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TOKYO, JAPAN

May 31, 2013

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Attention: Mr. Jeffrey A. Ciocco

Docket No. 52-021
MHI Ref: UAP-HF-13110

Subject: **MHI's Amended Responses to US-APWR DCD RAI No.574-4633 Revision 2 (SRP 10.02.03)**

Reference: 1) "Request for Additional Information No. 574-4633 Revision 2," SRP Section: 10.02.03 – Turbine Rotor Integrity, Application Section: 10.2.3 ," dated April 20, 2010, ML101110687.
2) "Safety Evaluation Report with Open Items for Chapter 10," dated 07/19/2011, ML111990458

With this letter, Mitsubishi Heavy Industries, Ltd. (MHI) transmits to the U.S. Nuclear Regulatory Commission (NRC) a document entitled "MHI's Amended Responses to Request for Additional Information No. 574-4633 Revision 2"

Enclosed is the response to the RAIs contained within Reference 1.

As indicated in the enclosed materials, this document contains information that MHI considers proprietary, and therefore should be withheld from public disclosure pursuant to 10 C.F.R. § 2.390 (a)(4) as trade secrets and commercial or financial information which is privileged or confidential. A non-proprietary version of the document is also being submitted with the information identified as proprietary redacted and replaced by the designation "[ ]."

This letter includes a copy of the proprietary version (Enclosure 2), a copy of the non-proprietary version (Enclosure 3), and the Affidavit of Yoshiki Ogata (Enclosure 1) which identifies the reasons MHI respectfully requests that all materials designated as "Proprietary" in Enclosure 2 be withheld from public disclosure pursuant to 10 C.F.R. § 2.390 (a)(4).

Please contact Mr. Joseph Tapia, General Manager of Licensing Department, Mitsubishi Nuclear Energy Systems, Inc. if the NRC has questions concerning any aspect of the submittals. His contact information is below.

Sincerely,

Y. Ogata

Yoshiki Ogata,
Executive Vice President
Mitsubishi Nuclear Energy Systems, Inc.
On behalf of Mitsubishi Heavy Industries, LTD.

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NRO

Enclosure:

1. Affidavit of Yoshiki Ogata

2. MHI's Amended Responses to Request for Additional Information No. 574-4633 Revision 2 (proprietary version)

3. MHI's Amended Responses to Request for Additional Information No. 574-4633 Revision 2 (non-proprietary version)

CC: J. A. Ciocco
J. Tapia

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Enclosure 1

Docket No. 52-021
MHI Ref: UAP-HF-13110

MITSUBISHI HEAVY INDUSTRIES, LTD.
AFFIDAVIT

I, Yoshiki Ogata, state as follows:

1. I am Executive Vice President of Mitsubishi Nuclear Energy Systems, Inc., and have been delegated the function of reviewing MITSUBISHI HEAVY INDUSTRIES, LTD's ("MHI") US-APWR documentation to determine whether it contains information that should be withheld from public disclosure pursuant to 10 C.F.R. § 2.390 (a)(4) as trade secrets and commercial or financial information which is privileged or confidential.

2. In accordance with my responsibilities, I have reviewed the enclosed document entitled "MHI's Amended Responses to Request for Additional Information No. 574-4633 Revision 2," dated May 2013, and have determined that portions of the document contain proprietary information that should be withheld from public disclosure. Those pages containing proprietary information are identified with the label "Proprietary" on the top of the page and the proprietary information has been bracketed with an open and closed bracket as shown here "[ ]." The first page of the document indicates that all information identified as "Proprietary" should be withheld from public disclosure pursuant to 10 C.F.R. § 2.390 (a)(4).

3. The information identified as proprietary in the enclosed document has in the past been, and will continue to be, held in confidence by MHI and its disclosure outside the company is limited to regulatory bodies, customers and potential customers, and their agents, suppliers, and licensees, and others with a legitimate need for the information, and is always subject to suitable measures to protect it from unauthorized use or disclosure.

4. The basis for holding the referenced information confidential is that it describes the unique design by MHI for performing the turbine rotors design of the US-APWR.

5. The referenced information is being furnished to the Nuclear Regulatory Commission (NRC) in confidence and solely for the purpose of information to the NRC staff.

6. The referenced information is not available in public sources and could not be gathered readily from other publicly available information. Other than through the provisions in paragraph 3 above, MHI knows of no way the information could be lawfully acquired by organizations or individuals outside of MHI.

7. Public disclosure of the referenced information would assist competitors of MHI in their design of new nuclear power plants without incurring the costs or risks associated with the design of the subject systems. Therefore, disclosure of the information contained in the referenced document would have the following negative impacts on the competitive position of MHI in the U.S. nuclear plant market:

   A. Loss of competitive advantage due to the costs associated with development of turbine rotor materials.

   B. Loss of competitive advantage of the US-APWR created by benefits of information of turbine rotor material specification.

