Reactor Pressure Vessel Embrittlement Management Through EPRI-Developed Material Property Databases

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ABSTRACT. Uncertainties and variability in U.S. reactor pressure vessel (RPV) material properties have caused the U.S. Nuclear Regulatory Commission (NRC) to request information from all nuclear utilities in order to assess the impact of these data scatter and uncertainties on compliance with existing regulatory criteria. Resolving the vessel material uncertainty issues requires compiling all available data into a single integrated database to develop a better understanding of irradiated material property behavior. EPRI has developed two comprehensive databases for utility implementation to compile and evaluate available material property and surveillance data. RPVDATA is a comprehensive reactor vessel materials database and data management program that combines data from many different sources into one common database. Searches of the data can be easily performed to identify plants with similar materials, sort through measured test results, compare the “best-estimates” for reported chemistries with licensing basis values, quantify variability in measured weld qualification and test data, identify relevant surveillance results for characterizing embrittlement trends, and resolve uncertainties in vessel material properties. PREP4 has been developed to assist utilities in evaluating existing unirradiated and irradiated data for plant surveillance materials; PREP4 evaluations can be used to assess the accuracy of new trend curve predictions. In addition, searches of the data can be easily performed to identify available Charpy shift and upper shelf data, review surveillance material chemistry and fabrication information, review general capsule irradiation information, and identify applicable source reference information.

In support of utility evaluations to consider thermal annealing as a viable embrittlement management option, EPRI is also developing a database to evaluate material response to thermal annealing. Efforts are underway to develop an irradiation-anneal-reirradiation (IAR) database that will contain all available IAR data on U.S. RPV materials. This database will allow evaluation of material response to thermal annealing and reirradiation through display of available data and comparison with proposed re-embrittlement trend prediction methods.

These databases are essential tools to develop effective embrittlement management programs. The RPVDATA, PREP4, and IAR databases will be described in terms of data contained and program features.
INTRODUCTION

Uncertainties regarding the properties of reactor vessel material are not a new concern. Vessel material uncertainties contributed significantly to the generic reactor vessel safety concerns of Pressurized Thermal Shock (PTS) in the early 1980s. More recently, questions about embrittlement in the Yankee Rowe vessel centered around characterizing vessel material properties and predicting embrittlement behavior, including adjustments for uncertainties in chemistry and the effects of an irradiation temperature lower than that assumed (274°C [525°F]) in development of existing regulatory guidance on embrittlement trend prediction. The inability to accurately quantify the actual level of embrittlement in the Yankee Rowe vessel contributed to the premature shutdown of this plant. The NRC is continually monitoring embrittlement in all U.S. reactor pressure vessels, and the projected levels of embrittlement are updated as new data becomes available.

Recent data have shown greater variability in chemistry and initial reference temperature (RTNDT) than had previously been observed in some welds fabricated by Combustion Engineering. Variability was also observed earlier in welds fabricated by Babcock & Wilcox. This variability prompted the NRC to issue Generic Letter (GL) 92-01, Revision 1, [1] and a follow-on Supplement 1 [2] that requested additional plant-specific data for assurance that all data has been considered to determine “best-estimate” properties of the reactor vessel materials. At that time there was no readily available single database that contained all available data to be reported to the NRC under GL92-01 and could be used to assist in resolving material property uncertainties. Extensive industry searches were required (and are still under way) to locate and collect all available vessel material property information. In addition, no general guidance was available for establishing the licensing “best-estimate” values for welds or base metals once all data was available since many different approaches had been used by licensees in the past.

EMBRITTLEMENT MANAGEMENT

There are many aspects to managing embrittlement in reactor pressure vessels that must be considered. An overall approach is described in the EPRI Reactor Vessel Embrittlement Management Handbook [3]. This handbook provides detailed background information on reactor vessel materials, chronology and types of welds in vessels, specifics of irradiation damage mechanisms and test methods, and descriptions of the prior EPRI products for characterizing and managing reactor vessel embrittlement.

Managing Reactor Vessel Material Uncertainties

Resolving specific vessel material uncertainty issues is an important aspect to overall embrittlement management that has been further emphasized by GL92-01. Resolving material uncertainty issues requires compiling all available data into a single integrated database to develop a better understanding of irradiated material property behavior.

Since the time of publication of the Embrittlement Management Handbook, additional tools have been developed to assist in resolution of vessel material uncertainties. These include the NRC Reactor Vessel Integrity Database (RVID), the EPRI Reactor Pressure Vessel
Data (RPVDATA) database, and the update to the Power Reactor Embrittlement Program (PREP4) database.

