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[CORRECTED VERSION]

Review of Entergy Nuclear Vermont Yankee, LLC and Entergy Nuclear Operations, Inc. ("Entergy") Analyses of the Effects of Reactor Water Environment on Fatigue Life of Risk-significant Components During the Period of Extended Operation

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I. BACKGROUND

A. Basic Technical Principles

Fatigue is an age-related degradation mechanism caused by cyclic stressing of a component by either mechanical or thermal stresses that eventually cause the component to crack. Under such cyclic loading, a crack will be initiated and the component will fail under stresses that are substantially lower than those that cause failure under static loadings. During each loading cycle, some fraction of the component's fatigue life is exhausted, its size depending on the magnitude of the applied stress. Eventually, after N cycles, the component's allowable fatigue life is fully expended. The number of cycles n at any given stress amplitude divided by the corresponding N is called the usage fatigue factor. The cumulative usage fatigue factor, CUF, is simply a summation of the individual usage factors. ASME Code Section III requires that CUF must not exceed unity. The CUF is expressed as

$$CUF = \sum n_k / N_k$$

The basic equation that describes the crack growth rate for a given stress intensity includes two empirical constants, C and x. A large data base exists on the empirical constants C and x, which was derived from laboratory tests mostly in air under controlled conditions. This equation can predict crack growth reliably as long as it is used under the conditions that were used to calibrate C and x. This principle is very important in assessing how Entergy used laboratory data to calculate fatigue life of selected components at the VY plant.

To account for the fact that crack propagation in water is different than in air, the individual usage factor in air is multiplied by a corresponding correction factor Fen. Fen is simply the ratio of the fatigue life in air at room temperature to the fatigue life in water at the local temperature. The environmentally corrected CUF is defined as,

$$CUFen = Fen\,(CUF)$$

Fen is derived from laboratory data on the effect of strain on fatigue life, i.e. the number of cycles to failure. NUREG/CR-6909 describes such laboratory tests in detail.

The procedures to analyze components for fatigue are specified in Section III of the ASME Code. The Code provides fatigue curves for various materials, which specify the allowable number of cycles for a given stress intensity. The code requires that the CUF at any given location be maintained below one. Since the Code used data from laboratory tests with smooth specimens, the code made allowances (2 on stress and 20 on cycles) in recognition that a test specimen in air may have a longer fatigue life than actual components in a reactor. The most current ASME code also provides a simplified set of rules in Subparagraph NB-3600, and a more rigorous rule in Subparagraph NB- 3200, which is based on using a finite element analysis to calculate CUF values. Replacing the simplified analysis with a more detailed analysis has the advantage of removing unwanted conservatism from the results of the simplified analysis. Since the detailed analysis may require a larger data base than the simplified analysis, the user must ascertain that the necessary data base exists. When such information is not available, and the user instead makes arbitrary assumptions, the benefit of the detailed analysis is completely negated.

B. Regulatory Requirements

NRC regulation 10 CFR § 54.21(c) requires that each license renewal application must include "an evaluation of time-limited aging analyses" ("TLAA") for components covered by the license renewal regulations.[1] If

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[1] TLAAs are defined as:

Those licensee calculations and analyses that:

(1) Involve systems, structures, and components within the scope of license renewal, as delineated in § 54.4(a);
(2) Consider the effects of aging;
(3) Involve time-limited assumptions defined by the current operating term, for example, 40 years;
(4) Were determined to be relevant by the licensee in making a safety determination;
(5) Involve conclusions or provide the basis for conclusions related to the capability of the system, structure and component to perform its intended functions, as delineated in § 54.4(b); and

the applicant is unable to demonstrate that TLAAs "remain valid for the period of extended operation" or that they "have been projected to the end of the period of extended operation," it must demonstrate that "the effects of aging on the intended function(s) will be adequately managed for the period of extended operation." 10 C.F.R. 54.21(c)(1)(i)-(iii).

