ATTACHMENT 3
Limerick Generating Station, Units 1&2
Upper Shelf Energy Evaluation for LPCI Forging Material (non-proprietary version)

GE Hitachi Nuclear Energy

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Limerick Generating Station, Units 1&2

Upper Shelf Energy Evaluation for LPCI Nozzle Forging Material

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REVISION CONTROL SHEET

Revision	Date	Description
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ACRONYMS & ABBREVIATIONS

Short Version	Definition
1/4T	¼ Depth into the Vessel Wall from the Inside Diameter (Clad Is Not Considered)
ASME	American Society of Mechanical Engineers
ASME Code Edition	LGS was fabricated in accordance with the 1968 Edition, including Summer 1969 Addenda.
BWR	Boiling Water Reactor
BWROG	BWR Owners' Group
CMTR	Certified Material Test Report
Cu	Copper
CVN	Charpy V-Notch USE (ft-lbs)
EMA	Equivalent Margin Analysis
EOL	End of License
EPRI	Electric Power Research Institute
ft-lb	Foot-pound
GE	General Electric
GEH	GE Hitachi Nuclear Energy, LLC
GL	Generic Letter (originated by the NRC)
$J_{0.1}$	J-Integral from Applied Loads at a Ductile Crack Growth of 0.1 inch Depth into the Vessel Wall Plus Clad Thickness
$J_{applied}$	J-Integral from Applied Loads (in-lb/in^2)
$J_{material}$	Material's J-Integral Fracture Resistance J-R Curve (in-lb/in^2)
J_R	J-Integral Fracture Resistance Curve
J-R	J-Integral Fracture Resistance
ksi	psi/1000
LGS	Limerick Generating Station
LPCI	Low Pressure Coolant Injection
n/cm^2	Neutrons/ centimeter squared (measure of fluence)
Ni	Nickel
NRC	United States Nuclear Regulatory Commission (sometimes US NRC)
psi	Pounds per Square Inch
Region B	Vessel Region from the Bottom of the Jet Pump to the Bottom of the Feedwater Nozzle
RG	Regulatory Guide
RPV	Reactor Pressure Vessel
RT_{NDT}	Reference Temperature of Nil-Ductility Transition
RVID	NRC Reactor Vessel Integrity Database (available from nrc.gov)
S	Sulphur
TPO	Thermal Power Optimization
USE	Upper Shelf Energy
WLI	Water Level Instrumentation
wt%	Weight Percent (Elemental Content)

EXECUTIVE SUMMARY

10CFR50 Appendix G states that the reactor pressure vessel (RPV) must maintain upper shelf energy (USE) of no less than 50 ft-lbs throughout its life, unless it is demonstrated in a manner approved by the Director, Office of Nuclear Reactor Regulation, that lower values of USE will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code. The BWR Owners' Group developed a licensing topical report (NEDO-32205-A) on equivalent margin analysis for low USE BWR/2 through BWR/6 RPVs, which was reviewed and approved by the NRC for use by individual utilities.

In their Thermal Power Optimization (TPO) submittal, Limerick (LGS) Units 1&2 assumed a low USE for the Limerick LPCI nozzle forgings based on available Certified Material Test Report (CMTR) data. The data was the result of low temperature Charpy specimen testing that also had low Shear results. In addition, the Charpy energies were further reduced because there was no indication whether the specimens were prepared in the strong or weak direction. In accordance with MTEB 5-2, a Branch Technical Position for Fracture Toughness Requirements that provides a summary and clarification of the requirements of 10CFR50 Appendix G and Appendix H, the results were reduced by a factor of 0.65. The LGS minimum end of license (EOL) USE was reported as 24 ft-lbs, less than the 50 ft-lb requirement. Therefore, the Equivalent Margin Analysis (EMA) methodology was used to demonstrate that the reduction to account for embrittlement effects, as defined in Regulatory Guide 1.99, Revision 2 (RG1.99), was within the requirements defined in NEDO-32205-A.

However, the topical report does not provide evidence that the EMA methods for plate are applicable to forging material. Therefore, this report documents a plant-specific evaluation that was conducted to show compliance with the USE requirements.

It is demonstrated that the LGS N17 LPCI nozzles should have an initial USE of 70 ft-lbs or greater, based on a comprehensive review performed by Altran for the Brunswick Nuclear Station. Therefore, considering a maximum of 10.8% decrease as prescribed in RG1.99, the LGS LPCI nozzles will maintain 62.4 ft-lbs at end of license, which provides sufficient margin to the requirements of 10CFR50 Appendix G. To further demonstrate the acceptability of the nozzle USE, a J-R curve evaluation was performed.

This LGS forging material USE evaluation follows essentially the methodology outlined in ASME Code Case N-512-1, Appendix K of ASME Section XI and Regulatory Guide 1.161 (RG1.161). The evaluation shows that the Level A/B Condition is governing.

Based on the results of this plant-specific evaluation, it is concluded that the LPCI nozzle forgings in the LGS RPV meet the margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code and RG1.161. This conclusion is valid for operation including Thermal Power Optimization.

The LGS Water Level Instrumentation (WLI) nozzles are J-weld penetrations in the plate, with a forging fabricated from SB166 material that is less than 2.5 inches thick. Therefore, evaluation for fracture toughness is not required. As a result, the evaluation for the WLI nozzle is based upon the plate material in the shell where the WLI penetrations occur. Therefore, the application of the topical report is appropriate for the LGS WLI nozzles, and further evaluation is not required.

1.0 INTRODUCTION AND BACKGROUND

This report will demonstrate that the forging material for the LGS N17 LPCI nozzles exhibits sufficient tear resistance and ductile stability for Levels A, B, C, and D operating conditions. The Upper Shelf Energy (USE) margin evaluation methodology used in this report is consistent with that prescribed in Code Case N-512-1 (Reference 6), Section XI Code Non-Mandatory Appendix K (Reference 7), and (RG1.161) (Reference 8). Although Code Case N-512 (References 5, 6, and 7) were in development at the same time that the topical report (Reference 3) was being developed, and Reference 8 was published later, a review of the methodology used in Reference 3 indicated that in almost all respects, it is consistent with References 6, 7, and 8). If there were any small differences, such as that in the selection of J-R curves, the topical report used a conservative approach. The methodology prescribed in Reference 8 is exclusively followed in this report. An earlier evaluation was performed for the N16 nozzle at Brunswick Steam Electric Plants, Units 1 and 2 (Reference 15), which was accepted by the NRC (Reference 16) and established the applicability of this methodology for nozzle forgings.