I declare under penalty of perjury that the foregoing affidavit and the matters stated therein are true and correct to the best of my knowledge, information and belief.

Executed on this 31st day of May, 2013.

Y. Ogata

Yoshiki Ogata,
Executive Vice President
Mitsubishi Nuclear Energy Systems, Inc.

Docket No. 52-021
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Enclosure 3

UAP-HF-13110
Docket Number 52-021

MHI's Amended Responses to Request for Additional Information No. 574-4633 Revision 2

May 2013
(Non-Proprietary)

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

05/30/2013

US-APWR Design Certification

Mitsubishi Heavy Industries

Docket No. 52-021

RAI NO.:	**NO. 574-4633**
SRP SECTION:	**10.02.03 – Turbine Rotor Integrity**
APPLICATION SECTION:	**10.2.3**
DATE OF RAI ISSUE:	**4/20/2010**

QUESTION NO.: 10.02.03-8

Revision 2 to the US-APWR FSAR revised Section 10.2.3.1 to delete the reference to grade C (Classes 5, 6 and 7). Therefore the FSAR no longer specifies the type of material (Grade or Classification) from ASTM A470. Since there are different Grades and Classifications in ASTM A470 that have different chemical compositions and mechanical properties, the NRC staff cannot assess the acceptability of the material concerning the turbine rotor integrity as described in SRP 10.2.3, and whether the turbine rotor material is bounded by the turbine missile analysis. Therefore, the specific Grade and Classification of ASTM A470 material or reference to the specific material ordering requirements should be included in the US-APWR FSAR that is bounded by the turbine missile analysis.

ANSWER:

MHI deleted the reference to grade C (Classes 5, 6 and 7) in Revision 2 of US-APWR FSAR Section 10.2.3.1 in accordance with the NRC requirement of letter dated May 20 2009, in a response to RAI No. 324-1997, Question 03.05.01.03-1.

Additional NRC Comment (Open Item 10.2.3-1):

The response is incomplete, since ASTM A470 with no specific grade/class no longer specifies the type of material. Discuss;

1) What type of material shall be applied to the US-APWR LPT rotor?

2) How do the material properties relate to those used in the turbine missile analysis?

3) Specific LPT rotor material name and the details of chemical composition and mechanical properties of the rotor shall be placed in this RAI response. In addition, specific LPT rotor material name shall also be placed in the turbine missile analysis reports (MUAP-07028) so that the acceptance criteria of as-built rotor are bounded by the mechanical properties used in the turbine missile analysis (MUAP-07028).

MHI Response to Additional NRC Comment

I. MHI material type and the relation to the material properties used in the turbine missile analysis

1) Type of material to be applied to the US-APWR LPT rotor:

US-APWR LPT rotor material is an MHI proprietary material, but is similar to ASTM A470 Grade C, Class 6. There are some minor differences in chemical composition and mechanical properties as shown in Table 8-1 and Table 8-2. These tables are the same as those presented in MHI's response to RAI No. 199-2073, Question 10.02.03-1.

Table 8-1 Comparison of the chemical composition ranges

	Purchase Specification of LP Rotor Forging ([ ])			ASTM A470 Grade C/Class 6
	Heat Analysis	Allowable Deviation for Product Analysis		
		For Minimum	For Maximum	
C *	[ ]	[ ]	[ ]	0.28%
Mn	[ ]	[ ]	[ ]	0.20 - 0.60%
P	[ ] Desired Value : Less than [ ]	[ ]	[ ]	0.012%
S	[ ] Desired Value : Less than [ ]	[ ]	[ ]	0.015%
Si	[ ]	[ ]	[ ]	(B,C)
Ni	[ ]	[ ]	[ ]	3.25 - 4.00%
Cr	[ ]	[ ]	[ ]	1.25 - 2.00%
Mo	[ ]	[ ]	[ ]	0.25 - 0.60%
V	[ ]	[ ]	[ ]	0.05 - 0.15%
Sb **	[ ]	[ ]	[ ]	(E)
Al **	[ ]	[ ]	[ ]	0.015%
Cu **	[ ]	[ ]	[ ]	Not Specified
Sn **	[ ]	[ ]	[ ]	Not Specified
As **	[ ]	[ ]	[ ]	Not Specified

* It is desirable that carbon content shall be held to as low a level as possible.
** These are the desired values.

(B) 0.10% max, unless an alternative value, not in excess of 0.30%, is specified in the purchase order.
(C) 0.15 to 0.30% silicon is permitted for material that is subsequently VAR Processed.
(E) To be reported for information only on all Grades.

