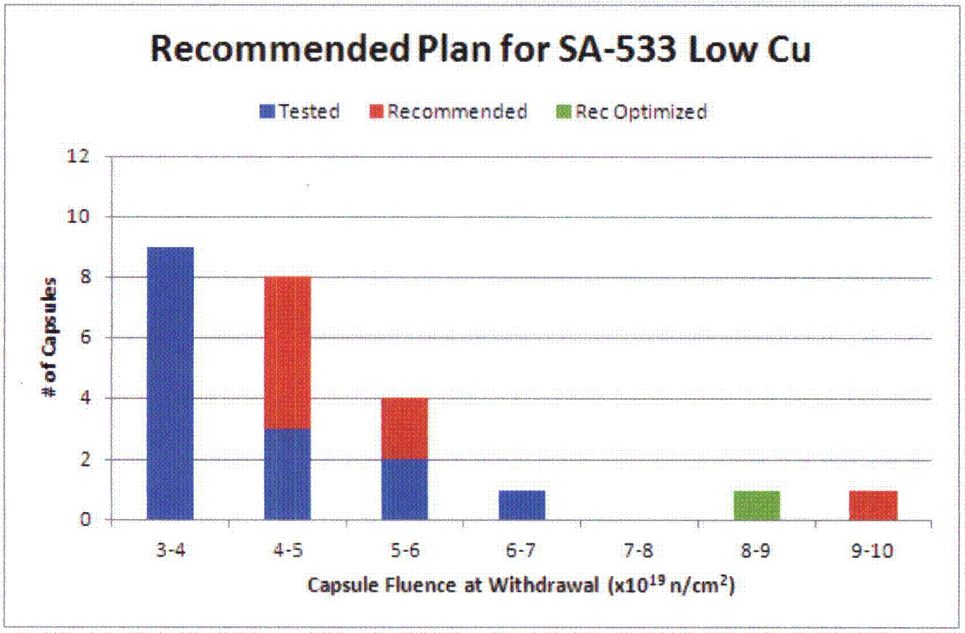
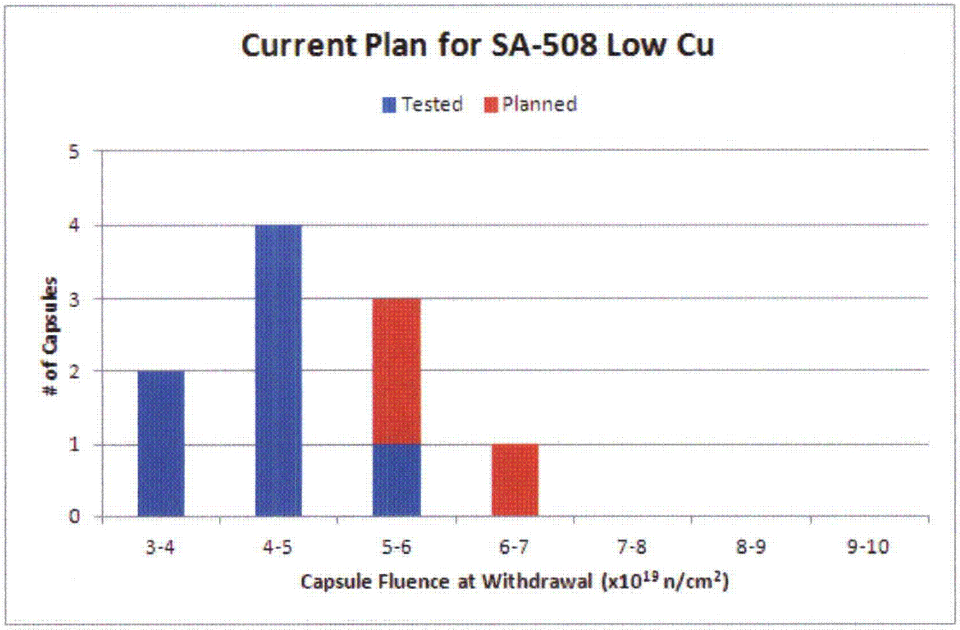


Figure 5-4
High Fluence Data Distribution for SA-533 Grade B Class 1 Plates with Cu $\leq$ 0.10 wt%.