The methodologies prescribed in Reference 7, 8, and 9 do not specifically identify that which is applicable to forging materials. It is noted in Reference 7, however, that the equations are applicable to SA508-2 as well as SA302B and SA533B. Therefore, portions of previous submittals and approvals will be utilized so as not to duplicate, and to take advantage of previous regulatory reviews. The use of the BWROG topical report (Reference 3) clearly defines an NRC-approved J-R curve methodology, including the use of specific transients applicable to BWRs, and is therefore cited throughout this report.

1.1 Historical Background

The nuclear reactor pressure vessels (RPVs) are typically made of low-alloy ferritic steels (e.g., SA302B; or SA533, Grade B, Class 1). They are exposed to high energy neutrons in the beltline region; as a result, the constituent parts (i.e., the plates, forgings, and welds) can experience degradation of material properties: yield and ultimate tensile strengths increase, brittle-to-ductile transition temperature increases, and the upper shelf toughness decreases. The last two effects are the most important from the point of view of structural margins during operation of an RPV. The impact of low Charpy USE on the LGS RPV integrity analyses is the subject of this report.

10CFR50 Appendix G (Reference 1) states that the RPV must maintain USE of no less than 50 ft-lbs throughout its life, unless it is demonstrated in a manner approved by the Director, Office of Nuclear Reactor Regulation, that lower values of USE will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code (Reference 2). In September 1992, the Nuclear Regulatory Commission (NRC), in discussing the preliminary review of the responses to Generic Letter 92-01, strongly recommended the equivalent margin analyses (EMA) be performed by the Owners' Group. In response to this, the BWROG developed a licensing topical report on equivalent margin analysis for low USE BWR/2 through BWR/6 vessels (Reference 3) that was reviewed and approved by the NRC (Reference 4). The topical report, which could be referenced by utilities as part of their

licensing basis, can be used to address compliance with the 50 ft-lb requirement. Appendix B of the topical report presents the steps required to show that the USE requirements presented in the report can be applied to individual BWR plants. The plants always have the option to perform a plant-specific USE margin evaluation.

The topical report followed the methods provided in the then-draft Appendix X of the ASME Code, which has since become Code Case N-512 (Reference 5) and subsequently revised as Code Case N-512-1 (Reference 6). This Code Case was incorporated in the Section XI Code as Non-Mandatory Appendix K (Reference 7). The NRC staff reviewed the analysis methods in Appendix K and found them to be technically acceptable but not complete with respect to information on the selection of transients, and the selection of material properties. As a result the NRC issued RG1.161 (Reference 8) providing specific guidance on these issues.

1.2 Limerick Generating Station (LGS) N17 LPCI Nozzle

At LGS, the LPCI nozzles are included in the beltline region because they will accumulate fluence greater than 1.0e17 n/cm^2 by end of license (32 EFPY). At the time of vessel fabrication, forgings were not included in the beltline region; hence, the available data does not provide sufficient information to determine the upper shelf energy. In lieu of high Shear results, the plant used Charpy values from low temperature tests with correspondingly low Shear. For LGS Units 1 and 2, the minimum Charpy values were a result of tests at -20°F with Shear of only 40%. Because the data was not identified as being in the strong or weak direction, the USE was assumed to be in the strong direction, and was reduced using a factor of 0.65 in accordance with MTEB 5-2 (Reference 9). For LGS Unit 1, the minimum initial USE for the LPCI nozzle was 26.7 ft-lbs; for Unit 2, the minimum initial USE was 28 ft-lbs. The end of license USE values did not meet the minimum required value of 50 ft-lbs defined in 10CFR50 Appendix G. Therefore, a plant-specific evaluation was conducted to show compliance.

As stated above, the LGS data does not demonstrate USE. Therefore, this evaluation uses the Brunswick approach as presented in Reference 15 and accepted by the NRC in Reference 16. Extensive research was performed in Reference 15, resulting in an initial USE of 70 ft-lbs. The NRC database, RVID2, was reviewed; Table 5-5 includes several additional data points that were not included in the corresponding table in Reference 15.

The plant-specific evaluation essentially followed the methodology consistent with the requirements of Section XI Code Case 512-1 (Reference 6), Appendix K (Reference 7), and RG1.161 (Reference 8). Also, the selection of transients was justified in relation to the LGS vessel transients for Levels A through D operating conditions. The most limiting transients were considered for Levels A, B, C, and D, in accordance with the requirements of Section 4 of RG1.161, as discussed in more detail in the following sections.

1.3 Methodology

It is noted that neither Appendix K nor RG1.161 specifically identifies methodology to perform these calculations for forgings. However, Section K-4210 of Appendix K states that,

for SA508-2, it is applicable to use the same properties as for SA302B and SA533B. The applicability of this methodology for nozzle forgings was also established by the NRC acceptance (Reference 16) of the Altran report (Reference 15) prepared for the N16 nozzle at Brunswick Steam Electric Plants, Units 1 and 2.

1.4 LGS Water Level Instrumentation (WLI) Nozzle

The LGS Water Level Instrumentation (WLI) nozzles are J-weld penetrations in the plate, with a forging fabricated from SB166 material that is less than 2.5 inches thick. Therefore, evaluation for fracture toughness is not required. As a result, the evaluation for the WLI nozzle is based upon the plate material in the shell where the WLI penetrations occur. Therefore, the application of the topical report is appropriate for the LGS WLI nozzles, and further evaluation is not required.

2.0 SCOPE

The objective of the analysis documented in this report is to demonstrate that the LGS RPV forging materials meet the margins of safety against fracture equivalent to those required by 10CFR50 Appendix G. This will be accomplished by demonstrating that the EOL USE exceeds 50 ft-lbs, and further demonstrating, by equivalent margin analysis, that a USE less than 50 ft-lbs maintains the required margin of safety against fracture, thereby meeting the requirements of 10CFR50 Appendix G.