Table 8-2 Comparison of the mechanical properties

Test	Item	Purchase Specification of LP Rotor Forging ([ ])	ASTM A470 Grade C/Class 6
Tensile Test	Tensile Strength	[ ]	725 - 860 MPa
	Yield Strength (0.2% offset)	[ ]	Min.620 MPa
	Elongation	[ ]	Min.17%
	Reduction of Area	[ ]	Min.50%
Charpy Test	Charpy V-notch energy at 21-27 deg C	[ ]	Min.61J
	50% FATT	[ ]	Max.-7 deg C
	Upper Shelf Energy (USE) Level	[ ]	-

2) Relation between material properties of the purchase specification and those used in the turbine missile analysis:

The specified minimum yield strength in the MHI purchase specification of the LPT rotor material is used in the turbine missile analysis (MUAP-07028) and the actual yield strength of the as-built rotor will be confirmed. A Charpy V-notch energy at 21-27 deg. C of [ ], 50 percent fracture appearance transition temperature (FATT) of [ ] and Upper Shelf Energy (USE) Level of [ ], are required in the purchase specification to support the turbine missile analysis results. These mechanical properties, along with the yield strength will be confirmed on the as-built rotors to demonstrate the as-built LPT rotors satisfy the calculated K_{IC} of [ ] applied to the turbine missile analysis, Please refer to our response to Question 10.2.3-9.

Based on the above discussion, the second paragraph of the turbine missile analysis report (MUAP-07028) Section 2.1 "Material Feature" will be revised as is shown in "Impact on Technical/Topical Report".

II. Placing specific LPT rotor material name

MHI agrees to place the LPT rotor material name [ ] in this RAI response (Table 8-1 and Table 8-2) and the turbine missile analysis report (MUAP-07028). The turbine missile analysis report (MUAP-07028) Section 2, "DESIGN FEATURES" will be revised as is shown in "Impact on Technical/Topical Report".

Impact on DCD

Refer to "Impact on DCD" in the response to RAI 574-4633, Question 10.02.03-10,

Impact on R-COLA

There is no impact on the R-COLA.

Impact on PRA

There is no impact on the PRA.

Impact on Technical/Topical Report

Based on the above MHI Response to Additional NRC Comment, item I (MHI material type and the relation to the material properties used in the turbine missile analysis), the second paragraph of the Technical Report MUAP-070028 Section 2.1 "Material Feature" will be replaced by the following paragraph.

2.1 Material Feature

(Second paragraph)

The specification for the integral rotors requires testing at the locations shown in Figure 2.1-1 to confirm uniformity of the rotor. Using these specimens, the tensile test (tensile strength, yield strength, elongation and area reduction) and Charpy test (Charpy V-notch energy, 50% FATT and upper shelf energy) will be performed to confirm that the required K_{IC} of [ ] and the other mechanical properties used in this report are satisfied.

Based on the above MHI Response to Additional NRC Comment, item II (Placing specific LPT rotor material name), the Technical Report MUAP-070028, Section 2 "DESIGN FEATURES" will be replaced by the following paragraphs.

2.0 DESIGN FEATURES

A typical integral rotor is shown in Figure 2-1. A major advantage of this design is the elimination of the disc bores and keyways. Rotors with shrunk-on discs have peak stresses around the locations where the discs are shrunk-on and keyed to the shaft. The elimination of these structures has shifted the location of peak stress from the keyways to the blade fastening regions at the rim of the rotor, whose local stress is much lower than that of the shrunk-on discs. Since cracks are likely to occur in high stressed regions, reduction of the peak stress throughout the rotor significantly contributes to the reduction in rotor burst probability.

In addition to lower local stress throughout the rotor, the integral structure also has the benefit of reduced average tangential stress of the discs thus applying lower yield strength material with traditional safety margins remaining unchanged. Many years of experience and testing of the rotor material have demonstrated better ductility, toughness and resistance to stress corrosion cracking at lower yield strength. These benefits can be important factors in reducing the possibility of turbine missile generation. The integral rotor forgings of the 3.5% Ni-Cr-Mo-V alloy steel [ ] are to be applied to the US-APWR LPT rotors and heat-treated to obtain minimum yield strengths of [ ], Charpy V-notch energy at 21-27 deg. C of [ ], maximum FATT of [ ], and minimum upper shelf energy of [ ].

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

05/30/2013

US-APWR Design Certification

Mitsubishi Heavy Industries

Docket No. 52-021

RAI NO.:	**NO. 574-4633**
SRP SECTION:	**10.02.03 – Turbine Rotor Integrity**
APPLICATION SECTION:	**10.2.3**
DATE OF RAI ISSUE:	**4/20/2010**

QUESTION NO.: 10.02.03-9

In a letter dated March 10, 2009, the response to RAI No. 199-2073, Question 10.02.03-2 provided acceptance criteria for the 50% FATT and Charpy V-notch energy which do not meet the acceptance criteria of -18°C (0°F) and 8.3 kg-m (60 ft-lbs), respectively, as provided in SRP Sections 10.2.3 (paragraphs II.1b and II.1c). Therefore, provide a discussion on why the material properties for the 50% FATT and Charpy V-notch energy provided in the response to RAI No. 199-2073, Question 10.02.03-2 ensures that the turbine rotor has adequate fracture toughness during startup and normal operating temperatures.