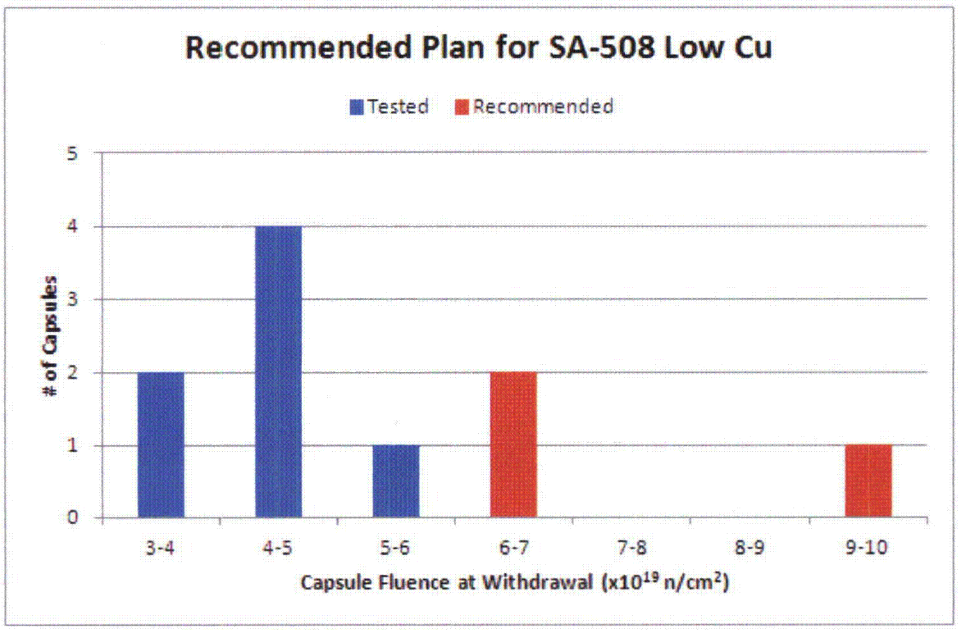
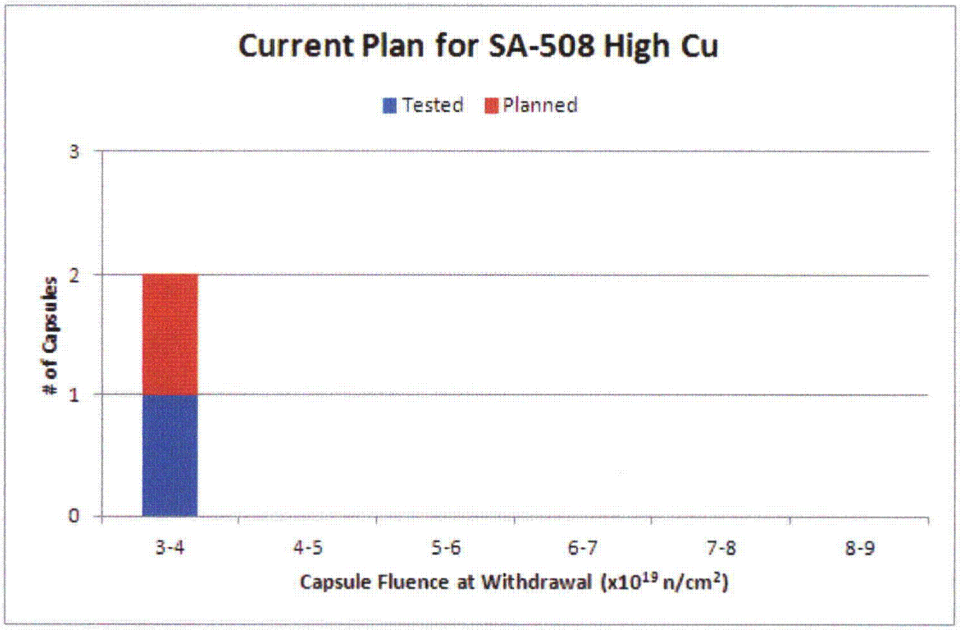


Figure 5-5
High Fluence Data Distribution for SA-508 Class 2 and Class 3 Forgings with Cu ≤ 0.10 wt%.



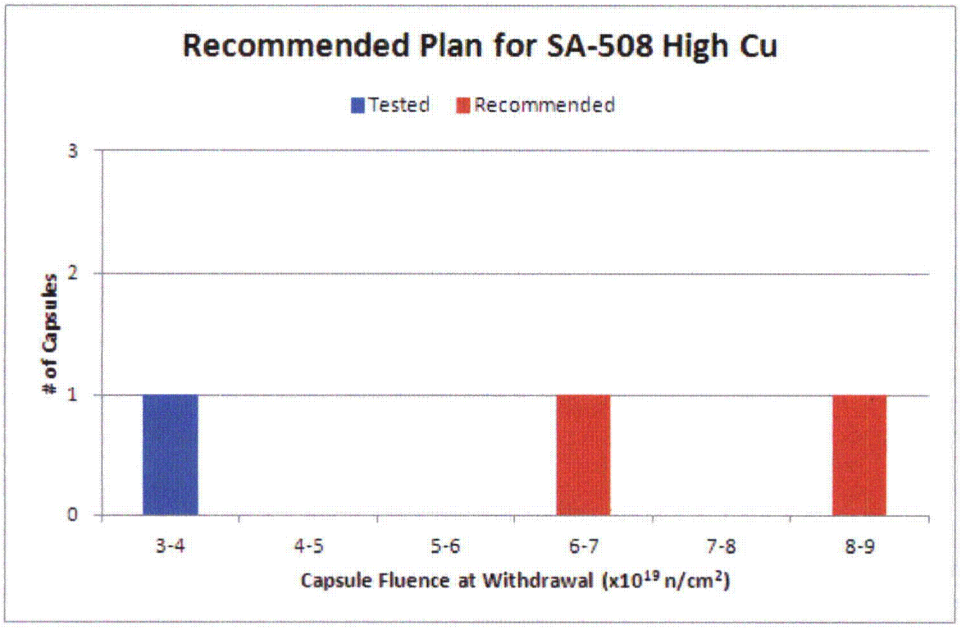


Figure 5-6
High Fluence Data Distribution for SA-508 Class 2 and Class 3 Forgings with Cu > 0.10 wt%