In the LGS Thermal Power Optimization (TPO) submittal, USE EMA methods were applied to both the Water Level Instrumentation (WLI) nozzles and the LPCI nozzles. It will be demonstrated that the WLI nozzles are appropriately evaluated using EMA methods, and that the LPCI nozzles meet the USE requirements for the SA508-2 materials.

3.0 SUMMARY OF ANALYSIS RESULTS

10CFR50 Appendix G states that the RPV must maintain USE throughout its life of no less than 50 ft-lbs, unless it is demonstrated in a manner approved by the Director, Office of Nuclear Reactor Regulation, that lower values of USE will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code. The BWROG developed a licensing topical report on equivalent margin analysis for low USE BWR/2 through BWR/6 RPVs, which was reviewed and approved by the NRC for use by individual utilities.

At LGS, the plant assumed a low USE for the Limerick RPV LPCI nozzle forgings due to insufficient data. As a result, the initial USE was determined to be less than 50 ft-lbs; hence, the EOL USE value did not meet the minimum required value of 50 ft-lbs. This report documents a plant-specific evaluation that was conducted to show compliance with the USE requirements. Following the Brunswick approach (Reference 15), the minimum resulting end of license USE for LGS Units 1 and 2 is 62.4 ft-lbs, which provides sufficient margin to the requirements of 10CFR50 Appendix G. The applicability of this methodology for nozzle forgings was established by the NRC acceptance (Reference 16) of the Altran report (Reference 15).

This LGS USE evaluation followed essentially the methodology outlined in ASME Code Case N-512-1 (Reference 6), Appendix K of ASME Section XI (Reference 7), and RG1.161 (Reference 8). The evaluation showed that the Level A/B Condition was governing.

Based on the results of this plant-specific evaluation, it is concluded that the LPCI nozzle forging material in the LGS RPV meets the margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code. This conclusion is valid for operation at Thermal Power Optimization (TPO) conditions.

The LGS Water Level Instrumentation (WLI) nozzles are J-weld penetrations in the plate, with a forging fabricated from SB166 material that is less than 2.5 inches thick. Therefore, evaluation for fracture toughness is not required. As a result, the evaluation for the WLI nozzle is based upon the plate material in the shell where the WLI nozzles occur. Therefore, the application of the topical report is appropriate for the LGS WLI nozzles, and further evaluation is not required.

4.0 LGS USE EVALUATION FOR THE WLI NOZZLE

The LGS WLI nozzle forging is fabricated from SB166 and is less than 2.5 inches thick. Therefore, evaluation for fracture toughness is not required. Instead, the penetration for the WLI nozzle is evaluated considering the plate material and fluence at the location of the penetration. Because the fluence at the penetration is much lower than the maximum for the beltline plates, the WLI nozzle USE is bounded by that for the plate location.

For the WLI nozzle, the limiting plate initial USE was used; this value is 71 ft-lbs reduced by a factor of 0.65 to equal 46.2 ft-lbs. This material is appropriately qualified using the EMA methods defined in Reference 3 because the evaluation is performed for the plate material, and not for the forging. Therefore, the WLI nozzle requires no further evaluation.

5.0 LGS RPV & LPCI NOZZLE DATA and K_I

5.1 LPCI Nozzle Forging Material Test Data

The LGS vessel was purchased to the 1968 Edition of the ASME Boiler & Pressure Vessel Code, Section III, with Addenda up to and including Summer 1969. At that time, requirements for determining USE had not yet been established. The LGS LPCI nozzles did not include sufficient testing to enable determination of USE. The LGS Certified Material Test Reports (CMTRs) are provided in Appendix A and a summary of the data obtained from the CMTRs is shown in Tables 5-1 through 5-3.

Table 5-1: LGS Unit 1 LPCI Nozzle Test Data for Heat Q2Q25W

Chemistry			
%Cu*	%Ni	%S	
N/A	[[		Ladle
N/A			Check
N/A		]]	Check

* As no copper data was reported, the copper content for this material was determined using heats of materials used for beltline nozzles at other plants. The mean from nine (9) nozzles plus one (1) standard deviation was used to obtain a value of 0.18%.

Tensile Properties at Room Temperature		
Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation (%)
[[		
		]]

Fracture Toughness Properties							
Test Temperature (°F)	Charpy Impact Test Energies (ft-lb)			Shear (%)			Drop Weight NDTT (°F)
[[							
							]]

Table 5-2: LGS Unit 1 LPCI Nozzle Test Data for Heat Q2Q35W

Chemistry			
%Cu*	%Ni	%S	
N/A	[[		Ladle
N/A			Check
N/A		]]	Check

* As no copper data was reported, the copper content for this material was determined using heats of materials used for beltline nozzles at other plants. The mean from nine (9) nozzles plus one (1) standard deviation was used to obtain a value of 0.18%.

Tensile Properties at Room Temperature		
Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation (%)
[[		
		]]

Fracture Toughness Properties							
Test Temperature (°F)	Charpy Impact Test Energies (ft-lb)			Shear (%)			Drop Weight NDTT (°F)
[[							
							]]

Table 5-3: LGS Unit 2 LPCI Nozzle Test Data for Heat Q2Q33W

Chemistry			
%Cu*	%Ni	%S	
N/A	[[		Ladle
N/A			Check
N/A			Check
N/A			Check
N/A		]]	Check

* As no copper data was reported, the copper content for this material was determined using heats of materials used for beltline nozzles at other plants. The mean from nine (9) nozzles plus one (1) standard deviation was used to obtain a value of 0.15%.

Tensile Properties at Room Temperature		
Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation (%)
[[		
		]]

Fracture Toughness Properties							
Test Temperature (°F)	Charpy Impact Test Energies (ft-lb)			Shear (%)			Drop Weight NDTT (°F)
[[							
							]]

5.2 SA508-2 Nozzle Forging USE

The 70 ft-lb value of initial USE in the Brunswick report was based on a comprehensive review of available data that included the NRC RVID database. Therefore, this initial USE is

used in this evaluation. The data from Tables 3-3 and 3-4 of Reference 15 are provided in Tables 5-4 and 5-5 below. Table 5-5 has been updated to include additional data currently contained in the NRC database RVID2.

