Further Evaluation of the Supplemental USE Analysis of the Diablo Canyon Unit 1 RPV that was Performed in the Part 2 Report

Mark Kirk · 2 July 2024

Background and Objective

In the [Part 2 report] I performed a supplemental ("supplemental" meaning "not required by the NRC") evaluation of the upper shelf energy (USE) of the Diablo Canyon Unit 1 limiting weld (weld wire heat 27204) to assess Unit 1's current and future compliance with the NRC's 68 Joule (68J) screening criteria on average USE [10CFR50-AppG]. This analysis used both the surveillance data from weld wire heat 27204, which is required by the NRC, as well as data from materials having similar chemical composition (copper and nickel) and, therefore, similar embrittlement characteristics. This greater amount of data is summarized in **Figure *1***, which is copied from the [Part 2 report]. The additional data included that from the sister weld at the Palisades plant (diamonds in the figure) as well as data from several PWRs that had operated in Germany (triangles in the figure). The Palisades data controls the supplemental analysis because it appears to show a greater effect of embrittlement (greater % drop[1] in the figure) than do either the German data or the data from the Diablo Canyon Unit 1 surveillance program.

The objective of this document is to investigate possible reasons for the differences between the Palisades and the Diablo Canyon data.

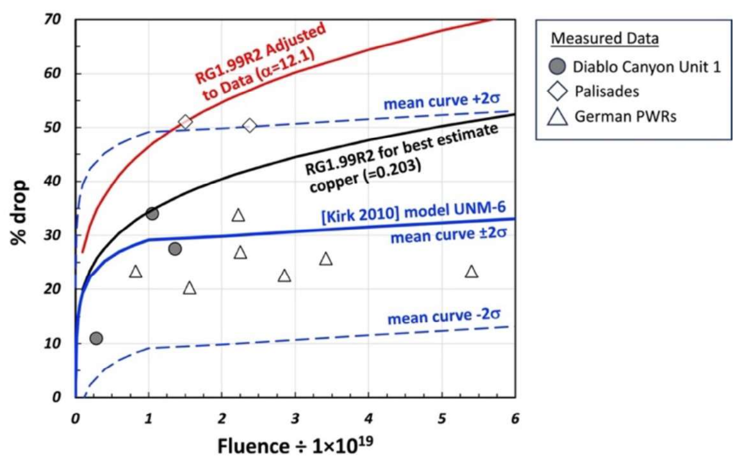

Figure 1. Estimates of percent USE % drop determined from data having similar chemical composition and exposure temperature to the Diablo Canyon Unit 1 weld. The blue curves [Kirk 2010] was estimated for Cu=0.203, Ni=1.018, Mn=1.347, P=0.013, coolant temperature = 281.1 °C and illustrated the uncertainty in USE prediction typical of RPV steels. The black curve is based on the [RG1.99R2] formula whereas the red curve is adjusted to all data shown following the procedures of [RG1.99R2]. This was originally Figure 10 of the [Part 2 Report].

[1] The value "% drop" quantifies how much the average USE has reduced due to neutron irradiation.
% drop = ($USE_{UNIRRADIATED}$ - $USE_{IRRADIATED}$) ÷ $USE_{UNIRRADIATED}$.

Estimation of % Drop from Charpy Data

Figure 2 illustrates how the value "% drop" is estimated from mean hyperbolic tangent fits (the green and the red curves) to unirradiated and irradiated Charpy transition temperature data. The values of unirradiated and irradiated USE needed for this calculation are the average value of Charpy absorbed energy calculated from specimens that show 95% or more shear fracture area. Percent shear fracture area is a measure of the proportion of the fracture surface of a Charpy specimen that has experienced shear (or ductile) fracture versus that proportion of the fracture surface of a Charpy specimen that has experienced the cleavage (or brittle) fracture. The [ASTM E2215] standard considers all specimens that have experienced ≥ 95% shear fracture area to be at or above the "Charpy upper-shelf onset temperature." The average energy of all specimens having ≥ 95% shear fracture area is defined by [ASTM E2215] as being the "Charpy upper-shelf energy level," or USE. While slightly different definitions of USE have been used over time by [ASTM E185] and [ASTM E2215], a comparison analysis of these different definitions demonstrated that all produce similar values of USE [Kirk 2018].