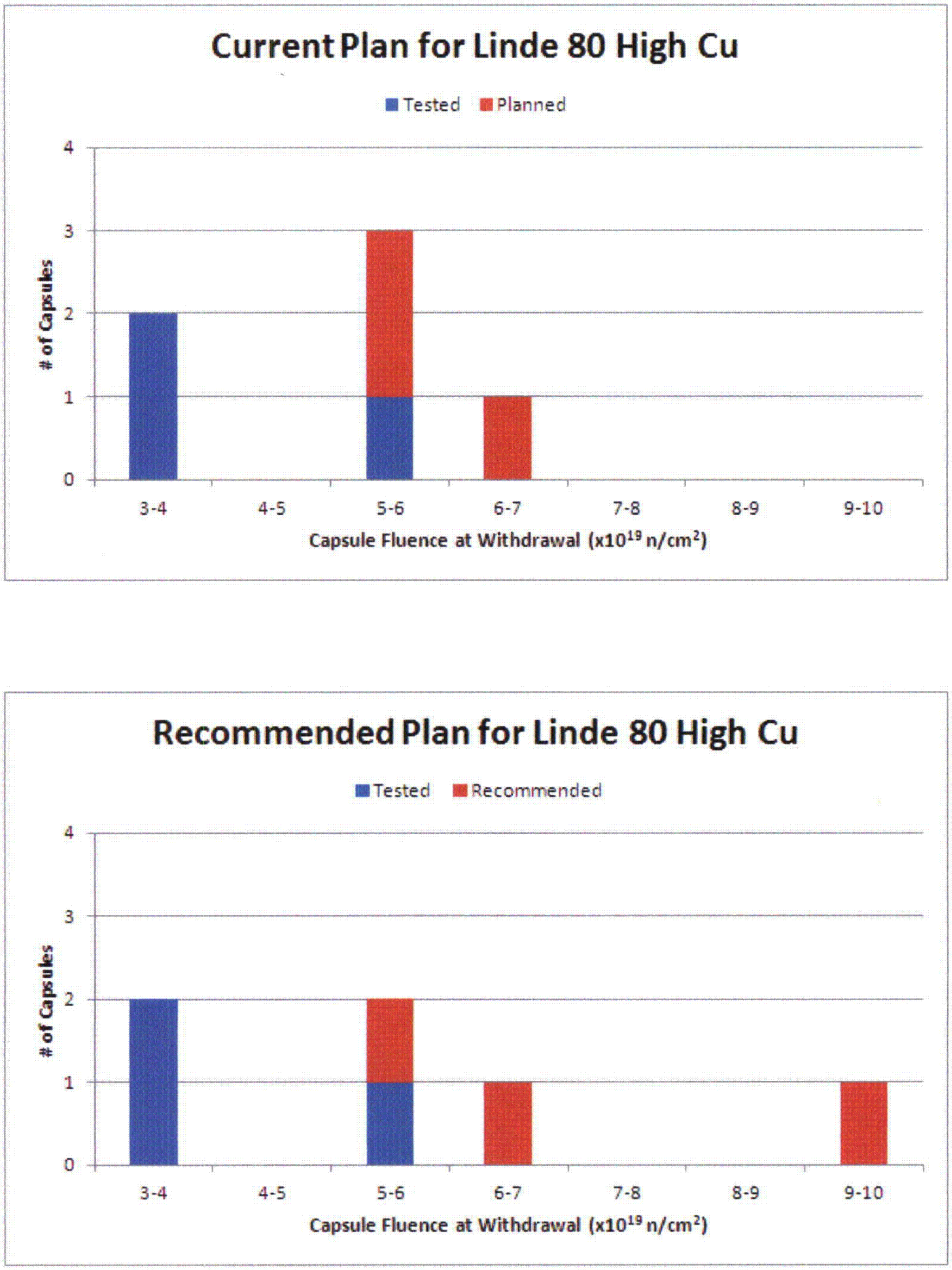
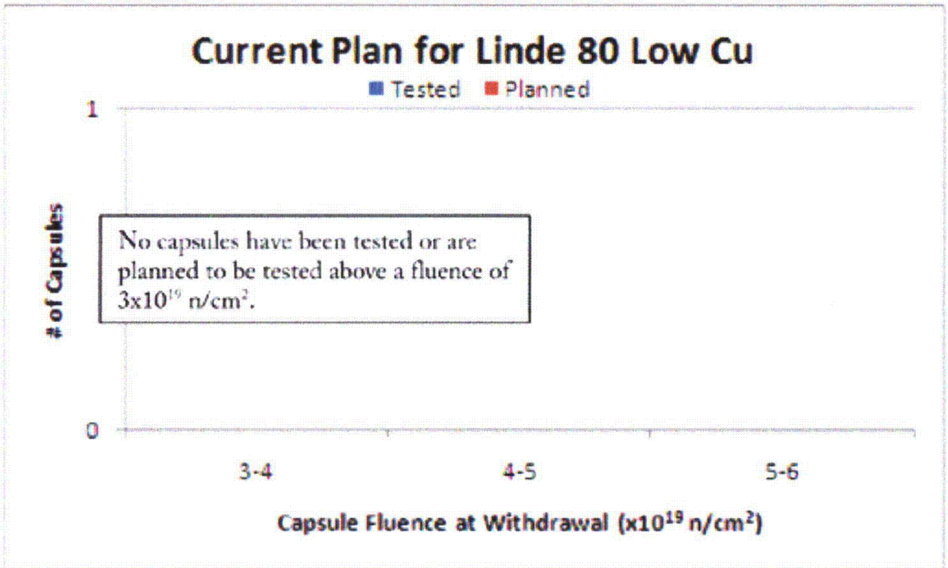


Figure 5-7
High Fluence Data Distribution for Linde 80 Welds with Cu > 0.10 wt%.



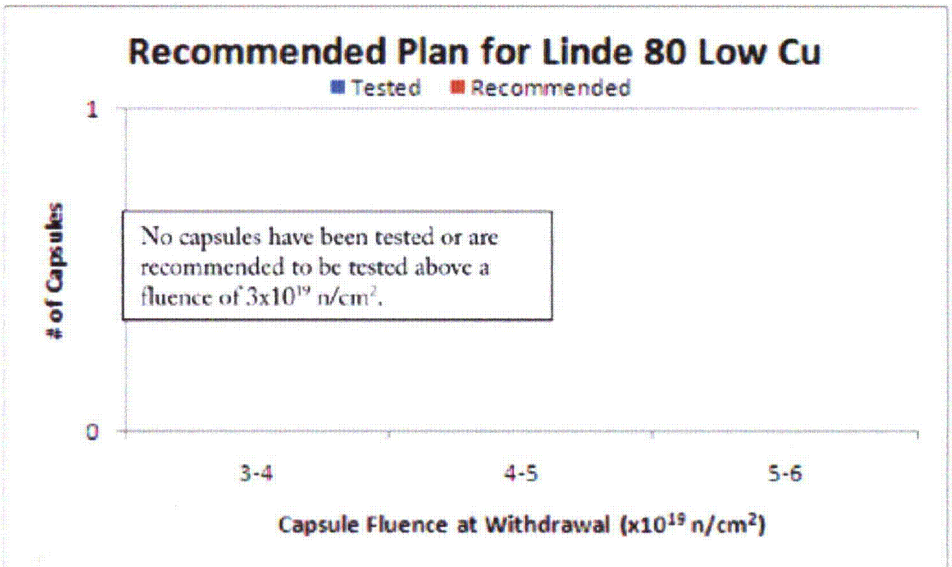


Figure 5-8
High Fluence Data Distribution for Linde 80 Welds with Cu < 0.10 wt%.