NUREG-1801, Rev. 1, Generic Aging Lessons Learned (GALL) Report (2005) ("NUREG-1801") also provides guidance for the preparation of TLAAs.[2] NUREG-1801 advises that a license renewal applicant may address "the effects of the coolant environment on component fatigue life by assessing the impacts of the reactor coolant environment on a sample of critical components for the plant." Id., Vol. 2 at X M-1. Examples of critical components are identified in NUREG/CR-6260, Application of NUREG/CR-5999 Interim Fatigue Curves to Selected Nuclear Power Plant Components (1995). The sample of critical components "can be evaluated by applying environmental life correction factors to the existing ASME Code fatigue analyses." NUREG-1801, Vol. 2 at X M-1. If these components are found not to comply with the acceptance criteria (i.e., CUF less than one), "corrective actions" must be taken that "include a review of additional affected reactor coolant pressure boundary locations." Id. at X M-2. As explained further in industry guidance document MRP-47:

> The locations evaluated in NUREG/CR-6260 [2] for the appropriate vendor/vintage plant should be evaluated on a plant-unique basis. For cases where acceptable fatigue results are demonstrated for these locations for 60 years of plant operation including environmental effects, additional evaluation or locations need not be considered. However, plant-unique evaluations may show that some of the NUREG/CR-6260 [2] locations do not remain within allowable limits for 60 years of plant operation when environmental effects are considered. In this situation, plant specific evaluations should expand

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(6) Are contained or incorporated by reference in the CLB [current licensing basis].

[2] NUREG-1801 is referenced with approval in Regulatory Guide 1.188, Rev. 1, *Standard Format and Content for Applications to Renew Nuclear Power Plant Operating Licenses* (2005) ("Reg. Guide 1.188").

the sampling of locations accordingly to include other locations where high usage factors might be a concern.[3]

II. ENTERGY'S CUFen ANALYSES

A. Brief History

The VYNPS License Renewal Application (LRA) Table 4.3-3 summarizes Entergy's evaluation of effects of reactor water environment on the fatigue life of nine components for the period of extended operations. The components selected correspond to the limiting locations identified in NUREG/CR-6260.[4] LRA Table 4.3-3 states that the environmentally corrected Cumulative Usage Factor (CUFen) of the following risk-significant reactor components will exceed unity: feedwater nozzle, RR inlet nozzle, RR outlet nozzle, RR piping tee, core spray nozzles, core spray safe end, and feedwater piping.

To address this problem, Entergy chose to "refin[e] the fatigue analyses to lower the predicted CUFs to less than 1.0."[5] Entergy's refinement of its CUFen analysis proceeded in two steps: (1) an initial reanalysis involving, in part, the use of a simplified Green's function method to calculate stress loads during plant transient operations; and (2) a "confirmatory" reanalysis of only the feedwater nozzle that did not involve use of the simplified Green's function method. I have reviewed the reports of both Entergy's initial CUFen reanalysis, and its "confirmatory" reanalysis of the feedwater nozzle that Entergy produced to NEC.[6]

The five elements of Entergy's initial reanalysis included:

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[3] MRP-47, Revision 1, Electric Power Research Institute, *Materials Reliability Program: Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application* at 3-4 (2005).

[4] Safety Evaluation Report Related to the License Renewal of Vermont Yankee Nuclear Power Station (February 2008)("FSER"), NRC Staff_Exh_01 at 4-32.

[5] LRA at 4.3-7.

[6] These reports are submitted in this proceeding as Exhibits NEC-JH_04 – NEC-JH_21.

1. Development of a finite element model
2. Development of heat transfer coefficients
3. Development of Green Functions
4. Development of thermal transient definitions
5. Performance of Stress and Fatigue Analysis.

Entergy reported the results of its initial reanalysis in the Table 1, reproduced below:

TABLE 1
VYNPS Cumulative Usage Factors for NUREG/CR-6260 Limiting Locations[7]

	NUREG-6260 Location	Material	Overall* Environmental Multiplier (F_{en})	Environmentally Adjusted CUF
1	RPV vessel shell/ bottom head	Low alloy steel	9.51	0.08
2	RPV shell at shroud support	Low alloy steel	9.51	0.74
3	Feedwater nozzle forging blend radius	Low alloy steel	10.05	0.64
4	RR Class 1 piping (return tee)	Stainless steel	12.62	0.74
5	RR inlet nozzle forging	Low alloy steel	7.74	0.50
6	RR inlet nozzle safe end	Stainless steel	11.64	0.02
7	RR outlet nozzle forging	Low alloy steel	7.74	0.08
8	Core spray nozzle forging blend radius	Low alloy steel	10.05	~~0.0432~~ 0.1668
9	Feedwater piping riser to RPV nozzle	Carbon steel	1.74	0.29

* Effective multiplier for past and projected operating history, power level, and water chemistry.