Table 5-4: A508-Class 2 Material Pre-Irradiated CVN Data

Plant	Charpy Test Direction	CVN @ 40°F (ft-lb)	CVN @ USE (ft-lb)
Turkey Point 4	L-T	85	130
Turkey Point 4	L-T	55	143
Turkey Point 3	L-T	115	150
Turkey Point 3	L-T	110	165
Watts Bar 1	L-T	65	135
Sequoyah 1	T-L	35	70
Sequoyah 1	L-T	80	120
Sequoyah 2	L-T	90	140
Sequoyah 2	T-L	40	100
Point Beach 2	L-T	90	165
Point Beach 2	L-T	110	180
Oconee 3	T-L	50	110
Oconee 3	L-T	85	155
Oconee 3	T-L	75	140
Oconee 2	L-T	95	145
Oconee 2	T-L	80	130
North Anna 2	T-L	25	75
North Anna 2	L-T	70	125
North Anna 1	T-L	25	90
North Anna 1	L-T	70	130
Kewaunee	T-L	125	165
Kewaunee	L-T	120	160
Kewaunee	T-L	65	145
Kewaunee	L-T	70	165
RE Ginna 1	L-T	80	170
RE Ginna 1	L-T	100	185

Table 5-5: Updated Summary A-508 Class 2 Material Upper Shelf Energy From NRC Database RVID

Plant	Unirradiated USE (ft-lb)	Method [1]
Arkansas 1	109	Generic
Braidwood 1	162	Direct
Byron 1	138	Direct
Byron 1	138	Direct
Byron 1	150	Direct
Byron 2	149	Direct
Byron 2	127	Direct
Byron 2	155	Direct
Catawba 1	134	Direct
Catawba 1	134	Direct
Crystal River 3	109	Generic
Davis-Besse	140	Direct
Davis-Besse	132	Direct
Davis-Besse	122	Direct
RE Ginna	117	65%
RE Ginna	114	65%
RE Ginna	91	65%
Kewaunee	92	65%
Kewaunee	97	65%
McGuire 2	97	65%
McGuire 2	100	Direct
North Anna 1	74	Surveillance Plate
North Anna 1	92	Direct
North Anna 1	85	Direct
North Anna 2	74	Direct
North Anna 2	80	Direct
North Anna 2	74	EQ to Forging
Oconee 1	109	Generic
Oconee 2	133	Direct
Oconee 2	109	Generic
Oconee 2	138	Direct
Oconee 3	109	Generic
Oconee 3	144	Direct
Oconee 3	112	Direct
Point Beach 1	78	65%
Point Beach 2	94	65%
Point Beach 2	78	65%

Plant	Unirradiated USE (ft-lb)	Method [1]
Point Beach 2	117	65%
Sequoyah 1	79	Direct
Sequoyah 1	72	Direct
Sequoyah 2	100	65%
Sequoyah 2	88	Direct
Surry 1	83	65%
Surry 2	104	65%
TMI 1	109	Generic
Turkey Point 3	99	65%
Turkey Point 3	93	65%
Turkey Point 3	100	65%
Turkey Point 4	86	65%
Turkey Point 4	88	65%
Turkey Point 4	103	65%
Watts Bar 1	88	65%
Zion 1	87	65%
Zion 2	109	Generic

Notes:

[1] Direct: This indicates that the unirradiated USE was from a transverse specimen.
65%: This indicates that the unirradiated USE was 65% of the USE from a longitudinal specimen.
Generic: This indicates that the unirradiated USE was reported by the licensee from other plants with similar materials to the beltline material.

With the update to the data as obtained from RVID2 at the time this report was written, it can be seen that the lowest initial USE is shown to be 72 ft-lbs. However, this report will continue to consider 70 ft-lbs to be consistent with the USE previously accepted by the NRC.

5.3 Fluence

The LGS TPO submittal was based upon a license of 40 years, considering 32 EFPY. The peak surface fluence applied in the LGS USE evaluation was 1.9e18 n/cm^2; this is representative of a bounding calculation that was performed using the GEH licensing topical report for fluence methodology that was approved by the NRC (Reference 20), consistent with the requirements of Regulatory Guide 1.190. The fluence at the elevation of the LPCI nozzles was determined using an attenuation factor, resulting in a fluence of 2.81e17 n/cm^2. The 1/4T fluence was calculated in accordance with RG1.99, Revision 2, resulting in a fluence of 1.9e17 n/cm^2.

5.4 Nozzle Forging and Vessel Dimensions

The LGS vessel and nozzle geometry information is provided in References 11 and 12, and summarized in Tables 5-6 and 5-7 below.

Table 5-6 LGS Vessel and LPCI Nozzle Dimensions

Parameter	Abbreviation	Value
Vessel Radius	R_i	[[ ]]
Vessel Thickness	t_v	6.19 inches
Clad Thickness	t_{clad}	[[
Nozzle Inner Radius	r_i	
Nozzle Corner Radius	r_c	
Nozzle Thickness	t_n	
Apparent Nozzle Radius	r_n	
Hoop Stress	S	]]

Table 5-7 LGS Parameters

Parameter	Abbreviation	Value
Design Pressure	P	1250 psig
Maximum Temperature	T	[[ ]]
Cooling Rate		100 °F/hr
Young's Modulus at 70°F	E	27900 ksi
Yield Strength @ Room Temperature	S_y	[[ ]]
Clad Stress, Emergency Conditions	$S_{clad\text{-}emergency}$	6 ksi
Clad Stress, Faulted Conditions	$S_{clad\text{-}faulted}$	16.5 ksi

The design pressure was unchanged with the introduction of TPO. The selection of appropriate transients for various operating conditions is discussed in the later sections of this report.

5.5 Plant-Specific Transients

The limiting transients for each level of operating conditions were selected for this evaluation in accordance with Section 4 of RG1.161. The limiting Level A and B condition is the 100°F/hr heatup/cooldown; limiting for Level C is the "Improper Start of a Cold Recirculation Loop"; and limiting for Level D is the "Pipe Rupture and Blowdown". These are discussed in more detail in the following sections.

5.6 K_{Ip} Evaluation for Flaws in Plate vs. LPCI Nozzle Forging

As shown in Tables 5-8 and 5-9 below, the K_{Ip} value for the 1/4T nozzle corner flaw bounds the K_{Ip} value for a 6:1 aspect ratio 1/4T flaw in the plate based upon the same internal pressure loading of 1250 psi, increased by a safety factor of 1.1 to equal 1375 psi.