The NRC RVID database [4] was designed and developed to assist the NRC staff with licensing based actions by consolidating licensing data and information on vessel materials in a concise form. Data submitted by the nuclear licensees in response to GL92-01 were used as input to RVID. However, the RVID database does not constitute the licensing basis for each plant since some data categories have been recomputed and are not necessarily docketed values.

The RPVDATA database [5] contains all of the licensing information from RVID, plus additional utility “best-estimate” material properties, and all available measured chemistries and initial RTNDT data for welds, plates, and forgings. Both of these databases are intended to summarize vessel material properties, and ultimately resolve the regulatory concerns expressed in Generic Letter 92-01, Revision 1, and the subsequent Supplement 1 requesting additional plant-specific data. Of the two, only the RPVDATA database has been designed to identify plants with common vessel materials, to compare the submitted or “best-estimate” licensing values, and to evaluate all available data forming the technical bases for vessel integrity determinations.

The PREP4 database [6] includes all surveillance results (including the raw data from each surveillance capsule evaluation) currently available for U.S. vessels. The original genesis of PREP4 was a collaborative review effort with Oak Ridge National Laboratory in the development of their surveillance database, PR-EDB (Power Reactor - Embrittlement Data Base) [7]. The evaluated surveillance results from PREP4 are summarized in RPVDATA. Uses of the RPVDATA and PREP4 databases as tools for resolving vessel material uncertainties are described later in this paper.

Thermal Annealing

In support of utility evaluations to consider thermal annealing as a viable embrittlement management option, EPRI is presently developing a database to evaluate material response to thermal annealing with emphasis on re-embrittlement (post-anneal) response. The irradiation-anneal-reirradiation (IAR) database will contain all available IAR data on U.S. RPV materials. This database will allow evaluation of material response to thermal annealing and reirradiation through display of available data and comparison with possible re-embrittlement trend prediction methods.

A brief description of the RPVDATA, PREP4, and IAR Databases are provided next.

RPVDATA DATABASE

RPVDATA is a comprehensive reactor vessel materials database and data management program. The system is an IBM-compatible database program that uses the MS-DOS operating system with the Microsoft Windows graphical user interface. The database program includes a customized menu-driven interface, special search capabilities for data navigation and review, and built-in report generation.
The RPVDATA program has been developed to assist utilities in identifying and retrieving data and information for reactor vessel beltline materials and related plant surveillance materials. RPVDATA is the only database currently available that is capable of retrieving, sorting, and comparing vessel materials data from many different sources.

The RPVDATA database combines information on vessel material properties from the following databases and original source references:

- RVID & GL92-01 Data & Information
- RMATCH & WOG Heats & Chemistries
- PREP4, EDB & WOG Surveillance Data
- Fabrication Records & Plant Systems Info
- Additional Test Data & Supplemental Info

RPVDATA Database Input

Several types of data and information are contained in RPVDATA, including:

1. licensing (best-estimate) data reported in response to Generic Letter 92-01,
2. information on reactor vessel fabricator and fabrication methods,
3. base metal and weld material type, heat numbers, weld flux lot, and weld flux type,
4. measured chemistries, upper shelf energies, and initial RTNDT values,
5. reported data from Westinghouse surveillance capsule reports, and
6. evaluated data from the PREP4 surveillance database.

The title screen for RPVDATA is shown in Figure 1.

An evaluation using RPVDATA initially begins in one of three categories: (1) General Plant Information, (2) RPV Fabrication Information, and the real power of RPVDATA, (3) Data Search Menu. The RPVDATA Menu Screen is shown in Figure 2.

General Plant Information

Figure 3 illustrates the output from RPVDATA when General Plant Information is selected. For illustration purposes the Consumer's Power Palisades plant was selected. Similar information is available for all U.S. operating reactors.

Fabrication Information

Fabrication information can be presented arranged according to the RPV fabricator, i.e., fabrication information grouped according to vessels fabricated by Combustion Engineering, Chicago Bridge & Iron Nuclear, Babcock & Wilcox, etc. Fabrication information includes...
plant name, nuclear steam supply system designer, reactor type, base metal condition (plate or forging), base metal type, and construction dates.

Figure 1. RPVDATA Database Title Screen

Figure 2. RPVDATA Menu Screen
The real power of the RPVDATA database is through the Data Search Menu. Searches of available data can be easily performed to identify plants with similar materials, sort through measured test results, compare the "best-estimate" values for reported chemistries with licensing basis (RVID) values, identify relevant surveillance results for characterizing embrittlement trends, and resolve uncertainties in vessel material properties. Figure 4 illustrates the options available under the Data Search Menu.