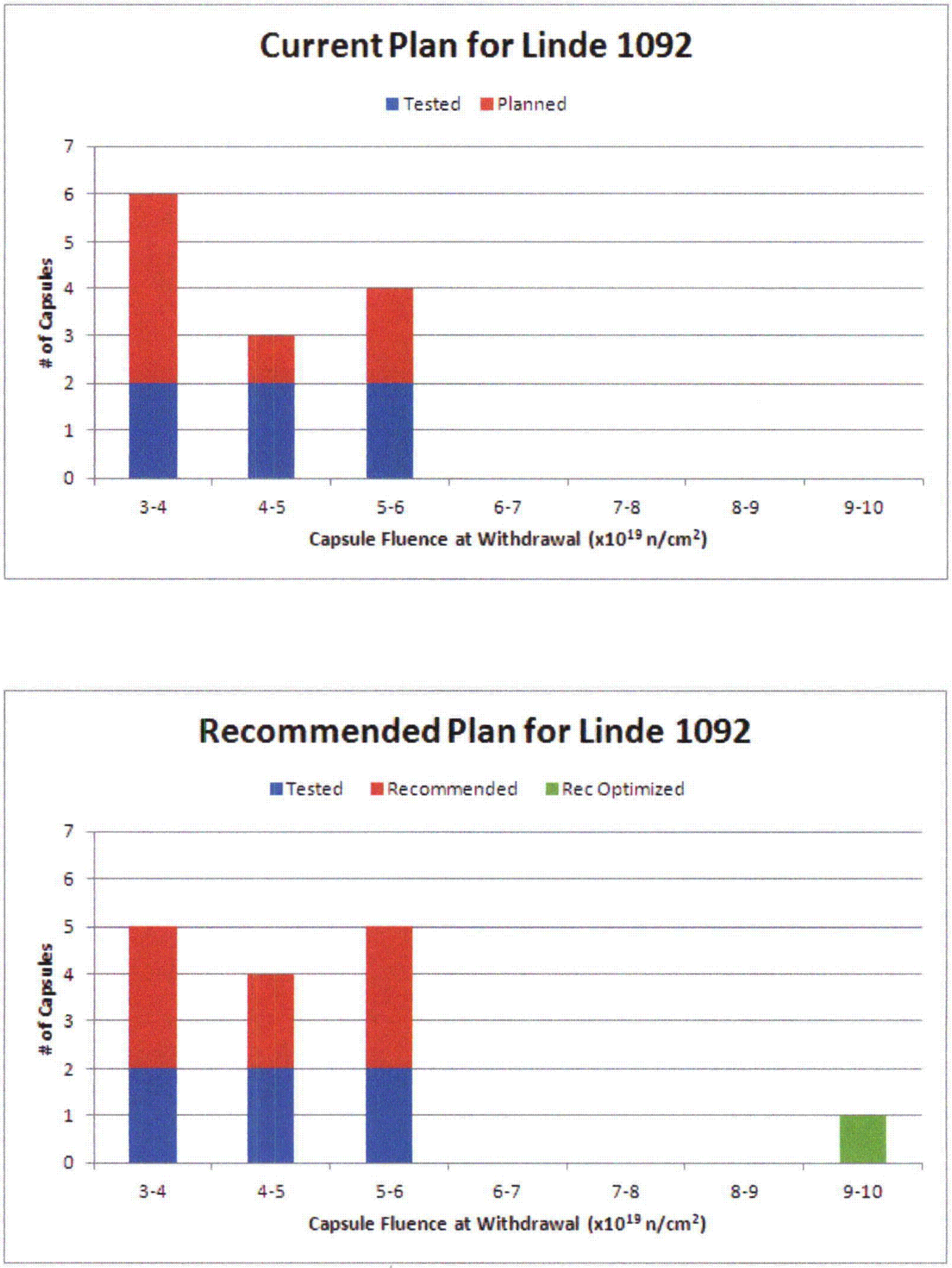
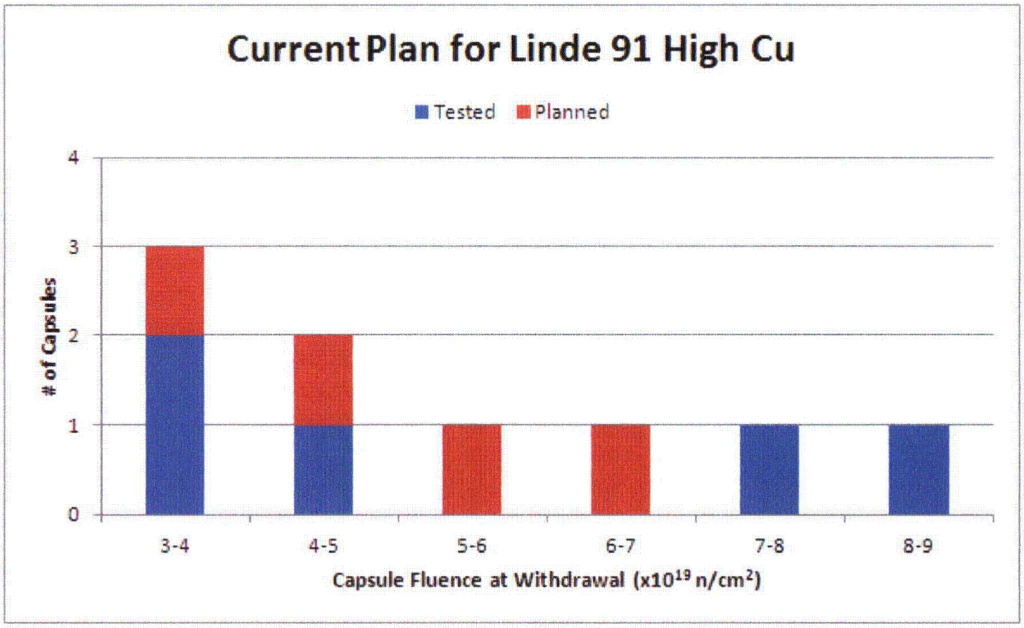