The NRC Staff rejected Entergy's initial CUFen reanalysis. As reported in the FSER, Entergy and the NRC Staff "were unable to resolve the issues raised [with respect to Entergy's use of Green's functions to calculate stress loads]."[8] The NRC Staff therefore requested that Entergy perform, and Entergy did perform, the additional "confirmatory" CUFen analysis of the feedwater nozzle, using the ASME Code Section III, Subsection NB-3200 methodology to calculate the stress intensities "without referencing Green's function."[9]

[7] Exhibit NEC-JH_34 at Attachment 2.

Deleted: 35

[8] FSER, NRC Staff Exhibit 01 at 4-40.

[9] FSER, NRC Staff Exhibit 01at 4-41; *See also,* Exhibit NEC-JH_22 (Summary of Meeting Held on January 8, 2008, Between the U.S. Nuclear Regulatory Commission Staff and Entergy Nuclear Operations, Inc. Representatives to Discuss the Response to a Request for Additional Information Pertaining to the Vermont Yankee Nuclear Power Station License Renewal Application).

At the February 7, 2008 meeting of the ACRS, which I attended, the NRC Staff informed the ACRS that it was satisfied with the CUFen calculations based on Entergy's then-reported "confirmatory" results for the feedwater nozzle. As reported in the FSER, however, during a subsequent February 14, 2008 audit of Entergy's confirmatory analysis, the NRC Staff requested that Entergy recalculate the feedwater nozzle CUFen yet again, substituting a different Fen value. Specifically, NRC Staff requested use of "the maximum Fen value used in [Entergy's] previous analyses," rather than "different, but appropriate" Fen values Entergy had used in its "confirmatory" analysis.[10]

The following Table 2 summarizes how Entergy's reported CUFen values for the feedwater nozzle have changed with each iteration of its analysis.

Table 2- CUFen Calculations For the Feedwater Nozzle

REFERENCE	CUF	Fen	CUFen
License Renewal Application Table 4.3-3	0.750	3.81	2.86
Entergy Initial CUFen Reanalysis Using Simplified Green's Function. NEC Exhibit JH_18 at 3-18, Table 3-10.	0.0636	10.05	0.6392
Entergy "Confirmatory" CUFen Reanalysis. NEC Exhibit JH_21 at 7, Table 1.	0.0889	3.97	0.3531
Adjusted "Confirmatory" Reanalysis result verbally provided during February 14, 2008 NRC Staff audit of Entergy's "Confirmatory" Reanalysis. FSER, NRC Staff Exhibit 1 at 4-42.			0.8930

A comparison of Entergy's result using the simplified Green's function method, 0.639, with its "confirmatory" result, ultimately 0.8930 as recalculated February 14, 2008, demonstrates that the simplified Green's

[10] FSER, NRC Staff Exhibit 01 at 4-42.

function method underestimates CUF by about 40%. As reported in the FSER, the NRC Staff therefore concluded that "the results of the Green's function application using the specific software could underestimate CUF, and therefore cannot be the analysis of record."[11]

The NRC Staff has designated Entergy's "confirmatory" analysis the "analysis of record" for the feedwater nozzle.[12] The NRC Staff has also recommended a license condition that would require Entergy to perform the "confirmatory" analysis for the spray (CS) and recirculation (RR) nozzles no later than two years before the start of the life extension period.[13]

The NRC Staff is now revisiting the sufficiency of environmentally-assisted fatigue analyses based on the simplified Green's function method, which the NRC had previously accepted in support of license renewal for plants other than Vermont Yankee. On April 18, 2008, the NRC Staff issued a Regulatory Issue Summary ("RIS"), requesting that "license renewal applicants that have used this simplified Green's function methodology perform confirmatory analyses to demonstrate that the simplified Green's function analyses provide acceptable results."[14] This RIS also states: "For plants with renewed licenses, the staff is considering additional regulatory actions if the simplified Green's function methodology was used."[15] On April 3, 2008, the NRC Staff issued a Notification of Information in Docket No. 50-219-LR (License Renewal for Oyster Creek Nuclear Generating Station), stating that it will require "confirmatory" fatigue analyses due to Oyster Creek's reliance on the simplified Green's function method.[16]

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[11] Id. at 4-43.

[12] Id. at 4-43.

[13] Id.

[14] Exhibit NEC-JH-23 at 2.

[15] Id.

[16] Exhibit NEC-JH_24.