ANSWER:

The rotor design analysis confirmed that the rotor has adequate fracture toughness.

The fracture analysis done during the design includes determining the stresses in the rotor resulting from rotation, steady-state thermal loads and transient thermal loads from startup and stop. The fracture toughness K_{IC} used in the fracture analysis is introduced through the mechanical properties of the rotor material, 50%FATT and Upper Shelf Energy, with Begley-Logsdon method.

Figure 9-1 Begley-Logsdon method

Additional NRC Comment (Open Item 10.2.3-2):

The acceptance criteria provided in the response to RAI 199-2073, Question 10.2.3-2, for the 50 percent FATT and Charpy V-notch energy do not meet the acceptance criteria of -18 °C (0 °F) and 8.3 kg-m (60 ft lbs or 81 J), respectively, which are provided in SRP Sections 10.2.3 (Paragraphs II.1b and II.1c).

Therefore, the applicant is requested to provide a discussion on why the material properties for the 50 percent FATT and Charpy V-notch energy of [ ] and [ ] respectively provided in the response to RAI 199-2073, Question 10.2.3-2, is sufficient to ensure that the turbine rotor has adequate fracture toughness during startup and normal operating temperatures.

SRP section 10.2.3 paragraph II.1b and c require the Charpy V-Notch energy and FATT curves to be well defined to use the Begley-Logsdon method. The applicant is requested to provide NRC with the confirmation that The Charpy V-Notch energy and FATT curves are well defined for the material which is to be used for the US-APWR LP turbine rotor.

MHI Response to Additional NRC Comment

I. Minimum requirement for the 50 percent FATT and Charpy V-notch energy

It is true that criteria for the 50 percent FATT and Charpy V-notch energy in the MHI purchase specification is equivalent to those specified in ASTM A470 Grade C, Class 6, which is not as conservative as the SRP Criteria shown in the following table.

Table 9A-1 Comparison of mechanical property requirements

	Unit	MHI purchase specification	ASTM A470 Grade C Class 6	SRP 10.2.3
50 percent FATT	Max. °C	[ ]	-7	-18
Charpy V-notch energy	Min. J at RT	[ ]	61	81
Upper shelf energy (USE)	Min. J	[ ]	- (not specified)	- (not specified)

RT: Room Temperature

However, the following two reasons show that the above requirements of the MHI purchase specification,[ ] are enough to obtain a higher fracture toughness (K_{IC}) than the K_{IC} used in the turbine missile analysis supporting the probability of a turbine missile ejection less than $1x10^{-5}$ per year (criteria for unfavorably oriented turbine).

<u>**The reasons why the requirements of the MHI purchase specification are conservative enough are:**</u>

<u>**Reason 1 :**</u> The fracture toughness K_{IC} of [ ] is calculated based on the minimum allowable mechanical properties specified in the purchase specification of Yield Strength ([ ]), USE ([ ]), and 50 percent FATT ([ ]) using the Begley-Logsdon Method. The K_{IC} of [ ] used in the turbine missile analysis includes a [ ] margin against the above calculated K_{IC} for the compensation of the uncertainty of the Begley-Logsdon Method..

Reason 2 : Based on MHI experiences, K_{IC} at the center bore core region of the as-built LPT rotor is expected to be greater than 220 MPa·m$^{1/2}$ (200 ksi·in$^{1/2}$), while the much lower value for K_{IC} of [ ] was applied to the turbine missile analysis.

(1) The fracture toughness K_{IC} of [ ] is calculated based on the minimum allowable mechanical properties specified in the purchase specification of Yield Strength ([ ]), USE ([ ]), and 50 percent FATT ([ ]) using the Begley-Logsdon Method. The K_{IC} used in the turbine missile analysis of [ ] includes a [ ] margin against the above calculated K_{IC} for the compensation of the uncertainty of the Begley-Logsdon Method.

Yield Strengths (σ_{ys}) of [ ] and [ ] at point A and B respectively were used in the Begley-Logsdon method. These yield strengths were obtained from Figure 9A-0-1, which was established to provide a conservative fracture toughness design. The minimum USE of [ ] that is specified in the MHI purchase specification, was applied to the Begley-Logsdon method. The Maximum 50 percent FATT of [ ] was used in the Begley-Logsdon method to define Point C. This FATT is equal to or higher than that of as-built rotor.