Plant-Specific Vessel Data

The first option identified in Figure 4 is to display plant-specific vessel data. Selection of this option provides several types of plant data that can be presented on a plant-specific basis, including: (1) NRC RVID database reports, (2) utility best-estimate reports, (3) sister plant weld reports, (4) surveillance weld data, and (5) base metal surveillance data. The type of data presented through each of the options is listed below.

NRC RVID Database Reports. The information presented under this option is a summary of that available in the NRC RVID database. It is also included in RPVDATA for comparison purposes. Three separate reports are available under this option, including: (1) vessel integrity data report, (2) upper shelf energy report, and (3) PTS summary report.

Utility Best Estimate Reports. This data represents each utility's determination of the appropriate material properties to be used in evaluating reactor vessel embrittlement and vessel integrity. Under this option the following information can be viewed:
Figure 4. Data Search Menu Options

1. Reactor Beltline Material Identification
2. Heat Number of specified material
3. Flux type of weld (if the material is a weld)
4. Flux Lot of Weld (if the material is a weld)
5. End-of-license (EOL) fluence ($n/cm^2$, $E > 1$ MeV)
6. Initial Reference Temperature ($IRT_{NDT}$)
7. The method for determining $IRT_{NDT}$
8. Chemistry Factor (CF)
9. The method for determining the Chemistry Factor
10. Percent Copper and Percent Nickel in the material
11. The RTPTS (pressurized thermal shock reference temperature)

In addition, the user can view the utility's PTS summary report based on the best-estimate material property values and can compare these results with those presented in the NRC RVID database.

**Sister Plant Weld Reports.** This option provides plant-specific data for vessels with similar heats of weld metal. This part of the RPVDATA program identifies other plants which have the same weld heat number. The following information is provided in regards to sister plants having common weld materials.

1. Weld Heat Number
2. Weld Flux Type
3. Sister Plant Names
4. Component (i.e. Location and direction of weld)
5. Percent Copper and Percent Nickel (from RVID Database)
**Surveillance Weld Data.** This option reports surveillance Charpy test results for a given plant for a given weld wire heat number, flux type, and flux lot. The following information is provided:

1. Surveillance Capsule ID
2. Capsule fluence (n/cm$^2$, E > 1 MeV)
3. ft-lb transition temperature ($^\circ$F)
4. ft-lb transition temperature ($^\circ$F)
5. Upper shelf energy (ft-lbs)
6. Change in transition temperature ($^\circ$F)
7. Percent drop in upper shelf energy
8. Reference for surveillance capsule test report

**Base Metal Surveillance Data.** This option reports surveillance Charpy test results for a given plant for a given plate heat number and specimen orientation. The following information is provided:

1. Surveillance Capsule ID
2. Capsule fluence (n/cm$^2$, E > 1 MeV)
3. ft-lb transition temperature ($^\circ$F)
4. ft-lb transition temperature ($^\circ$F)
5. Upper shelf energy (ft-lbs)
6. Change in transition temperature ($^\circ$F)
7. Percent change in upper shelf energy
8. Reference for surveillance capsule test report

**Specific Weld Heat Data**

This option from the Data Search Menu provides the capability to search for materials property information on a specific weld heat basis. Data for each weld heat number is separated by data type (e.g., licensing data vs. measured test data). Three data categories are available under this option, including: (1) NRC data on reactor vessel welds, (2) weld qualification and test data, and (3) surveillance weld test results.

**NRC Data on Reactor Vessel Welds.** This option provides weld property information from the NRC RVID Database. All plants with a given weld heat number have the following information provided:

1. Plant Name
2. Beltline Identification of Weld
3. Material Type
4. Flux Type
5. Flux Lot
6. Initial Reference Temperature (IRT$_{NDT}$)
7. Method to determine IRT$_{NDT}$
8. Chemistry Factor (CF)
9. Method used to determine CF
10. Percent Copper and Percent Nickel
Weld Qualification and Test Data. This option will perform a query of all measured weld qualification and test data for a particular weld heat. These reports contain all the measured test results of chemistry and mechanical properties for the particular weld heat of interest.

Surveillance Weld Test Results. This option provides evaluated surveillance test results for a given weld heat number from the EPRI PREP4 database. This information is separated by plant identification and each plant has identified surveillance capsule data. The accumulation of data is the result of unirradiated and irradiated surveillance capsule data reports. The updated version of EPRI’s surveillance database, PREP4, will be described later.

Similar Flux Type Welds

This option will provide a summary of plant vessel data for the weld flux of interest. The following information is provided in the report.