III. ASSESSMENT OF ENTERGY's CUFen REANALYSES

The following discussion explains my assessment of both Entergy's initial and "confirmatory" CUFen reanalyses. Part A explains that Entergy failed to produce information necessary to validate both analyses. Part B lists key assumptions underlying both analyses. Part C explains why, as a results of Entergy's key assumptions, both analyses underestimated CUFen, and overestimated expected fatigue life. Part D discusses the significance of Entergy's failure to perform an error analysis. Part E explains why the "confirmatory" analysis of the feedwater nozzle does not bound the analysis for other components.

A. Incomplete Information

The materials Entergy has produced to NEC in the ASLB proceeding do not include all the information necessary to establish the validity of Entergy's CUFen reanalyses, initial or "confirmatory." Specifically, Entergy has not provided:

1. Adequate layout drawings of the plant piping. Based on the information provided, I cannot determine how the connecting pipes are oriented with respect to the nozzles; how many diameters the pipe is straight upstream of each nozzle; or whether there are any discontinuities, such as welds, upstream of the nozzle.[17] This information is necessary to validate the assumption of uniform heat transfer distribution.

2. A complete description of the methods or models used to determine velocities and temperatures during transients. For example, the following discussion appears in the Structural Integrity Associates, Inc. ("SIA") report of Entergy's initial CUFen reanalysis, VY-16Q-307:

> The internal heat transfer coefficient h for the transients with flow occurring in the pipe is calculated based on the following relation for forced convection:

[17] Exhibit NEC-JH_25 is illustrative of the layout drawings Entergy produced to NEC.

$h = 0.023\ Re^{0.8}\ Pr^{0.4}\ k/D$

Where Re = Reynolds number
Pr = Prandtl number
k = Thermal conductivity
D = Pipe diameter

The heat transfer coefficients were calculated by PIPESTRESS using the above relation. The flow rates described for each transient in Section 3 were used. For the transients where flow is stopped, the natural convection heat transfer coefficient was used. The formula for h is:

$h=0.55\ (Gr\ Pr)^{0.25}\ k/L$

Where Gr = Grashof Number
L = Pipe diameter

PIPESTRESS only has the forced convection heat transfer formula built in, so an equivalent flow rate was determined that would give the same heat transfer coefficient as the free convection coefficient.[18]

I cannot determine, based on this discussion, how this was done when the flow goes to zero. I discuss this issue in more detail in Part III(C)(2) of this report.

B. Entergy's Assumptions

Both Entergy's Initial and "Confirmatory" CUFen Reanalyses incorporated the following assumptions:

1. The environmental correction factor, Fen, depends only on the temperature, the dissolved oxygen, the sulphur content and the strain rate.

[18] Exhibit NEC-JH_10 at 12-13,(emphasis added).

2. With respect to determination of the heat transfer coefficients in all three nozzles:

    a. Nozzle entrance and exit effects can be neglected
    b. Water properties do not change with temperature
    c. Uniform circumferentially.

3. The base metal under the cladding at the feedwater blend radius has no cracks.

4. The number of transients will increase linearly with time during the life extension period.[19] It was assumed that the 40-year CUFs can be multiplied by 1.5 to project those values to the end of the 60 year extended period.

5. The oxygen at the surface of any component can be evaluated based on plant records, using the EPRI –BWRVIA computer code.

Entergy's Initial CUFen Reanalysis also included the following additional assumption:

6. Green's functions can be used as a substitute for the ASME Code Section III, Subsection NB-3200 method.

C. Assessment of Assumptions

Entergy's above-stated assumptions resulted in the underestimation of CUFen, and the overestimation of expected fatigue life, for the following reasons.

1. Environmental Correction Factor, Fen

Entergy calculated the Fen parameters based on outdated Argonne National Laboratory (ANL) statistical equations stated in NUREG/CR 6583 and NUREG/CR 5704 ("the NUREG equations"), which were derived more

[19] Exhibit NEC-JH_18 at 3-18, note 2 (CUF results based on "actual cycles accumulated to-date and projected to 60 years.").

than nine years ago.[20] In February 2007, ANL updated the previous data and published its results in NUREG/CR-6909.[21] The revised ANL equations are based on a much larger database and the limits of their applicability is more clearly stated.