Begley-Logsdon Method:

As shown in Figure 9-1, the equations of the Begley-Logsdon Method are as follows:

$$K_{IC}^{A} = \sigma_{ys}\sqrt{0.646\frac{C_V}{\sigma_{ys}} - 0.00635} \qquad \text{(Equation-1)}$$

$$K_{IC}^{B} = 0.072\sigma_{ys} \qquad \text{(Equation-2)}$$

$$K_{IC}^{C} = (K_{IC}^{A} + K_{IC}^{B})/2 \qquad \text{(Equation-3)}$$

where,

K_{IC}^{A} : Fracture toughness at point A, where 100% ductile fracture surface is obtained (MPa·m$^{1/2}$)

K_{IC}^{B}: Fracture toughness at point B where 100% brittle fracture surface is obtained (MPa·m$^{1/2}$)

K_{IC}^{C}: Fracture toughness at point C where 50 percent FATT appears (MPa·m$^{1/2}$)

C_V : Charpy V-notch Energy at Point A = USE (Joule).

σ_{ys} : Yield Strength at each point (temperature) (MPa)

The K_{IC} at the evaluation temperature of [ ] can be obtained by interpolation based on the above three values of K_{IC} at points A, B and C.

K_{IC} Calculations by Begley-Logsdon Method:

First - the temperatures at points A, B and C are defined.

The temperature at point A is the one at which a 100% ductile fracture surface can be obtained. A temperature of less than or equal to [ ] has been chosen based on

MHI's past experience with similar material. (For further details, refer to Figure 9A-0-2 and its notes).

The temperature at point B is the one at which a 100 % brittle fracture surface can be obtained. A temperature of less than or equal to [ ] was decided in a same manner as the temperature at point A.

It should be noted the two temperatures of [ ] were determined for the design purposes. The actual temperatures at points A and B of the as-built rotor depend on the properties of each rotor.

Yield Strength (σ_{ys}) was determined from Figure-9A-0-1, which was developed based on MHI's experience of similar LPT rotor material. The black solid line in the same figure shows the lowest limit of the yield strength of the similar LPT rotor material. The yield strength of the as-built LPT rotor for the US-APWR is expected to be higher than the black solid line at any temperature. The σ_{ys} at points A and B are [ ] and [ ] respectively.

The C_V at point A (USE) is [ ], which is same as the minimum USE required in the purchase specification.

The temperature of point C is equal to 50 percent FATT and is specified in the purchase specification as a maximum 50 percent FATT ([ ]). This FATT is to be equal to or higher than that of the as-built rotor.

Once the temperatures at points A, B and C are defined, the calculation is performed based on the Begley-Logsdon method, and results in a graph showing the relation between K_{IC} and temperature as is shown in Figure 9A-1 of this response.

Substituting,

σ_{ys} = [ ] and [ ] (From Figure 9A-0-1)

C_V = USE = [ ]

into Equation 1,2, and 3 gives the following values,

$$K_{IC}{}^{A} = \sigma_{ys}\sqrt{0.646\frac{C_V}{\sigma_{ys}} - 0.00635} = \left(\qquad \right)$$

= [ ]

$K_{IC}{}^{B} = 0.072\sigma_{ys}$

$=0.072\times$[ ]

= [ ]

$K_{IC}{}^{C} = (K_{IC}{}^{A} + K_{IC}{}^{B})/2$

= [ ]/2

=[ ]

K_{IC} at evaluation point of [ ] can be interpolated by $K_{IC}{}^{A}$ and $K_{IC}{}^{C}$.

$$K_{IC}\ @[\quad] = \left(\qquad \right)$$

= [ ] = [ ]

A [ ] margin is included to the above calculated K_{IC} of [ ] (refer to Figure 9A-1)

K_{IC} with [ ] margin = [ ] × [ ] = [ ] = [ ]

The value of K_{IC} of [ ] is actually used in the turbine missile analysis

Figure-9A-0-1 Relation between σ_{ys} (Yield Strength) and metal temperature

Notes on the above figures:

(1) The black solid line has been established for the purpose of design and goes under the minimum σ_{ys} specified in the purchase specification of [ ] in order to keep the evaluation of fracture toughness conservative.

(2) The X-marks show samples of the full integral (mono-block) LPT rotor material [ ]. All the data for recent full integral rotors have been verified as being located above the design-purpose-lower-limit of the similar material.

Figure-9A-0-2 Relation between Charpy V-notch Energy and metal temperature

Notes on the above figures:

(1) The black solid line shows the lowest limit of the material similar to [ ] based on MHI past experience, which was developed for the purpose of design. The line shows that a 100 percent ductile fracture surface can always be obtained at temperatures less than or equal to [ ]. The temperature at Point A (Minimum temperature to show 100 percent ductile fracture surface, refer to Figure 9-1) was set to be [ ] based on MHI's past experience with similar material.