(1) The weld heat number
(2) The weld (material) type
(3) The weld flux lot
(4) The plant name
(5) The location or component of the weld
(6) Percent Copper and percent Nickel
(7) Initial Upper Shelf Energy (IUSE)
(8) The method to determine the Initial USE.

Specific Base Metal Data

This option will present available data as a function of the plate/forging heat of interest selected. Three data categories are available under this option, including: (1) NRC data on vessel base metal, (2) certification and test data, and (3) base metal surveillance data. The type of information presented is similar to that for the Specific Weld Heat Data option.

PREP4 DATABASE

PREP4 is a power reactor vessel materials database program. The system is an IBM-compatible database program that uses the MS-DOS operating system with the Microsoft Windows graphical user interface. The database program includes a customized menu-driven interface, special search capabilities for data navigation and review, and built-in report generation.

The PREP4 program has been developed to assist utilities in accessing existing materials data for power reactor vessel beltline materials and related plant surveillance materials. The PREP4 database was designed to be the qualified irradiated materials database to be used in support of future nuclear plant aging research and management of embrittlement for vessel life extension. PREP4 was designed to provide the user the ability to display and print reactor vessel surveillance material information along with the associated shift predictions for reactor vessel embrittlement.
Several types of data and information are contained in PREP4, including:

1. Charpy V-notch tanh plots,
2. Charpy shift predictions,
3. Information on reactor vessel fabricator,
4. Base metal and weld material type, heat numbers, weld flux lot, and weld flux type,
5. Measured chemistries, transition temperature shift values, and upper shelf energies,

Three principal data query options are available under PREP4, including (1) view/plot surveillance data, (2) search materials data, and (3) system utilities. These options are illustrated in Figure 5. System utilities allows the user to display data in either English or Metric units. The remaining options are discussed below.

![Figure 5. PREP4 Menu](image)

**View/Plot Surveillance Data**

This option allows plant-specific surveillance data to be viewed in terms of Charpy Energy, lateral expansion, or percent shear/fracture appearance data. After a plant and data type are selected, available data sets along with plant-specific information about the RPV are displayed. Figure 6 illustrates Select Capsule Data screen for Palisades.

Note that a similar screen would be generated if lateral expansion or percent shear/fracture appearance were desired. From this point individual Charpy data sets can be selected and viewed by choosing the View Selected Charpy Data option. For consistency, all Charpy data sets are fit and plotted to a hyperbolic tangent function. A single data set, or multiple Charpy data sets can be plotted simultaneously. Coefficients of the resultant hyperbolic tangent curve fit as well as the 41J (30 ft-lb) and 68J (50 ft-lb) temperatures are provided.
Charpy transition temperature shift data can also be viewed directly from the Select Capsule Data Screen. Shift data is presented with a corresponding chemistry factor from Regulatory Guide 1.99, Revision 2 based on the chemistry values reported for the surveillance material [8]. In addition, a fitted chemistry factor is provided that illustrates the best-fit chemistry factor for the actual surveillance results.

Search Materials Data

The Search Materials Data options provides the ability to view specific information relating to any capsule data set contained in PREP4. The options available are illustrated in Figure 7 and include (1) view chemistry information, (2) view capsule information, (3) fabricator information, and (4) source reference information.

View Chemistry Information provides the reported chemistry data for each material heat in a surveillance capsule data set contained in PREP4.

View Capsule Information provides information specific to the capsule irradiation, including: irradiation start/stop dates, irradiation capsule fluence and irradiation time, minimum and maximum capsule temperatures, and the reference document for the particular capsule.

Fabricator Information provides any information regarding the fabrication of the specific material heat, including heat treatment conditions.

Source Reference Information provides details on the source reference documentation that summarizes the capsule testing results.
Figure 7. Select Capsule Materials Information Screen

IRRADIATION-ANNEAL-REIRRADIATION (IAR) DATABASE

The IAR database is presently under development by EPRI to provide a useful tool for the evaluation of thermal annealing as an embrittlement management option. A utility's selection of an appropriate embrittlement management option will ultimately be an economic decision. Thermal annealing provides an advantage over other present options in that it is the only technique to restore a large percentage of material properties and provide a realistic expectation of long-term extended operation (including license renewal). The potential for material property recovery following a thermal anneal has been well documented. However, an important aspect of optimizing the thermal annealing process is to maximize the amount of material property recovery coupled with the minimum rate of material re-embrittlement following the anneal.