The developer of the revised ANL equations, O. Chopra, stated to the ACRS:

> To apply the laboratory data to actual reactor components, we need to adjust these results to account for parameters or variables which we know affect fatigue life but are not included in this data. And these variables are **mean stress, surface finish, size, and loading history.**[22]

This same caveat is repeated in NUREG/CR-6909. To account for uncertainties, the NUREG report states:

> **"Under certain environmental and loading conditions, fatigue lives in water relative to those in air can be a factor of ≈12 lower for austenitic stainless steels, ≈3 lower for Ni-Cr-Fe alloys, and ≈17 lower for carbon and low-alloy steels."**

NUREG/CR-6909 at 62.[23]

Entergy did not provide any data on the surface roughness of the components it evaluated. The ANL equations were developed using a crack free, smooth specimen. In comparison to a smooth surface, a rough surface would reduce the fatigue life by a factor of 3.[24] Since most of the components Entergy evaluated were fabricated from carbon or low alloy steel, they are susceptible to flow accelerated corrosion, FAC, which characteristically increases surface roughness. In the case of the VY

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[20] Exhibit NEC-JH_18 at 3-1.

[21] Exhibit NEC-JH_26.

[22] Exhibit NEC-JH_27 at 22.

[23] Exhibit NEC-JH_26 at 62.

[24] Exhibit NEC-JH_26 at 14.

feedwater nozzle, the existence of surface cracks at the blend radius both in the clad and the base metal is another factor that must be considered (see Comment 3 below).

Because of the above uncertainties, I believe that it is appropriate to use a factor of 17, at a minimum, to correct the CUFs for environmental effects.

At the February 7, 2008 ACRS meeting, which I attended, in response to an ACRS member question as to why Entergy is allowed to use old fatigue data, the NRC staff stated only that it has traditionally used the old data in approving LRAs and did not want to change the procedures at this time.[25] The Staff stated that the new data will apply to new reactor applications.[26] It would appear that it would be equally important, if not more important, to apply the new data to a 40 year reactor.

2. Heat Transfer

Entergy used the following heat transfer equations to calculate the thermal stress for each transient:

1. $h = 0.023\ (Re)^{.8}\ (Pr)^{.4}\ k/D$[27]

2. $h = 0.55\ (GrPr)^{.25}\ k/L$[28]

3. $h = 0.555\ (R\ (R-Rs) g k^3 h_{fg} / (ud\ \ del\ T))^{.25}$ (R=rho, u =mu)[29]

Equation 1 is applicable only to a fully developed turbulent flow, constant fluid properties in pipes. The flow in all three nozzles is not the same as in a straight pipe because the nozzle is relatively short and it

[25] Exhibit NEC-JH_28 at 96-97.

[26] Id.

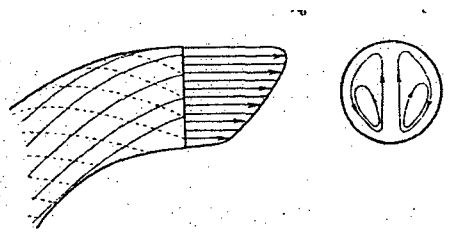
[27] Exhibit NEC-JH_04 at 11, Table 4.

[28] Exhibit NEC-JH_14 at 14.

[29] Exhibit NEC-JH_19 at 7.

contains discontinuities. It is difficult to see how the flow could be fully developed, especially at the exit from the nozzle at the blend radius area (Region 6).[30] Nevertheless, depending on the Reynolds number and the distance from the inlet to the nozzle, the heat transfer can be either above or below the value specified by Equation 1. Plots for calculating the heat transfer at the entrance section of pipes can be found on page 212 of Reference 2.[31] Equation 1 also must be corrected by the ratio of the viscosities evaluated at the bulk and wall temperatures during each transient. Page 212 of Reference 2 also provides such a correction.[32]

To justify the use of the axixsymetrical model, Entergy must first show that the flow upstream of each nozzle is fully developed at the entrance to the nozzle and its main axis coincides with the axis of



the nozzle. As shown in Reference 3 and the above sketch, the velocity distribution in the nozzle will vary circumferentially.[33] Such flow distribution would lead to circumferentially varying wall temperature and different stress distribution than would be predicted by an axixsymetrical model.

To my knowledge, Entergy has not provided to NEC the complete piping layout as it exists now in the plant. Unless special precautions were

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[30] See, Exhibit NEC-JH_04 at 16.

[31] Exhibit NEC-JH_29.

[32] Id.

[33] Exhibit NEC-JH_30.

taken during installation, one must assume that the connecting pipe is at some angle with respect to the nozzle and therefore the axixsymetrical assumption is not valid.

Equation 2 is used to calculate average heat transfer coefficients when the flow is driven by gravitational forces. This equation is not appropriate for applications where one is required to determine local stress distributions along the pipe and not average stress distributions.