(2) The black solid line is the lowest limit of the Charpy V-notch Energy of the material which is procured using the purchase specification. It is not expected that the USE for the US-APWR falls under the black solid line, because the black solid line is the lowest limit of the similar material and was developed conservatively based on MHI's experience.

(2) Based on MHI experience, the obtainable K_{IC} at the center bore core region of the full integral LPT rotor is expected to be greater than 220 MPa·m1/2 (200 ksi·in1/2), while much lower value for K_{IC} of [ ] was applied to the turbine missile analysis (refer to Figure 9A-1).

As shown in Figure 9A-1, actual values of K_{IC} based on MHI experience are greater than 200 ksi·in$^{1/2}$. The as-built K_{IC} is expected to be much greater than the K_{IC} used for turbine missile analysis.

Figure 9A-1 Relation between K_{IC} used in missile analysis and actual obtainable K_{IC} based on MHI Purchase Specification

Notes on the above figures;

(1) Actual Fracture toughness (K_{IC}) at the center bore core of the full integral rotor are significantly higher than that used in the turbine missile analysis [ ].

(2) This fact ensures that the turbine missile ejection probability can be kept low enough compared to the criteria in the SRP, even if MHI's purchase specification does not comply with the requirement of SRP 10.2.3 in regard to 50 percent FATT and Charpy V-notch Energy.

II. Application of the Begley-Logsdon method to the LPT rotor material [ ]

(1) Measured "Percent of brittle fracture" and "Charpy V-notch energy" of the material [ ] are given in Figure 9A-2.

(2) Those parameters and their approximate curves show prominent temperature-dependent characteristics.

(3) FATT and USE are well (clearly) defined by the approximate curves. The material properties of [ ] surely satisfies the conditions stipulated in the SRP section 10.2.3 paragraph II.1b for the application of Begley-Logsdon method to estimate actual K_{IC} of manufactured LPT rotors.

(4) Measuring method of those parameters;

- ✓ Confirm temperature-dependent properties by measuring the brittle fracture appearance rate and the Charpy V-notch energy at different temperatures and draw approximate curves.
- ✓ 50%FATT is determined by this approximate curves and Charpy V-notch energy is determined by approximating the curve at both room temperature (approx. 25℃) and at the temperature value of 0% of brittle fracture

Figure 9A-2 Example of measured "Percent of brittle fracture" and "Charpy V-notch energy" of the LPT rotor material

Notes on the above figure;

(1) Percent brittle fracture; Brittle fracture appearance/Area of fracture surface

(2) Charpy V-notch energy; The energy to fracture a test specimen in a Charpy test

Impact on DCD

The title and the last paragraph of the US-APWR, Tier 2, Section 10.2.3.2.1 will be revised as follows:

10.2.3.2.1 Brittle Fracture Analysis

Minimum material fracture toughness of the turbine rotors is provided by specifying the minimum yield strength, the maximum 50 percent FATT, and the minimum USE for the selected material.

Impact on R-COLA

There is no impact on the R-COLA.

Impact on PRA

There is no impact on the PRA.

Impact on Technical/Topical Report

The Technical Report MUAP-070028 (R1) "Probability of Missile Generation from Low Pressure Turbines" is to be revised per the response above.

For reference, major changes in the Technical Report MUAP-070028 (R1) are provided in this response.

The sentence which includes equation (3.6) and the following three paragraphs in Section 3.3 will be revised as follows:

"The critical crack size a_{cr} is obtained from the relation:

$$a_{cr} = \frac{Q}{\pi}\left(\frac{K_{IC}}{\sigma}\right)^2 \qquad (3.6)$$

where K_{IC} is the fracture toughness of the rotor and σ is the stress at ~~rated speed or~~ the design overspeed [ ]. ~~The stress is [ ] to be [ ], respectively at rated speed and design overspeed. These values are the sum of centrifugal stress and the maximum anticipated thermal stress during start-up cycle. The rotor metal temperature distribution at the rated condition is shown in Figure 3.3-1 for reference.~~

The fracture toughness K_{IC} of [ ] is applied on this analysis. The fracture toughness K_{IC} of [ ] was obtained through Begley-Logsdon Method with the safety margin of 20% using upper shelf energy of [ ] specified in the purchase specification as a minimum allowable value.

The size of the initial crack depth a_i is set to be [ ] under the assumption of [ ] flaw shape, since the inspection procedures used for integral rotor forgings can reliably detect flaws [ ].

The stress range of $\Delta\sigma$ is ~~taken to be a combined stress range occurring during a start-up and shut-down considering centrifugal and thermal stresses as previously discussed.~~ conservatively determined to be [ ], respectively at rated speed, trip setting speed and design overspeed. These values are the sum of centrifugal stress and the maximum anticipated thermal stress during start-up cycle. The rotor metal temperature distribution at the rated condition is shown in Figure 3.3-1 for reference."