Limited information is currently available regarding the re-embrittlement rate of U.S. RPV materials. As more information becomes available, the ability to easily compare re-embrittlement rates with initial embrittlement trends will be useful in selecting an appropriate annealing recipe. This is the premise behind development of the IAR Database. The IAR Database will present available anneal and reirradiation data for U.S. RPV materials and provide the ability to apply the vertical and lateral shift methods for comparing IAR predictive methodologies with actual data trends.

The two principal options available in the IAR Database are illustrated in Figure 8 and include (1) View/Plot Plate Annealing Data, and (2) View/Plot Weld Annealing Data.
View/Plot Plate Annealing Data

This option will present available annealing and reirradiation data for RPV plate materials as a function of plate type and heat. The type of plate is initially selected (at this time the database only contains information for A302B or A533B). The plate heats for which data are available are then displayed for the user to select.

Once a plate heat is selected, the available annealing data set conditions are displayed in terms of irradiation temperature, annealing temperature, and annealing time. The user is prompted to select a particular annealing data set condition for further evaluation. After a particular annealing data set condition is selected, all data sets available for the unirradiated, irradiated, annealed, and reirradiated conditions are displayed. The user then selects the data sets of interest and can either (1) view Charpy data or (2) view Charpy shift data.

View Charpy Data

This option presents available Charpy data for the material conditions selected. Charpy data points are displayed and plotted to a hyperbolic tangent curve fit.

View Charpy Shift Data

This option will present data associated with the shift in the 41J (30 ft-lb) Charpy transition temperature as a function of irradiation fluence. Several options are available during evaluation of Charpy shift data. These options are illustrated in Figure 9 and include, (1) chemistry factor, (2) curve to plot, (3) fluence factor calculation, (4) metal type, and (5) miscellaneous factors.
Chemistry Factor. The default reported material chemistry values initially are utilized in determining the chemistry factor (using the methodology in RG 1.99, Revision 2). The predicted initial irradiation embrittlement trend is then plotted. The user can change the chemistry values (e.g. when considering a revised best-estimate chemistry) to alter the position of the RG 1.99 embrittlement trend prediction curve.

Curve to Plot. This option allows the user to either display the embrittlement trend curve based on a least-squares fit through the existing data points using the RG 1.99, Revision 2 adjusted chemistry factor method or based on the stated chemistry values described above using the correlation methodology in RG 1.99, Revision 2.

Fluence Factor Calculation. This option controls the fluence factor that is used in determining the displayed embrittlement trend prediction curve. The user can either accept the default fluence factor function provided in RG 1.99, Revision 2 \((f^{0.28-0.10\log(f)})\) or provide a user-specific constant value for the term \((0.28-0.10\log(f))\) to account for test reactor irradiations, etc.

Metal Type. This option selects the appropriate chemistry factor tables identified in RG 1.99, Revision 2 for the material of interest.

Miscellaneous Factors. This option initially displays the fluence corresponding to the available annealing data and the percent recovery as calculated through the methodology developed by Eason, et al. [9]. However, these values can be changed to reflect the anticipated actual annealing fluence for the RPV and the measured percent recovery based on test data. This option also allows the user to predict reirradiation embrittlement using either the lateral shift method, the vertical shift method, or any trend between the two methods (percent lateral versus percent vertical).
View/Plot Weld Annealing Data

This option will present available annealing and reirradiation data for RPV weld materials as a function of weld flux type and heat. All other options are identical to those discussed above for plate materials.

CONCLUSIONS

The RPVDATA and PREP4 database programs have led to a major step forward in understanding and resolving reactor vessel material concerns. A thorough compilation of data from many different sources into a common database for RPV material properties (RPVDATA) and surveillance data (PREP4) are the essence of these advancements.

Searches of the data in RPVDATA can be easily performed to identify plants with similar materials, sort through measured test results, compare the "best-estimates" for reported chemistries with licensing basis values, quantify variability in measured weld qualification and test data, identify relevant surveillance results for characterizing embrittlement trends, and resolve uncertainties in vessel material properties.

Searches of the data in PREP4 can be easily performed to identify available Charpy data and Charpy shift data, review surveillance chemistry and general capsule information, review material fabrication information, and identify applicable source reference information. Embrittlement trend behavior of surveillance weld or base materials can be developed and easily compared to newly established regulatory prediction methodologies.

The IAR database presently under development will allow the user to identify available annealing and reirradiation material property data, predict material re-embrittlement following annealing, and compare results with established regulatory guide methodologies.

The common structure of the above products provides for easy updates to incorporate future surveillance program or other material property information in order to maintain a "current" record of available material property data. In addition, the structure of these products can easily accommodate international material property data and provide the same flexibility in use and allow for material property comparison on an international basis.

REFERENCES