Equation 2 does not apply because, for some transients, the forced convection internal flow in pipes stops, and the flow becomes driven by gravity forces.[34] Based on physical considerations, the flow does not just suddenly go from forced convection to natural convection, but it rather goes through a mixed forced/free convection region. In the free convection region, the flow is driven by gravity forces and its fundamental characteristic is commonly described by a flow down a vertical plate where both the velocity and the heat transfer coefficient vary with the height of the plate. The natural convection flow inside a pipe is more complex and is based on empirical correlations of the average heat transfer coefficient such as given in Equation 2 for laminar flow. This equation does not describe the variation in the heat transfer coefficient, and the stresses, along the pipe.

The following statement quoted from one report of Entergy's initial CUFen reanalysis demonstrates that Entergy ignored the inherently local feature of natural convection:

> PIPESTRESS only has the forced convection heat transfer formula built in, so an equivalent flow rate was determined that would give the same forced convection heat transfer coefficient as the free convection heat transfer coefficient.[35]

Such a procedure is appropriate for the determination of overall heat balances but not for the determination of stress distributions.
In my opinion, the stress analysis should not be dictated by what is available in a given computer program; it should be driven by the nature of the problem.

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[34] Exhibit NEC-JH_14 at 14.

[35] Id.

Equation 3 is an empirical equation for the average heat transfer coefficient during condensation of refrigerants at low laminar velocities. For higher flow rates, a different equation must be used. Entergy did not specify that the flow in the nozzle was laminar. More importantly, to calculate the temperature distribution in the nozzle, one must use local heat transfer coefficients, not average values. Average heat transfer coefficients can only be used to calculate overall heat balances, not local temperatures.

Entergy's CUFen results are based on the assumption that the stresses are axixsymetric in all nozzles. As shown on page 26 of SIA report VY-16Q-310, the stress in a given nozzle is very sensitive to the heat transfer coefficient.[36] Throughout its analyses, Entergy used location-independent heat transfer coefficients, which is inappropriate, as I have explained in the above discussion.

3. Base Metal Cracks

In the late 1970s, the feedwater nozzles of most BWR plants developed cracks due to high cycle fatigue because of differences in the thermal properties of the cladding and the base metal. The cladding was removed from most BWR plants, with the exception of Vermont Yankee and a few others. NUREG-O609. In the Millstone 1 plant, some cracks penetrated to 1/3' at the blend radius area. Because the cladding is 5/16" thick and high cycle fatigue cracks propagate to depths of about ¼" or more, the base metal may contain cracks, especially after 40 years of service. Id. In RAI 4.3-H-02, VY admitted that the cladding may contain cracks,[37] but has not provided any data to indicate that these cracks did not penetrate the base metal. They did, however, admit to the possibility that such cracks will penetrate the base metal. The 2001 inspection of the feedwater nozzles only indicates that the results were "acceptable".[38] Since Ultrasonic Inspection, UT, measures only the total length of a crack and, based on the VY drawings Entergy has produced, the exact thickness of the clad is not known,[39]

[36] Exhibit NEC-JH_13 at 26.

[37] FSER, NRC Staff Exhibit 1 at 4-26 – 4-27.

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[38] Exhibit NEC-JH_32 at 4.

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[39] Exhibit NEC-JH_25.

Entergy has not provided any proof that the base metal is not cracked. One therefore must assume that the base metal is cracked and account for these cracks in the ASME Code analysis. The ASME Section III, NB 3122.3 does not require Entergy to include the cladding in the structural analysis because the cladding is less than 10% of wall thickness. When, however, subsurface cracks are known to exist, they can not be ignored in the ASME Code analysis, and must be included together with the cladding.

4. Number of Transients

Entergy's apparent assumption that the number of transients the plant would experience varies linearly with time must be challenged. The failure frequency of pressure vessels (and mechanical and electrical components) is statistically very high later in life due to aging of the plant. The recent VYNPS 20% power uprate introduced new stresses on already aging components, and will likely increase the number of unanticipated transients, as demonstrated by the August, 2007 collapse of the VYNPS cooling tower and plant shutdown due to a steam valve failure. VYNPS experienced two unanticipated transients within 10 days in late August 2007. Based on this experience and the assumption of linearity, one could predict 912 transients during the next 25 years. The above extreme case illustrates that Entergy must consider a more conservative number of transients than predicted by the linear formula to project the number of transients during the extended period of operation.

Entergy provided no justification for selecting a non-conservative factor for projecting the number of transients. In my opinion, the number of transients proposed by Entergy should be at a minimum multiplied by 1.2 to account for the probability of an increase in unanticipated failures due to the 20% power uprate.