The last two paragraphs of Section 3.3 will be revised as follows:

"The calculated ~~results in regard to the~~ probability of a LP rotor rupture due to LCF ~~are~~is summarized in Table 3.3-2, which includes three case studies. In each case, the maximum rotating speed during start-up/shut-down is assumed to be 100%, 111% and 120% of rated speed respectively. The 111% overspeed is the trip set point of the overspeed trip device and the 120% overspeed is design overspeed which can only occur when the control system fails to function. Table 3.3-2 shows the probability of rupture at [ ] start-up/shut-downs and the number of start-up/shut-downs at which the probability of rupture reaches the NRC's guideline of $P_1 < 1 \times 10^{-5}$ per year being specified in SRP 3.5.1.3 (Reference 12), Table 3.5.1.3-1. It should be noted that the margin of [ ] in the number of start-up/shut-down used and listed in the Table 3.3-2 is taken into account for compensating the uncertainty in the variation of the propagation speed of cracks in the rotors. In the

Case-2 which assumes maximum rotating speed of 111% of rated speed at every start-up/shut-down and is conservative enough compared to the actual operation of the nuclear units, the number of the start-up/shut-down at the probability of rupture of 1×10^{-5} per year is [ ]. Even in the assumption of 120% overspeed at every start-up/shut-down (Case-3), it is demonstrated that the above NRC's guideline is satisfied in the range up to [ ] start-up/shut-downs while 120% overspeed can only occur with the control system failure. ~~The number of start and stops, at which the crack size is increased up to a critical one, is very large.~~

~~It takes [ ] of start and stops for the initial cracks to grow up to the critical size with their maximum potential, which corresponds even under the assumption of weekly start and stops for [ ] with [ ] overspeed condition.~~ It is concluded that a low pressure rotor rupture due to the LCF can-not ~~actually happen~~ occur before ~~under~~ the postulated plant life ~~actual plant operation~~ has expired."

The last paragraph of Section 3.4.3 will be revised as follows:

"The final probability profiles are given in terms of discrete inspection intervals in Table 3.4-2 and are shown in Figure 3.4-1. The results show that the necessary inspection interval to satisfy the requirement of missile generation probability less than 10^{-5} per year is [ ] even under the conservative assumptions ~~incorporated~~used in~~to~~ this analysis."

The last two paragraphs of Section 4.0 will be revised as follows:

Analysis of the LCF mechanism demonstrates that the probability of failure by this scenario is extremely low ~~even~~ under conservative assumptions. ~~[ ]. It is concluded that a low pressure rotor rupture can not happen before [600 cycles of start and stops], and the NRC safety guidelines can be satisfied by the periodic inspection in a proper interval within [ ].~~ In the case of assuming maximum rotating speed of 111% of rated speed at every start-up/shut-down cycles and being conservative enough compared to the actual operation of the nuclear units, the number of the start-up/shut-downs at which the probability of rupture reaches the NRC's guideline of $P_1 < 1\times10^{-5}$ per year being specified in SRP 3.5.1.3 (Reference 12), Table 3.5.1.3-1 is [ ]. With the assumption of 120% overspeed at every start-up/shut-down, it is demonstrated that the above NRC's guideline is satisfied in the range up to [ ] start-up/shut-down while 120% overspeed can only occur with the control system failure. It can be concluded that this number of cycles before the low-pressure rotor rupture probability due to LCF exceeds the NRC guide line is greater than the number of start-up/shut-downs expected to experience in the postulated plant life. Therefore, it is not necessary to take the LCF calculation results into consideration for determining the periodic inspection interval, provided that the life of the low-pressure rotors due to LCF is under the control of the plant license holder.

~~The SCC has the greatest influence on rotor integrity.~~ The probability of failure by the SCC~~this~~ mechanism is ~~however~~ significantly reduced by the application of integral rotor design. The analysis shows that a running time [ ] ~~may~~ can elapse before the first inspection without exceeding the above NRC safety guidelines even under highly conservative assumptions would occur. Considering ~~the fact~~ that the most probable crack locations are ~~readily~~ accessible during normal turbine inspections and maintenance, it is concluded from the design ~~view point~~ considerations show that the NRC safety guidelines can be satisfied by the periodic inspection in a proper interval within [ ]."

The following paragraph will be added at the end of Section 4.0:

"These calculation results demonstrate that the low-pressure rotor inspection before [ ] operation is sufficiently conservative to keep the turbine missile generation probability less than the NRC guideline during operation."