Table 5-8 demonstrates the calculation of K_{Ip} for a 1/4T nozzle corner flaw. The methodology is presented similar to that previously performed in Table 6-3 of Reference 15 for Brunswick and accepted by the NRC (Reference 16). The resulting K_{Ip} at 1/4T is [[ ]] psi√in.

Table 5-9 demonstrates the calculation of K_{Ip} for a 1/4T flaw in a flat plate. The methodology presented is that defined in Reference 8, which was previously provided to the NRC in Reference 15 and approved in Reference 16. The resulting K_{Ip} is [[ ]] psi√in.

As the K_{Ip} for a nozzle corner flaw bounds that for a flat plate, the applied J-Integral calculations for K_{Ip} are factored by the ratio of the nozzle to the plate [[ ]].

5.7 K_{It} for Flaws in Plate vs. LPCI Nozzle Forging

The stress intensity factor for a 1/4T nozzle corner crack with the applied thermal loading of 100°F/hour was calculated during the GEH effort related to addressing the water level instrumentation nozzles. The calculated K_I was less than [[ ]] ksi√in. On the other hand, the corresponding calculated value of K_I using RG1.161 procedures, for a 1/4 T flaw in the plate is approximately [[ ]] ksi√in (see K_t in Table 8-1). This demonstrates that for the 100°F/hour case, the 1/4T plate flaw solution for K_I using RG1.161 procedures can be conservatively used for the nozzle corner flaw case.

Table 5-8: Calculation of K_{Ip} for a 1/4T Corner Flaw in a Nozzle

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Table 5-9: Calculation of K_{Ip} for a 1/4T Flaw in a Flat Plate

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6.0 USE MARGIN EVALUATION METHODOLOGY

The USE margin evaluation methodology used in this report is consistent with that prescribed in References 6, 7, and 8. Although References 5, 6, and 7 were in development at the same time that the topical report (Reference 3) was being developed, and Reference 8 was published later, a review of the methodology used in Reference 3 indicated that in almost all respects, it is consistent with References 6, 7, and 8. If there were any small differences, such as that in the selection of J-R curves, the topical report used a conservative approach. The methodology prescribed in Reference 8 is exclusively followed in this report. The applicability of this methodology for nozzle forgings was established by the NRC acceptance (Reference 16) of the Altran report (Reference 15) prepared for the N16 nozzle at Brunswick Steam Electric Plants, Units 1 and 2.

The acceptance criteria and the equations for the calculation of J applied values are described in this section. The selection of appropriate J-R curves is described in the next section.

6.1 Acceptance Criteria

The acceptance criteria for Level A & B Normal/Upset conditions are described as:

$J_{applied} < J_{0.1}$ (1)

$\partial J_{applied}/\partial a < \partial J_{material}/\partial a$, load held constant at $J_{applied} = J_{material}$ (2)

Equation (2) assures stability under ductile crack growth as demonstrated in Figure 6-1 below:

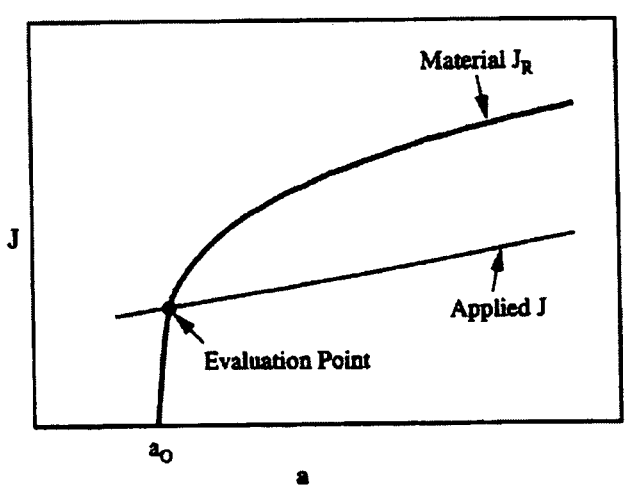

Figure 6-1: Illustration of Ductile Crack Growth Stability Evaluation

Both axial and circumferential flaws are postulated. For all operating conditions, the flaws are considered to be semi-elliptical surface flaws with an aspect ratio of 6:1 surface length to flaw depth. The assumed crack is ¼ of the thickness of the base metal wall.

The acceptance criteria for Level C conditions are provided in Section 3.1.2 of Reference 3 and are essentially the same as Equations (1) and (2) above. For Level C, however, the postulated flaw depth is 1/10 of the thickness of the base metal wall plus the clad thickness, with total depth < 1.0 inch. A safety factor of 1.0 is considered for applied pressure loading.

For Level D conditions, only the ductile crack growth stability is evaluated. The flaw depth is the same as that for Level C, and the material J-Integral resistance curve is based on best estimate. Level D also uses a safety factor on applied loading equal to 1.0.

6.2 Calculation of Applied J-Integral

The calculation of the applied J-Integral consists of three steps:

- Step 1 is to calculate the K_I values from pressure and heatup/cooldown loadings;
- Step 2 is to calculate the effective flaw depth, which includes a plastic zone size correction; and
- Step 3 is to calculate the J-Integral for small-scale yielding based on this effective flaw depth.

The calculated K_I values are in the units of ksi√in.