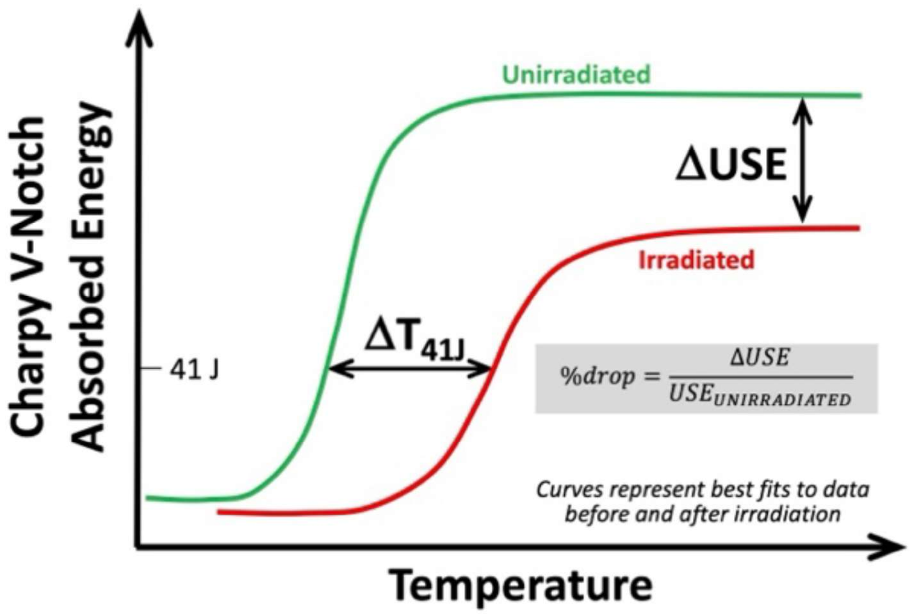

Figure 2. Schematic illustrating how the metrics ΔT_{41J} and % drop are estimated from mean hyperbolic tangent fits (the green and the red curves) to unirradiated and irradiated Charpy data. This was originally a portion of Figure 5 of the [Part 1 Report].

Assessment

As detailed in the [Part 2 report] there are three different sources for Charpy data on weld wire heat 27204:

- The Diablo Canyon Unit 1 surveillance program weld [WCAP-15958]. Data is available for the unirradiated condition and from three capsules at three different fluences.
- A "sister plant" weld that was tested as part of a supplemental surveillance program conducted at the Palisades plant [BAW-2398, BAW-2341R2]. Data are available for the unirradiated condition and from two capsules at two different fluences.

- A “surrogate” weld that was included as part of a supplemental program at Diablo Canyon Unit 1 [WCAP-13440]. This program began when four supplemental capsules were inserted into the Unit 1 reactor during the fifth refueling outage in 1992. Currently only unirradiated data is available. The first irradiated data from this “surrogate” weld will become available in 2025 when PG&E plans to test Capsule B.

As described in the [Part 2 report] these samples all have very similar copper and nickel contents (roughly 0.2 and 1.0 weight percent, respectively); they also share the same weld wire heat (27204) and were welded with the same flux type (Linde 1092). Further review of reports that I performed to support development of the current document revealed that the “surrogate” weld described in [WCAP-13440] is the exact same weld as the “sister” plant weld reported in [BAW-2398] and [BAW-2341 R2]. The information cited in all three references gives [CE-TR-MCC-189] as the source for unirradiated Charpy data on this single weld.

Figure 3 shows the unirradiated Charpy energy transition data for the Diablo Canyon Unit 1 surveillance weld (circles, data from [WCAP-15958]) and for the sister/surrogate weld (diamonds, data from [CE-TR-MCC-189]). Charpy data that have greater than 95% shear fracture area, corresponding to upper shelf behavior, are indicated by a small plus (+) mark appearing inside a circle or diamond). As stated earlier, the average of the absorbed energy values indicated by the plus marks establishes the average upper shelf energy (USE) of a particular data set.