Figure 5-9
High Fluence Data Distribution for Linde 1092 Welds (all Cu > 0.10 wt%).



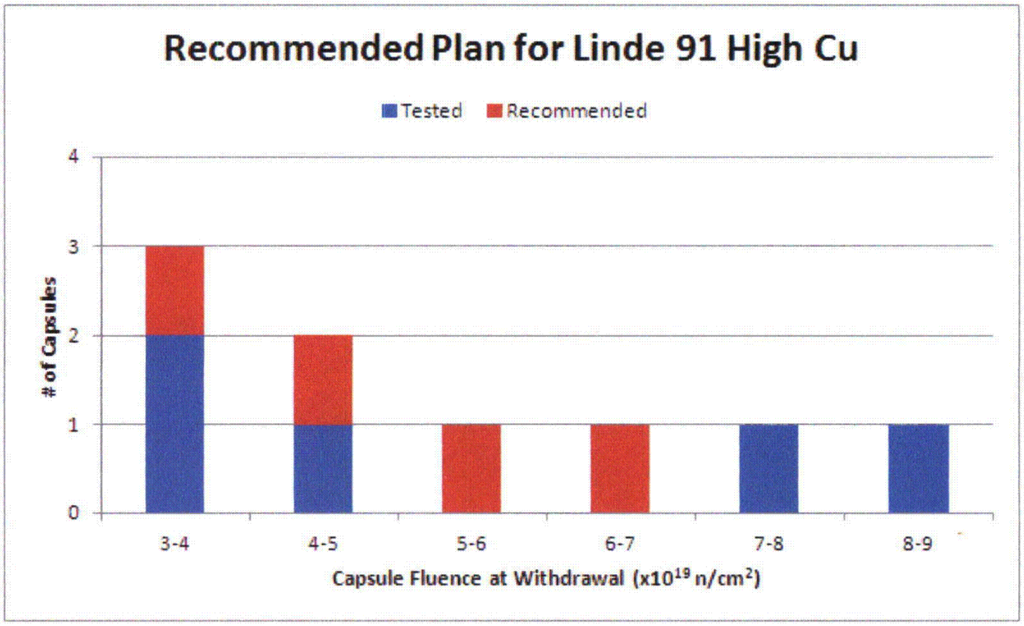
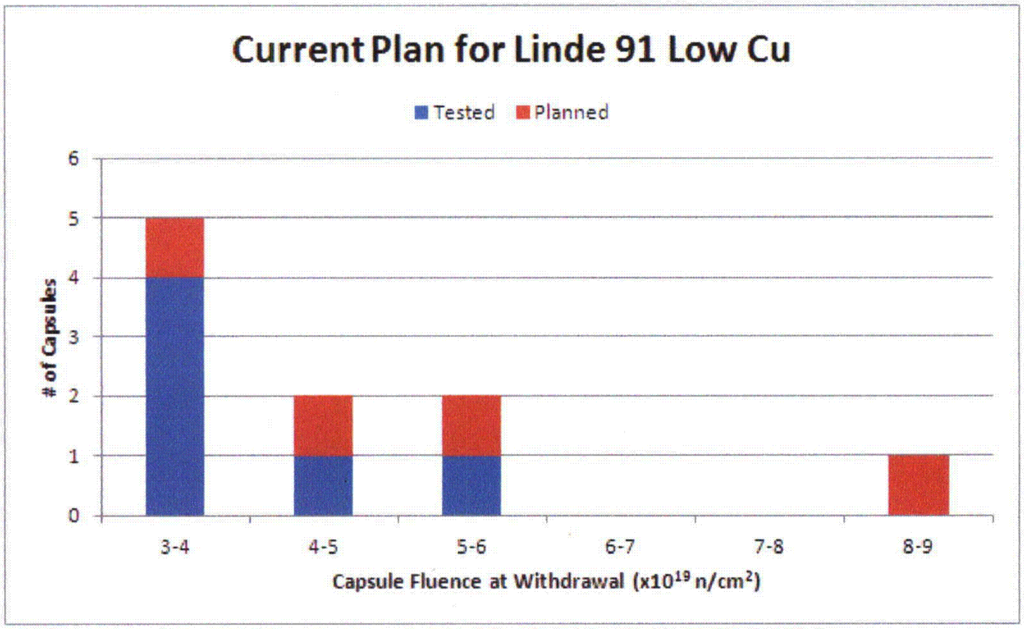


Figure 5-10
High Fluence Data Distribution for Linde 91 Welds with Cu > 0.10 wt%.