5. Oxygen

Even though the Fen varies exponentially with oxygen concentration, Entergy did not discuss the reasons for not including unanticipated changes in water chemistry (oxygen excursions) during the extended period. Nor did they explain how the chemistry data from the feedwater line or the

electrochemical potential measurements relate to the oxygen concentration at the component surface during transients.

Only in February 2008, in response to an NRC Staff request for information concerning how Entergy's CUFen analysis accounted for water chemistry effects, Energy stated for the first time that the EPRI –BWRVIA computer code was used at VY to assess the oxygen concentration at the surface of a given component.[40]

NRC requires that analytical codes be assessed and benchmarked against measured plant data. Safety Evaluation by the Office of Nuclear Reactor Regulation Related to Amendment No. 229 to Facility Operating License No. DPR-28, Entergy Nuclear Vermont Yankee, LLC and Entergy Nuclear Operations, Inc., Vermont Yankee Nuclear Power Station, Docket No. 50-271 § 2.8.7.1.[41] A code is only considered valid within the range in which the data was provided.[42] Entergy did not describe how the BWRVIA code was benchmarked.

The oxygen concentration at the surface of any given component can only be estimated by considering the kinetics of oxide buildup and dissolution throughout the plant. Since Entergy has not described the algorithm in the BWRVIA code, one must assume that the oxygen concentrations that were used by Entergy to calculate the Fens contain unknown errors.

6. Green's Function

In its initial analysis, Entergy applied a simplified Green's function method to calculate stresses for each transient, instead of using the ASME Code, Section III, Subsection NB-3200 approach.[43] The Green's function is a powerful tool that, when properly applied, can considerably reduce the cost of the ASME code analysis, especially when the number of transients is

[40] Exhibit NEC-JH_ 33 at Attachment 2.

Deleted: 34

[41] Exhibit NEC-JH_ 35.

[42] Id.

[43] See, e.g., Exhibit NEC-JH_04.

very large. The Green's function is also, however, an approximate technique in comparison to the NB-3200 methodology, which may introduce errors in the final calculations of the CUF.

As discussed in Part II(A) of this report, a comparison of Entergy's results using the simplified Green's function method with the results of its "confirmatory" analysis for the feedwater nozzle demonstrate that the Green's function method underestimated CUF by about forty percent. For this reason, also as discussed in Part II(A) of this report, the NRC Staff rejected Entergy's initial CUFen analysis.

D. Lack of Error Analysis

To validate its analytical techniques, Entergy should have performed an error analysis to show the admissible range for each variable. Based on the reports of Entergy's CUFen reanalyses produced to NEC,[44] it has not done so. The lack of error analysis is troubling. For example, Entergy reported a CUFen of 0.74 for the RHR Class 1 piping (Table 1, above). In light of the fact that data scatter in fatigue studies often exceeds an order of magnitude, the value of 0.74 without an error band has little significance and imparts little confidence that fatigue failure will not occur.

E. "Confirmatory" Analysis of Feedwater Nozzle

I have reviewed the reports produced to NEC of the additional "confirmatory" CUFen analysis of the feedwater nozzle that Entergy conducted at the request of the NRC Staff.[45] This analysis contains all of the errors in calculation of both CUF and Fen values that I have discussed in Part III(C) above, except that the simplified Green's function method was not used.

Even if it were valid, I do not agree that the "confirmatory" analysis would bound the analysis for components other than the feedwater nozzle. There are considerable differences in geometry, heat transfer characteristics, and loadings between the feedwater and the other two nozzles. These differences could result in different stress distributions which would affect

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[44] Exhibits NEC-JH_04 – NEC-JH_21.

[45] Exhibits NEC-JH_19 – NEC-JH_21.

the CUFs. Entergy did not discuss these differences; instead it only provided the following vague and unscientific statement:

> The analysis of the feedwater nozzle is bounding for the core spray and recirculation outlet nozzles since the calculated usage factors are at least 70% less than those for the feedwater nozzle and the number and severity of thermal transients are less.[46]

The statement that the feedwater nozzle results are bounding could only be justified if Entergy had demonstrated an understanding of the reasons for the differences in the CUFs obtained by the simplified Green's function analysis and those that were obtained by the more exact classical ASME analysis. **Entergy was not able to do so.**

IV. HOPENFELD CUFen RECALCULATION

The CUFens calculated by Entergy, with and without the simplified Green's function method, contain error and they are unreliable. An alternative to these calculations is to use the conservative CUFs as were originally provided in LRA and multiply them by the bounding values given in NUREG/CR-6909. The results of this procedure are given below in Table 3.