6.2.1 Internal Pressure Loading

For an axial flaw with depth 'a' equal to (0.25t + 0.1 inch), the stress intensity factor from internal pressure, p_a, with a safety factor, SF, on pressure equal to 1.15 using Equation (3) below, obtained from (Reference 8):

$$K_{Ip}^{Axial} = (SF)\, p_a\, [1 + (R_i/t)]\, (\pi a)^{0.5}\, F_1 \qquad (3)$$

$$F_1 = 0.982 + 1.006\, (a/t)^2$$

For a circumferential flaw with depth 'a' equal to (0.25t + 0.1 inch), the stress intensity factor from internal pressure, p_a, with a safety factor, SF, on pressure equal to 1.15 using Equation (4), obtained from (Reference 8):

$$K_{Ip}^{Circum.} = (SF)\, p_a\, [1 + \{R_i/(2t)\}]\, (\pi a)^{0.5}\, F_2 \qquad (4)$$

$$F_2 = 0.885 + 0.233\, (a/t) + 0.345\, (a/t)^2$$

6.2.2 Heatup/Cooldown Loading

For an axial or circumferential flaw with depth 'a' equal to (0.25t + 0.1 inch), the "steady state" (time independent) stress intensity factor from radial thermal gradients is obtained by using Equation (5), obtained from Reference 8:

$$K_{It} = (CR/1000)\, t^{2.5}\, F_3 \quad (5)$$

$$F_3 = 0.69 + 3.127\,(a/t) - 7.435\,(a/t)^2 + 3.532\,(a/t)^3$$

The above equation for K_{It} is valid for $0 \leq CR \leq 100°F/hr$.

For the transients in which the heatup/cooldown rates are greater than 100°F/hr, Reference 3 used finite element analysis to determine the stress distribution through the RPV wall and the K_I values were then calculated using the Raju-Newman method as described in Reference 3.

6.2.3 Effective Flaw Depth

The effective flaw depth for small-scale yielding, a_e, was based on Equation (6), obtained from Reference 8:

$$a_e = a + \{1/(6\pi)\}[(K_{Ip} + K_{It})/\sigma_y]^2 \quad (6)$$

The topical report (Reference 3) identifies the yield strength as 69 ksi; the average LGS LPCI nozzle CMTR value of σ_y for SA508-2 is approximately [[ ]] ksi at room temperature. The ASME Code value from the LGS Code of Construction is determined to be [[ ]] ksi at [[ ]] (Reference 19). The Code value at operating temperature was scaled by the Code value at room temperature (70°F) and the measured room temperature value from the CMTRs. Therefore, σ_y of approximately [[ ]] was used in this evaluation.

6.2.4 J-Integral Calculation

The J-Integral from the K_I values was calculated using Equation (7), obtained from (Reference 8):

$$J_{applied} = 1000\,(K'_{Ip} + K'_{It})^2/E' \quad (7)$$

where the K'_I values are stress intensity factors based on effective flaw depth and E' is $E/(1-\nu^2)$. The value of ν was taken as 0.3 and is consistent with Reference 3; the value of E was determined to be 27900 ksi at room temperature, obtained from the ASME Code for SA508-2 material. The units of J are in-lb/in^2.

7.0 SELECTION OF MATERIAL J-R CURVES

The generic J-Integral fracture resistance curve equation is given as Equation (8), obtained from Reference 8:

$$J_R = (MF)\{C1\,(\Delta a)^{C2}\exp[C3\,(\Delta a)^{C4}]\} \quad (8)$$

Forging materials are not discussed in Reference 8; therefore, Section 3.3 (Reactor Pressure Vessel Base (Plate) Materials) of Reference 8 is used to calculate the values of various constants in the preceding equation. Section 3.3 of Reference 8 provides different equations based upon the Sulphur (S) wt% content of the materials being evaluated. The LGS CMTRs (see Appendix A for the CMTRs or Tables 5-1 through 5-3 for a summary of the pertinent data) were reviewed; it was determined that the maximum S content is [[ ]] wt%. Therefore, Section 3.3.1 (High-Toughness Model for S < 0.018 wt%) of Reference 8 is used.

For analyses addressing Service Levels A, B, and C, the factor MF was set to 0.749 as defined in Section 3.3.1 of Reference 8. For analyses addressing Service Level D, the value of MF was set to 1.0. The mathematical expressions for other constants are given by Equations (9) through (12), obtained from Reference 8:

$$C1 = \exp[-2.44 + 1.13\ln(CVN) - 0.00277T] \quad (9)$$

$$C2 = 0.077 + 0.116\ln C1 \quad (10)$$

$$C3 = -0.0812 - 0.0092\ln C1 \quad (11)$$

$$C4 = -0.409 \quad (12)$$

The term 'CVN' is the Charpy USE. As indicated above, the EOL Charpy USE for the LGS LPCI nozzles is 62.4 ft-lbs. This value was used in calculating the value of constant C1. The normal operating temperature for region B (that contains the beltline region) of the vessel is specified as [[ ]] (References 17 and 18); for power re-rate and TPO this temperature was revised to [[ ]] (Reference 19). Therefore, this value was used in calculating the value of constant C1.

The calculated J-Integral resistance curves for the various operating conditions are shown in Figure 7-1 below.

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Figure 7-1: LGS LPCI Nozzle Forging J-Integral Resistance Curves

8.0 EVALUATION OF LEVEL A & B CONDITIONS

Key steps in this evaluation are the calculation of the applied J-Integral and the flaw stability evaluation.

8.1 Level A and B Service Loadings

The two loadings to be considered are internal pressure and thermal heatup/cooldown rates. The Level A and B heatup/cooldown rates for the LGS RPV are specified in the associated reactor thermal cycle diagram (Reference 18) amended by the TPO certified design specification (Reference 19); the TPO specification bounds the power re-rate modifications. The topical report (Reference 3) also analyzed an additional transient identified as "Loss of Feedwater Pumps" that is specified for BWR/6 standard plants in their RPV thermal cycle drawing. However, the analysis in the topical report showed that the 100°F/hr case was still bounding compared to this transient. The LGS plant-specific thermal cycle diagram was reviewed; it was determined that the heatup/cooldown case is bounded by the evaluation presented in the topical report.

The difference between the RPV geometry considered in the topical report (R= 126.7 inches and t= 6.19 inches) and the LGS RPV geometry (R=[[ ]] inches and t= 6.19 inches) is less than 1% and thus was considered insignificant in terms of the calculated thermal transient stress. Therefore, the conclusion reached in Reference 3 was also determined to be valid for the LGS case and therefore, only the 100°F/hr case was considered in this evaluation.

The specified design pressure for the LGS RPV is 1250 psi, defined in Reference 19. Consistent with the NRC-approved topical report, the accumulation pressure is 1.1 times the design pressure and is, thus, equal to 1375 psi. The internal pressure value used in the $J_{0.1}$ criterion is 1.15 times the accumulation pressure (i.e., 1375 * 1.15 or 1581 psi). Similarly, the internal pressure value used in the flaw stability criterion is 1.25 times the accumulation pressure or 1719 psi.