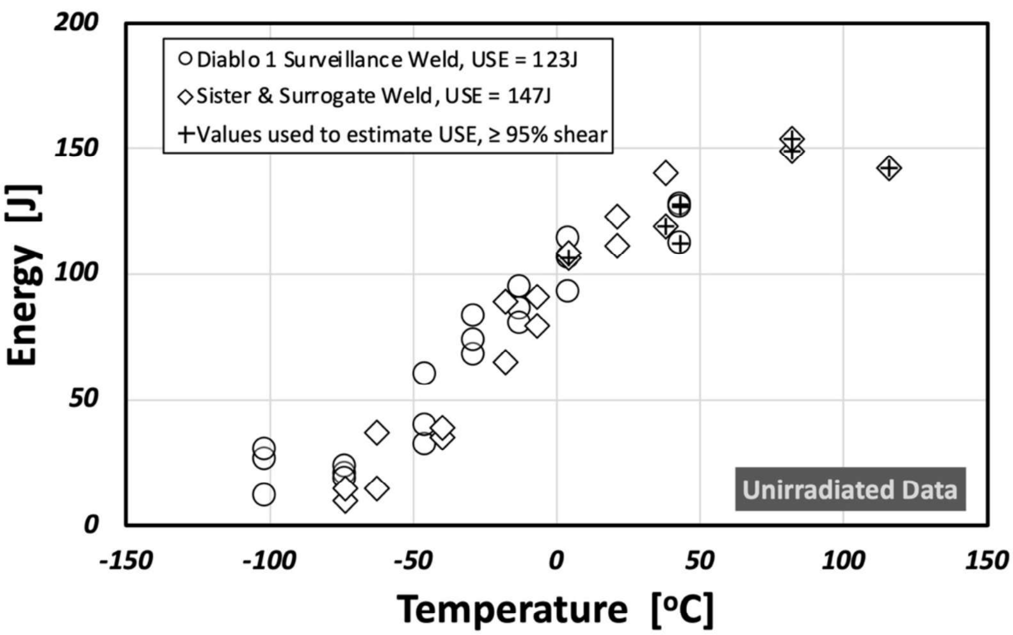

Figure 3. Unirradiated Charpy data for weld wire heat 27204.

Conventionally the unirradiated Charpy data from Diablo Canyon Unit 1 surveillance weld and from the sister/surrogate weld would be considered as two separate samples, so the USE values of the surveillance weld and the sister/surrogate weld would be estimated separately. These separately estimated USE values appear in the legend on the figure (123J for the Diablo Canyon Unit 1 surveillance weld and 147J for the sister/surrogate weld). Figure 4 summarizes the associated % drop analysis and comparison with the NRC’s 68J USE screening criteria that appeared in the [Part 2 report]. In Figure 4:

- The % drop values estimated from the irradiated Charpy USE data and the separately fit unirradiated USE values appear as circles (Diablo Canyon Unit 1 weld) or diamonds (Palisades sister weld). The values associated with these symbols are read off the left-hand vertical axis.
- The RG1.99R2 curves fit to these data appear as black and red solid curves; these read to the right-hand axis which provides the estimated value of USE after irradiation to a certain fluence, which is read off the horizontal axis.
    - The black curve is the NRC's required analysis, which considers only the Diablo Canyon Unit 1 surveillance data. As stated in Section 3.2 of the [Part 2 report], this analysis forecasts that the irradiated USE will not fall below the NRC's 68J screening criteria (horizontal dot-dash line) until well after 60-years of operation (vertical dashed line).
    - The red curve is the supplemental analysis that appeared in Section 4.2 of the [Part 2 report]; this analysis considers not only the Diablo Canyon Unit 1 surveillance data but also other similar data[2]. As stated in Section 4.2 of the [Part 2 report], this analysis forecasts that the irradiated USE will fall below the NRC's 68J screening criteria (horizontal dot-dash line) between 40- and 60-years of operation (vertical dashed lines).