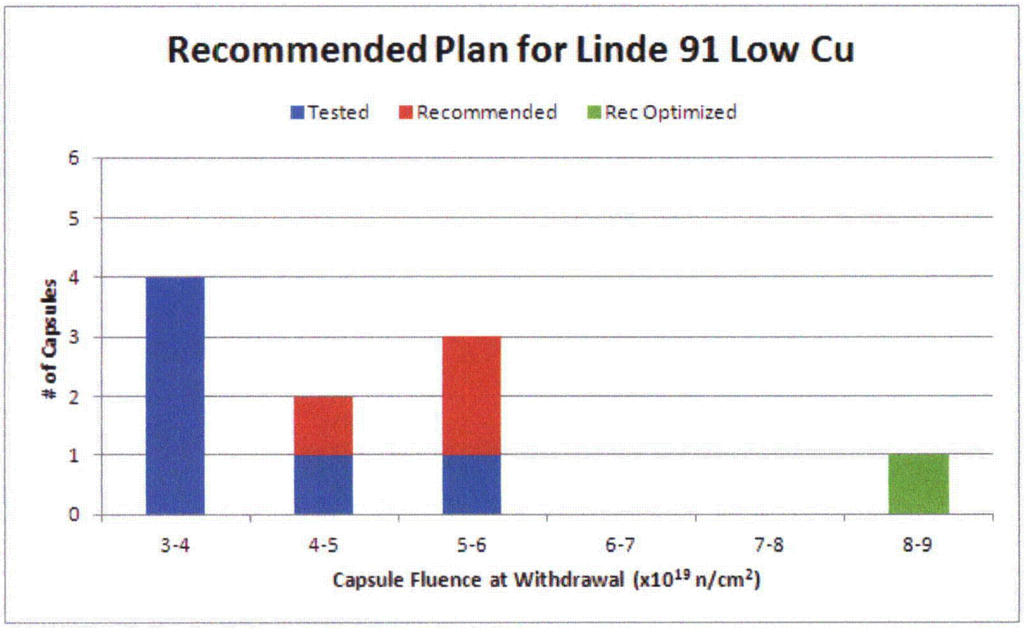
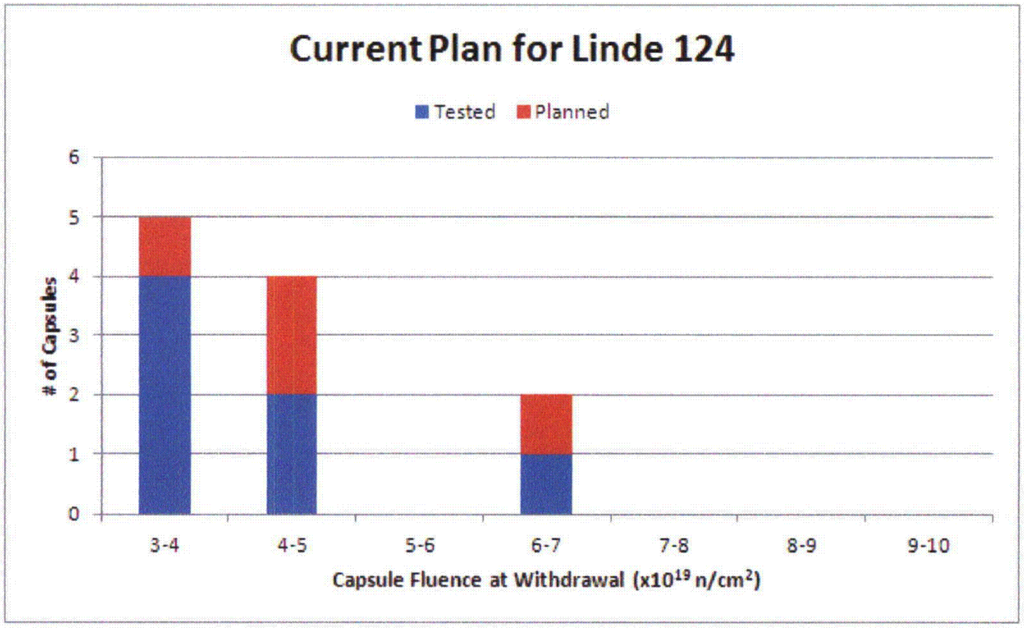


Figure 5-11
High Fluence Data Distribution for Linde 91 Welds with Cu < 0.10 wt%.