The LGS RPV wall thickness in the beltline region is 6.19 inches. RG1.161 states that, for Levels A and B, the evaluation is to postulate a semi-elliptical surface flaw with an a/t = 0.25 and with an aspect ratio of 6:1 surface length to flaw depth. Clad thickness is not required for this calculation. Therefore, the postulated 1/4T flaw has a depth of (6.19 * 0.25) or 1.55 inches.

8.2 Level A and B Conditions Evaluation

Table 8-1 below shows the calculated values of the applied J-Integral for 1.15 accumulation pressure at several crack depths beginning with the 1/4T depth. The calculations for the axial flaw are shown first, followed by those for the circumferential flaw. For the $J_{0.1}$ criterion, the applied J-Integral values at a = 1.65 inches are relevant. A review of this table indicates

that the applied J-Integral values for the axial flaw case bound those for the circumferential flaw case. Therefore, the $J_{0.1}$ criterion check was conducted only for the axial flaw case. Figure 8-1 shows a comparison between the calculated applied J-Integral value for the axial flaw and the LPCI nozzle J-R curve. It is seen that the $J_{0.1}$ criterion is satisfied for the limiting case of an axial flaw.

Table 8-1: Calculated Values of Applied J-Integral for 1.15 x Accumulation Pressure

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Figure 8-1: $J_{0.1}$ Criterion Evaluation for Axial Flaw and LGS LPCI Nozzle Forging J-R Curve

Table 8-2 shows the calculated values of applied J-Integral for 1.25 accumulation pressure at several crack depths beginning with 1/4T depth. The calculations are shown for both the axial and the circumferential flaws. However, a review of this table indicates that the axial flaw case is governing. Figure 8-2 shows the plot of the applied J-Integral curve and the LPCI nozzle material J-R curve. Flaw stability at a given applied load is assured when the slope of the applied J-Integral curve is less than the slope of the material J-R curve at the point on the J-R curve where the two curves intersect (see Figure 6-1). It is seen that the stability criterion is satisfied with the limiting EOL USE of 62.4 ft-lbs for the LGS LPCI nozzle forgings. (Note: In the stability evaluation, the J applied at Δa = 0.1 inch is not a concern; only the slope of the J applied curve is of importance.)

Table 8-2: Calculated Values of Applied J-Integral for 1.25 x Accumulation Pressure

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Figure 8-2: Flaw Stability Criterion Evaluation for Axial Flaw with LGS LPCI Nozzle Forging J-R Curve

9.0 EVALUATION OF LEVEL C & D CONDITIONS

The postulated flaw depth for the evaluation of Level C and D loadings is one-tenth the base metal wall thickness, plus the clad thickness, but with total depth not to exceed 1.0 inch. The plate thickness in the beltline region is 6.19 inches. The nominal thickness of the clad is [[ ]]inch. Therefore, the postulated crack depth is (6.19 * 0.1 + [[ ]]) or [[ ]] inch.

9.1 Level C Service Loading

The LGS RPV thermal cycle drawing (Reference 18) amended by Reference 19 specifies Level C events; the TPO specification bounds the power re-rate modifications. The topical report (Reference 3) used an RPV thermal cycle drawing to select a limiting Level C transient (or event). It was determined that for the BWR/3-6 product lines, the "Improper Start of a Cold Recirculation Loop" transient is the most limiting Level C transient. Figure 9-1 shows this transient, which is identified as Transient 26 in the LGS vessel thermal cycle diagram (Reference 18) (Transient 24 in Reference 3), amended by Reference 19. (Note that the pressure shown in Figure 9-1 specifies 1050 psig. The TPO pressure is [[ ]] psig; as the difference is less than 1%, the evaluation at 1050 psig would have an insignificant effect, and therefore remains applicable to the LGS evaluation.) Since the geometry differences between the LGS RPV and the RPV geometry analyzed in the topical report were minor (as previously discussed), the K_I values for Transient 26 calculated in the topical report were also used in this evaluation. This meant using the same K_t fit coefficients as shown in Table 6-1b of the topical report. The LGS plant-specific thermal cycle diagram was reviewed; it was determined that the Level C event defined in References 18 and 19 is bounded by the evaluation presented in the topical report.

Section 6.1.3 of Reference 3 discusses the calculation method for the K_I values due to cladding. The same technical approach and clad stress were used in this report.

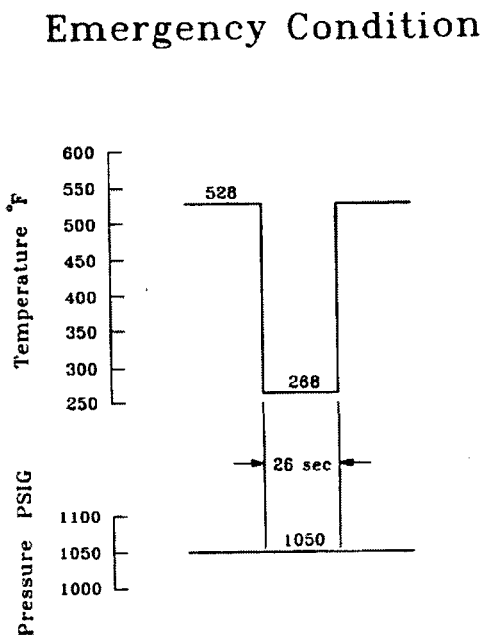

Figure 9-1: Pressure & Temperature Conditions During Improper Start of Cold Recirculation Loop Transient for Limiting Level C Event

9.2 Level C Service Evaluation

Table 9-1 shows the calculated values of the Level C condition applied J-Integral for axial and circumferential flaws. Since the internal pressure did not change during the thermal transient (see Figure 9-1), only one set of applied J-Integral calculations (shown in Table 9-1) was performed to evaluate the $J_{0.1}$ and the flaw stability criteria. As expected, the axial flaw case is governing. The material J-R curve for the Level C condition is the same as that for the Level A and B conditions. The $J_{0.1}$ criterion and the flaw stability evaluations are graphically shown in Figures 9-2 and 9-3, respectively. It is seen that both the criteria are satisfied.