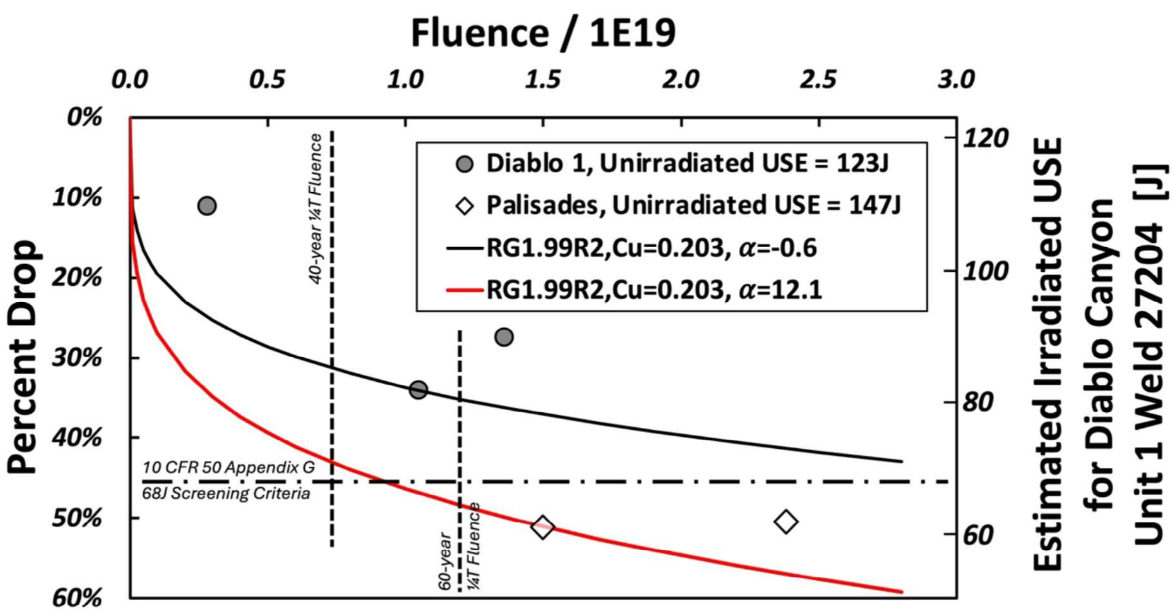

Figure 4. Summary of information on % drop of weld wire heat 27204 and comparison to the NRC's 68J screening criteria taken from the [Part 2 Report].

Returning attention to the unirradiated data in **Figure 3**, it is apparent that the unirradiated Charpy curves for the Diablo Canyon Unit 1 weld and for the Palisades sister weld are in fact quite similar, and that the conventional practice of treating these as separate samples may not be appropriate. Over the temperature range where there is common testing of the two samples the plotting symbols scatter together; there does not seem to be any strong tendency for the diamonds to be above the circles, or visa-versa. The difference in the separately estimated USE values (123J for the

[2] Similar data identified in the [Part 2 report] included both the Palisades sister weld as well as information from several German PWRs. The data from the German PWRs is not shown here because it is the limiting data from Palisades that limits the analysis.

Diablo Canyon Unit 1 surveillance weld and 147J for the sister/surrogate weld) appears to occur because of the different temperature range over which the samples were tested. The highest test temperature for the surveillance weld was 110 °C while the sister/surrogate weld was tested as high as 240 °C. The unirradiated USE values are critical to the analysis of irradiation effects on USE because the unirradiated USE is used to estimate % drop (see footnote 1 on page 1 and **Figure 2**). The higher USE of the sister/surrogate weld produces the much larger values of % drop associated with the sister weld shown on **Figure 4**. This higher percent drop drives the supplemental analysis to its conclusion that the irradiated USE of Unit 1 may fall below the NRC's 68J screening criteria before 60-years of operation.

If all unirradiated Charpy data shown in **Figure 3** for weld wire heat 27204 are fit together then the estimated value of unirradiated USE is 132J. The analysis of **Figure 4** is repeated, but now using an unirradiated USE of 132 J for both the Diablo Canyon Unit 1 weld and the Palisades sister weld. This analysis appears as **Figure 5**. The data from the sister weld still controls the analysis, but now the trend of increasing % drop with increasing fluence is seen to be more similar between all measurements, which is expected based on the chemical composition and similar welding techniques shared by all samples. This analysis, which considers both the Diablo Canyon Unit 1 weld as well as the Palisades sister weld, predicts that the USE of these welds will not fall below the NRC's screening criteria until well after 60-years of operation for Diablo Canyon Unit 1.

A supporting perspective on these data can be obtained by avoiding the %drop normalization entirely and considering only the measured USE values. The data summarized in Table 1 show that all measured USE values for weld wire heat 27204 exceed the NRC's 68J screening criteria. These data indicate that weld wire heat 27204 has a measured USE no lower than 72J up to a fluence of 2.38×10^{19} n/cm^2. The estimated ¼T fluence in the vessel after 60 years of operation is only 1.2×10^{19} n/cm^2. Thus, the direct measurements of USE on weld wire heat 27204 remain above the NRC's 68J screening criteria to a fluence nearly 2-times higher than the vessel will reach after 60 years of operation.