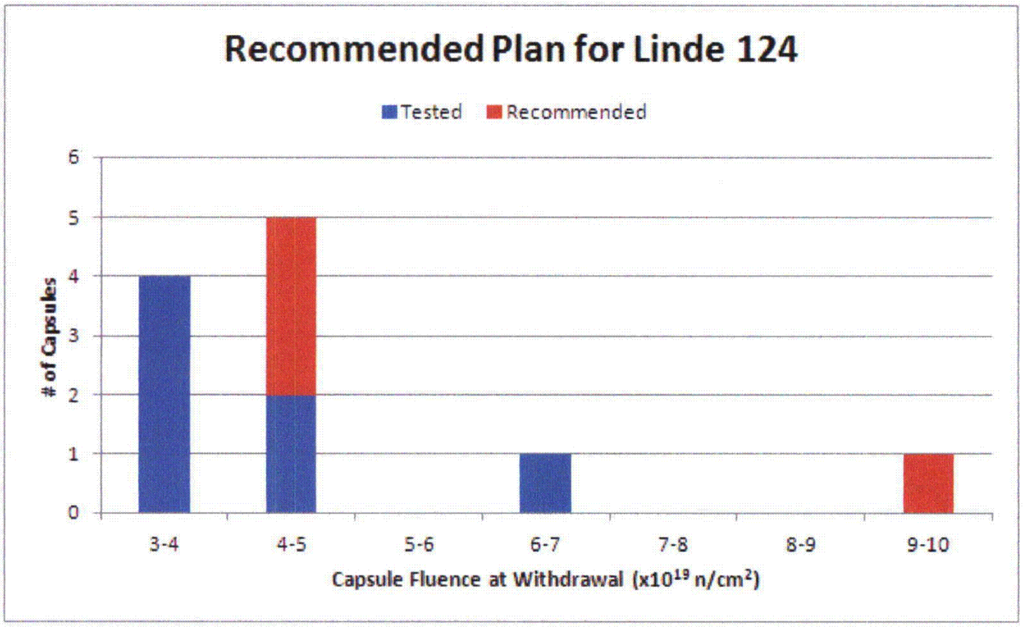
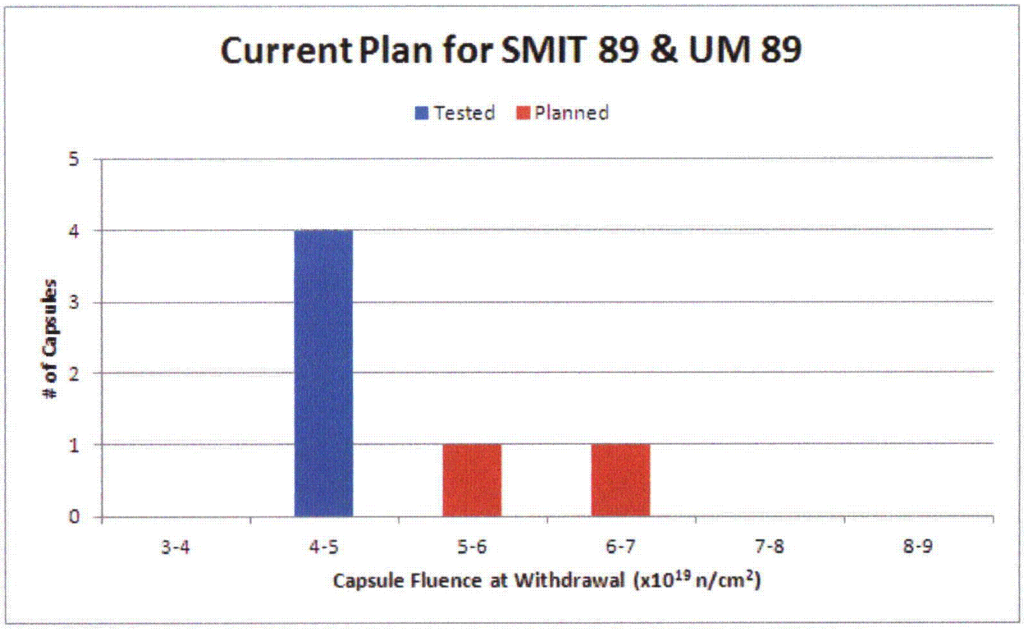


Figure 5-12
High Fluence Data Distribution for Linde 124 Welds (all Cu < 0.10 wt%).



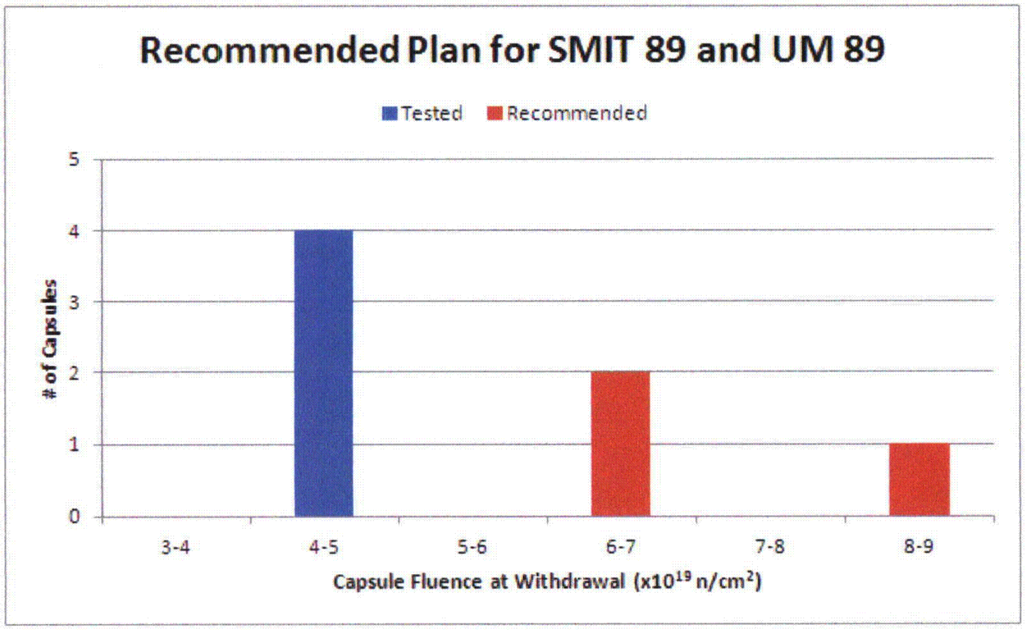
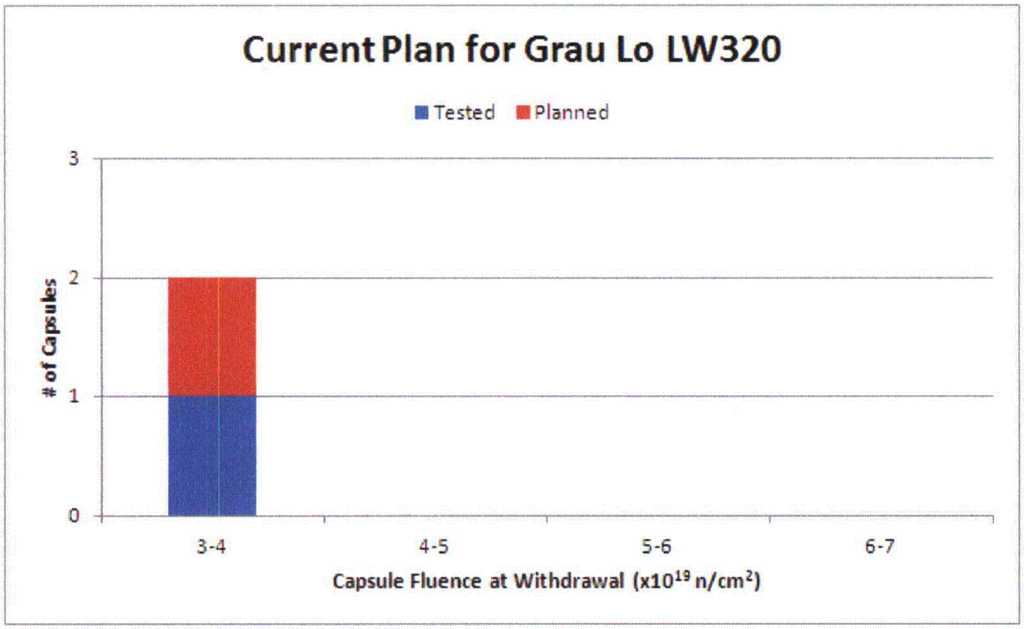