Table 9-1: Calculated Values of Applied J-Integral for Level C Transient

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Figure 9-2: $J_{0.1}$ Evaluation for Level C Condition

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Figure 9-3: Crack Growth Stability Criterion Evaluation for Level C Condition

9.3 Level D Service Loading

The limiting Level D transient is the "Pipe Rupture and Blowdown" event, identified as Transient 29 in the LGS vessel thermal cycle diagram (Reference 18) (Transient 27 in Reference 3), amended by Reference 19; the TPO specification bounds the power re-rate modifications. The pressure temperature profile is shown in Figure 9-4. Two differences are that the LGS pressure at the beginning of the transient is [[ ]] psig, and at the end of the transient is [[ ]] psig (as opposed to the 20 psig shown in Figure 9-4); the plant-specific pressure of [[ ]] psig at the end of the event has been used in the LGS evaluation as shown in Table 9-2. The difference between 1050 psig and [[ ]] psig is less than 1% and any impact to the evaluation is considered to be insignificant. Since the geometry differences between the LGS RPV and the RPV geometry analyzed in the topical report (Reference 3) are minor (as previously discussed), the K_I values for Transient 29 calculated in the topical report were also used in this evaluation. Section 6.2.2 of Reference 3 describes the fracture mechanics methodology used in the derivation of the K_I values. The K_t fit coefficients shown in Table 6-2 of the topical report were therefore also used in this evaluation. The LGS plant-specific thermal cycle diagram was reviewed; it was determined

that the Level D event defined in References 18 and 19 is bounded by the evaluation presented in the topical report.

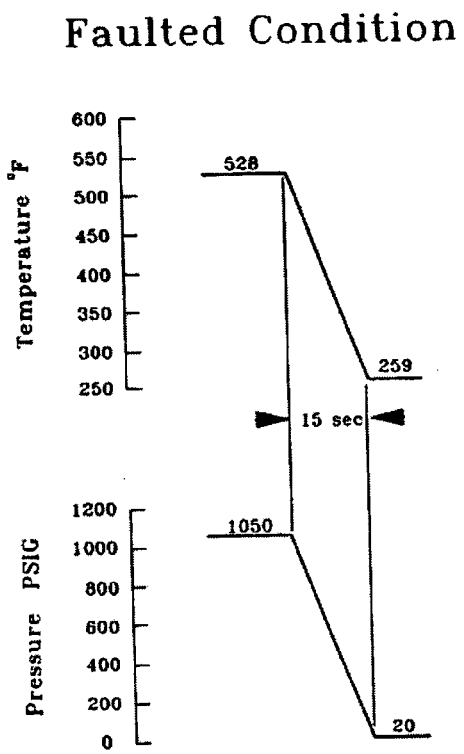

Figure 9-4: Limiting Level D Transient

9.4 Level D Service Evaluation

Table 9-2 shows the calculated values of the Level D condition applied J-Integral for axial and circumferential flaws. The internal pressure at the end of the transient was used in the applied J-Integral calculations. As expected, the axial flaw case is governing. The material J-R curve for Level D conditions is based on the margin factor (MF) of 1.0 as specified in Reference 8. Figure 9-5 graphically shows the flaw stability evaluation. It is seen that the ductile flaw crack growth stability criterion is satisfied.

Table 9-2: Calculated Values of Applied J-Integral for Level D Transient

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Figure 9-5: Crack Growth Stability Criterion Evaluation for Level D Condition

10.0 SUMMARY & CONCLUSIONS

10CFR50 Appendix G states that the RPV must maintain USE of no less than 50 ft-lbs throughout its life, unless it is demonstrated in a manner approved by the Director, Office of Nuclear Reactor Regulation, that lower values of USE will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code.

For the LGS TPO evaluation, the plant assumed a lower bound USE for the LPCI nozzle forgings based on low temperature Charpy tests with low Shear results. When the material was evaluated using RG1.99, Revision 2 (Reference 13), the minimum predicted EOL USE value (24 ft-lbs) did not meet the required value of 50 ft-lbs defined in Reference 1. Consequently, the USE EMA methodology defined in Reference 3 was applied. However, the topical report (Reference 3) does not specifically identify that forging materials were included in the statistical calculations. Therefore, the calculation in this report documents a plant-specific evaluation that was conducted to show compliance with the USE requirements using RG1.161 (Reference 8) and ASME Appendix K (Reference 7). It is noted that RG1.161 does not address forging materials; however, Appendix K, Section K-4210 indicates that it is applicable to SA508-2 materials. It is therefore deemed acceptable and reasonable to evaluate using the plate material methodology from References 7 and 8 to represent the LGS LPCI nozzle forging materials. In addition, the applicability of this methodology for nozzle forgings was established by the NRC acceptance (Reference 16) of the Altran report (Reference 15) prepared for the N16 nozzle at Brunswick Steam Electric Plants, Units 1 and 2.

This LGS LPCI nozzle forging USE evaluation followed essentially the methodology outlined in ASME Code Case N-512-1 (Reference 6), Appendix K of ASME Section XI (Reference 7), and RG1.161 (Reference 8). The evaluation shows that the Level A and B Condition is governing. The predicted LGS plant-specific EOL USE value of 62.4 ft-lbs was obtained using the methods defined in RG1.99 and an initial USE of 70 ft-lbs from Reference 15, approved by the NRC in Reference 16.

Based on the results of this plant-specific evaluation, it is concluded that the LPCI nozzle forgings in the LGS RPV meet the margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code.

The LGS Water Level Instrumentation (WLI) nozzles are J-weld penetrations in the plate, with a forging fabricated from SB166 material that is less than 2.5 inches thick. Therefore, evaluation for fracture toughness is not required. As a result, the evaluation for the WLI nozzle is based upon the plate material in the shell where the WLI nozzles occur. Therefore, the application of the topical report is appropriate for the LGS WLI nozzles, and further evaluation is not required.

11.0 REFERENCES

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APPENDIX A: CMTRS FOR LGS N17 LPCI NOZZLE

Unit 1 Heats:
Q2Q25W
Q2Q35W

Unit 2 Heat:
Q2Q33W

LGS Unit 1 Heat Q2Q25W

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LGS Unit 1 Heat Q2Q35W

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LGS Unit 2 Heat Q2Q33W

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