[46] Exhibit NEC-JH_34 at Attachment 1.

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TABLE 3 - Recalculated Cumulative Usage Factors for Sample Locations at VYNPS

No.	NUREG/CR-6260 Sample Location (License Renewal Application, Table 4.3-3)	CUF (VYNPS License Renewal Application, Table 4.3-3)	Fen (Ref. 1)	**Recalculated CUFen**
1	Vessel shell & bottom head	0.400	17	6.80
2	Core spray safe end	0.182	12	2.18
3	Feed water nozzle	0.750	17	12.75
4	RHR return Piping	0.032	12	0.38
5	RR inlet nozzle	0.610	17	10.37
6	RR piping tee	0.397	12	4.76
7	RR outlet nozzle	0.810	17	13.77
8	Core spray nozzle	0.625	17	10.62
9	Feed water piping	0.427	17	7.26

V. SUMMARY

By introducing five key assumptions, excluding those connected with use of the Green's function methodology, Entergy purports to show that the CUFens for all NUREG/CR-6260 limiting locations are less than one. My assessment demonstrates that Entergy ignored critical factors in making its assumptions. When these assumptions are lifted and more appropriate and conservative assumptions are introduced, the CUFen for all but one of the components exceeds unity.

Entergy has not demonstrated that the predicted fatigue life of risk-significant components at VY will meet the ASME criteria for safe operation for the extended period of operation. Neither Entergy's initial analysis nor its "confirmatory" analysis demonstrate that CUFens for the components listed in License Renewal Application 4.3-3 or NUREG/CR-6260 limiting locations are less than one. It is my opinion that acceptance of Entergy's results will lead to an unjustified reduction in the scope of fatigue monitoring at the Vermont Yankee plant.

Entergy should be required to develop a valid methodology for calculating CUFen; expand its fatigue analysis to components in addition to the NUREG/CR-6260 locations if a valid CUFen analysis indicates that CUFen for any NUREG/CR-6260 location will exceed unity; and formulate a meaningful plan to properly inspect and maintain all components which are susceptible to fatigue.

VI. REFERENCES

1. J. P. Holman, Heat Transfer, 1981 Ed.

2. E. R. G. Eckert and R. Drake, Heat and Mass Transfer 2nd, Ed 1959.

3. H. Schlichting, Boundary Layer Theory, 4th Ed. 1960.

4. NUREG/CR-6909, "Effect of LWR coolant Environment on Fatigue Life of Reactor Materials" (Final Report), ANL -06/08 U.S. NRC, Wash., D.C. Feb. 2007.

5. NUREG/CR-6583, "Effect of LWR Coolant Environment on Fatigue-Design Curves of Carbon and Low Alloy Steels," March 1998.

6. NUREG/CR 5704, "Effect of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steel," April 1999.

7. NUREG/CR-6936, "Probability of Failure and Uncertainty Estimate for Passive Components – A Literature Survey," May 2007.

VII. GLOSSARY OF TERMS

Cumulative Usage Factor (CUF) – A summation of usage fatigue factors.

Fatigue -- An age-related degradation mechanism caused by cyclic stressing of a component by either mechanical or thermal stresses that eventually cause the component to crack

Feedwater Nozzle- A short pipe welded to the reactor vessel through which feedwater enters the vessel.

Fen – An environmental correction factor used to account for differences between fatigue in water and fatigue in air, defined as the ratio of the fatigue life in air at room temperature to that in water at the service temperature.

Green's Function – A simplified numerical technique for thermal stress calculations.

Laminar Flow – Sometimes known as streamline flow, it occurs when a fluid flows in parallel layers, with no disruption between layers.

Recirculation Nozzle - A short pipe welded to the reactor vessel through which water flow either in or out of the jet pump.

Spray Nozzle – A nozzle on top of the vessel used to cool the core in case of an accident.

Transient – Plant response to a change in power level.

Turbulent Flow – Fluid (gas or liquid) flow in which the fluid undergoes irregular fluctuations or mixing, in contrast to laminar flow, in which the fluid moves in smooth paths or layers. In turbulent flow, the speed of the fluid at a point is continuously undergoing changes in both magnitude and direction.

Usage Fatigue Factor -- The number of cycles n at any given stress amplitude divided by the corresponding number of cycles to end of life, N.