Figure 5-13
High Fluence Data Distribution for SMIT 89 and UM 89 Welds.



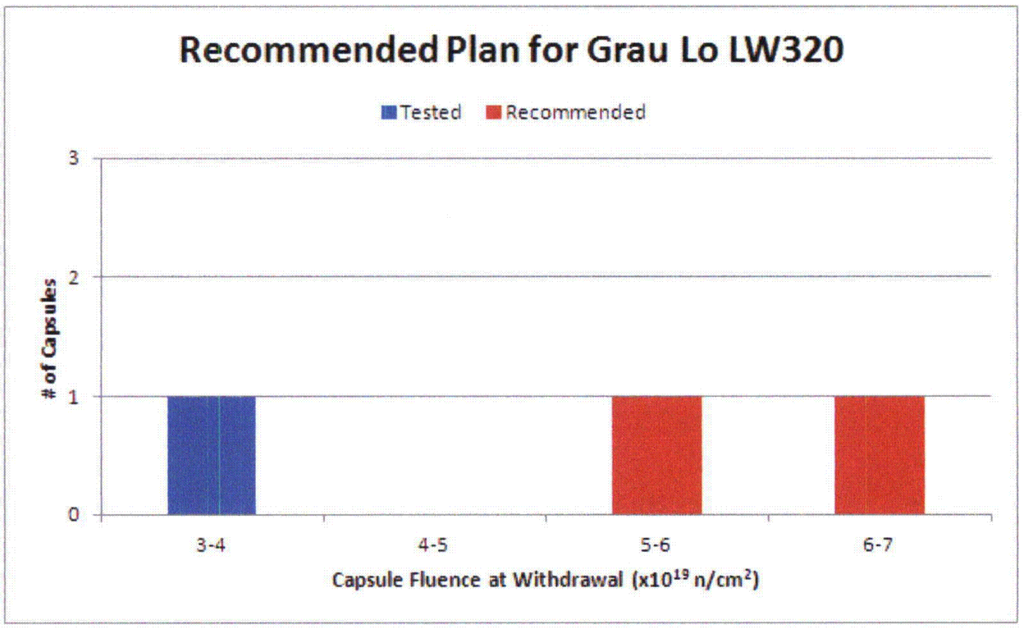


Figure 5-14
High Fluence Data Distribution for Grau Lo LW320 Welds.

Discussion

It is noted in Figure 5-8 that no capsules >3x10^{19} n/cm^2 in the "Linde 80 Low Cu" material category are recommended for testing. No recommendation was included in the CRVSP for the following reason: The Linde 80 flux weld (low Cu) is unique to Braidwood Units 1 and 2 and Byron Units 1 and 2. None of these plants have applied for the first license renewal (although future application is planned). Once these plants are granted a renewed license, the plant(s) will be required to test a high fluence capsule as a condition of the renewed license. Therefore, there was no need for the CRVSP to recommend testing in this unique material category; no need exists until one of these plants receives a renewed license, after which the gap will be resolved by the requirement to test a license renewal capsule. Eleven of the 12 remaining (available) capsules at those four plants are estimated to have fluence >3x10^{19} n/cm^2 (E> 1.0MeV).

Conclusions

The recommended coordinated U.S. PWR RVSP management plan will significantly add to the quantity and quality of high fluence surveillance data by the year 2025 by adding approximately 30 base metal and weld metal data points to the database. The addition of this substantial high fluence PWR transition temperature shift data will assist in the development of embrittlement trend curves based on PWR data for use in 60 and 80 year RPV evaluations rather than reliance on test reactor data which may not be representative of PWR embrittlement trends. The CRVSP will also produce the PWR surveillance transition temperature shift data necessary to address concerns of irradiation damage of reactor vessel materials for extended license renewal.

The CRVSP will not fill all high fluence data gaps by 2025. Recall that these gaps were determined by taking the high fluence data that will be obtained by the CRVSP by 2025 and comparing it to the projected 80-year peak RPV fluence for each plant in that material group. Two gaps will remain after the CRVSP.

The first gap is between 9-10x10^{19} n/cm^2 for Linde 91 (low Cu) weld metal. This gap is due to San Onofre Unit 2. The CRVSP will not provide data at a similar fluence level to the projected 80-year license fluence at San Onofre Unit 2 by 2025. However, the data will bound the fluence range of the projected 60-year peak RPV fluence at San Onofre Unit 2. Since San Onofre Unit 2 will not reach 60 years until around 2040, this 80-year high fluence data gap is not of immediate concern.

The second gap is between 7-9x10^{19} n/cm^2 for Grau Lo LW320 weld metal. This gap is due to Surry Unit 2 and North Anna Unit 2, both of which have projected 80-year peak RPV fluences between 7-9x10^{19} n/cm^2. North Anna Unit 2 currently plans to test a capsule with approximate fluence of 8.3x10^{19} n/cm^2 in 2029. Based on the definition of a high fluence data gap, the testing of this capsule in 2029 will fill both the 7-8 and 8-9x10^{19} n/cm^2 gaps.