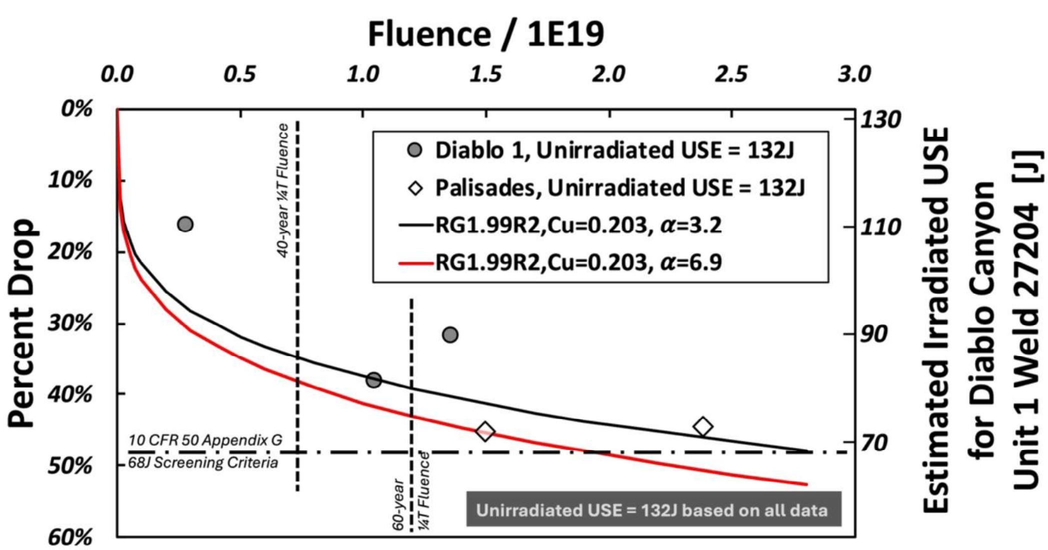

Figure 5. Updated analysis of % drop and assessment of Diablo Canyon Unit 1 relative to the NRC's 68J screening criteria based on using a single unirradiated USE value for both the Diablo Canyon Unit 1 and Palisades samples.

Table 1. Summary of USE values for weld wire heat 27204.

Plant	Capsule	Fluence / 1E19	Measured USE [J]
Diablo Canyon Unit 1	--	0	123
	S	0.283	110
	Y	1.05	81
	V	1.36	89
Palisades	--	0	147
	SA-60-1	1.5	72
	SA-240-1	2.38	73

Future Data

As described in the [Part 2 report], Capsule B contains both samples of the Diablo Canyon Unit 1 surveillance weld as well as samples of a "surrogate weld," which was identified earlier to be identical to the sister weld from Palisades. While NRC procedures did not require consideration of USE data from the Palisades sister weld in assessment of Diablo Canyon Unit 1 relative to the 68J screening criteria, it is in my opinion likely that consideration of the surrogate weld samples in Capsule B will be required as part of a future 68J screening criteria analysis because these samples are an acknowledged part of the Diablo Canyon Unit 1 surveillance program. In this situation PG&E may, in the interest of consistency, also consider the results from the Palisades "sister" weld, which as discussed earlier is the same weld as the "surrogate" samples in Capsule B.

As is always true, the future measurements obtained by testing Capsule B may change the outcome of current assessments.

Summary

The information presented herein may be summarized as follows:

1. Conventional upper shelf energy (USE) analysis of Diablo Canyon Unit 1 data for weld wire heat 27204 following the NRC's requirements show that USE should remain above the NRC's 68J screening criteria until after 60 years of operation.
2. The supplemental USE analysis (not required by NRC) in the [Part 2 report] which incorporated data from the Palisades plant, indicated that the USE of Diablo Canyon Unit 1 may fall below the 68J screening criteria after 40 but before 60-years of operation. Further assessment of the Palisades and Diablo Canyon Unit 1 data performed in this document reveals that the reason for this conclusion is most likely the different unirradiated USE values associated with the Diablo Canyon and Palisades samples. Since these samples are both from a similar weld and display similar behavior, it is appropriate to combine unirradiated data into a single data set, producing a single estimate for the unirradiated USE value. The supplemental analysis of the [Part 2 report] was repeated herein using this single USE estimate. Using this approach the revised supplemental analysis shows that the USE for Diablo Canyon Unit 1 is estimated to remain above the NRC's 68J screening criteria until after 60-years of operation.
3. All measured USE values from weld wire heat 27204, including samples from both the Diablo Canyon Unit 1 and Palisades surveillance programs, maintain a value of USE above

the 68J screening criteria even to a fluence that is 2-times higher than the Diablo Canyon Unit 1 RPV will reach at the ¼T location after 60 years of operation.

When Capsule B is withdrawn from the Diablo Canyon Unit 1 reactor in 2025 and tested new data will become available on USE. These new data will need to be incorporated into USE and other analyses and may alter the conclusions associated with current analyses.

Citations

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