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

05/30/2013

US-APWR Design Certification

Mitsubishi Heavy Industries

Docket No. 52-021

RAI NO.:	**NO. 574-4633**
SRP SECTION:	**10.02.03 – Turbine Rotor Integrity**
APPLICATION SECTION:	**10.2.3**
DATE OF RAI ISSUE:	**4/20/2010**

QUESTION NO.: 10.02.03-10

In a letter dated March 10, 2009, MHI provided a response to RAI No. 199-2073, Question 10.02.03-2, stated that the tensile and charpy testing will be performed on five specimens from the outer periphery of the turbine rotor. For a bored rotor, additional tensile and Charpy testing will be performed from three specimens on the interior bore periphery of the turbine rotor. However, the staff notes that Revision 2 of the US-APWR FSAR did not include the number of specimens to be tested as provided in the response to RAI No. 199-2073, Question 10.2.3-2. In addition, the staff notes that neither MHI's response to RAI No. 199-2073, Question 10.02.03-2 provided in a letter dated March 10, 2009, nor Section 10.2.3.2 of the US-APWR FSAR, Revision 2, Tier 2 provides the method of calculating the fracture toughness value for the turbine rotor material.
SRP Section 10.2.3 (paragraph II.2) lists four acceptable methods for obtaining the fracture toughness properties. Therefore, the staff requests that the USAPWR FSAR be revised to:

a. Include the number of test specimens as stated in its response to RAI No. 199-2073, Question 10.02.03-2
b. Include the test method and fracture toughness acceptance criteria that will be used for the turbine rotor design.

ANSWER:

a. The numbers of test specimens will be added to FSAR section 10.2.3.
   The location of test coupons is shown as Figure 10-1.
b. The Charpy test criteria will be added to FSAR section 10.2.3.
   The Acceptance criteria for the Charpy test are shown as Table 10-1.

[ ]

Note: Test specimens for Tensile test (TT) and Charpy test (VT) are to be taken from X-1 through X-5. The number of the test specimens taken from each sampling location is shown below.

Sampling location	Number of specimens for Tensile test (TT)	Number of specimens for Charpy test (VT)
X-1	4	Min. 8 (Note 1)
X-2	4	Min. 8 (Note 1)
X-3	4	Min. 8 (Note 1)
X-4	4	Min. 8 (Note 1)
X-5	4	Min. 8 (Note 1)
Total	20 per LPT rotor	Min. 40 per LPT rotor

Note 1: Min. 3 specimens for the Charpy tests at Room Temperature
Min. 5 specimens for the Charpy tests at other temperature for the determination of a transition temperature.

Figure 10-1 Location of sampling for Tensile and Charpy tests

Table 10-1 Acceptance criteria of the Charpy test

Test	Item	Purchase Specification of LP Rotor Forging
Charpy Test	Charpy V-notch energy at 21-27 deg C	[ ]
	50% FATT	[ ]
	Upper Shelf Energy (USE) Level	[ ]

Additional NRC Comment (Open Item 10.2.3-3):

Regarding the locations of the test specimens and the material properties of the internal regions for a non-bored rotor, the applicant stated in its response to RAI 199-2073, Question 10.2.3-2, that the tensile and Charpy testing will be performed on five coupons from the outer periphery of the turbine rotor. For a bored rotor, additional tensile and Charpy testing will be performed from three coupons on the interior bore periphery of the turbine rotor. The staff finds the number of specimens acceptable since it meets the guidance provided in SRP 10.2.3.

However, the staff identifies that Revision 2 of the DCD should include the number of coupons and specimens to be tested as provided in the response to RAI 199-2073, Question 10.2.3-2.

MHI Response to Additional NRC Comment

The following sentence will be added in Revision 3 of the DCD:

Five coupons will be taken from one LPT rotor. Four tensile test specimens and minimum eight Charpy V-notch (C_v) test specimens, which includes minimum three C_v test specimens at room temperature are cut out from each coupon.

Impact on DCD

The 1st paragraph of the US-APWR, Tier 2, Section 10.2.3.1 and the 1st paragraph of the US-APWR, Tier 2, Section 10.2.3.2 will be revised as follows:

10.2.3.1 Materials Selection

Fully integral turbine rotors are made from ladle refined, vacuum deoxidized Ni-Cr-Mo-V alloy steel by processes that maximize the cleanliness and toughness of the steel. The lowest practical concentrations of residual elements are obtained through the melting process. The LP turbine rotor material is similar to ASTM A470, Grade C, Class 6 (Reference 10.2-5) as specified in the turbine missile analysis (Reference 10.2-9). This material has the lowest fracture appearance transit temperatures (FATT) and the highest Charpy V-notch energies obtainable on a consistent basis from water-quenched Ni-Cr-Mo-V material at the sizes and strength levels used. Mechanical properties such as tensile strength, yield strength, elongation, reduction of area, Charpy V-notch energy at room temperature, upper shelf energy and 50 percent FATT are equal to or more conservative than those of ASTM A470, Grade C, Class 6. Charpy tests and tensile tests are conducted in accordance with ASTM, A370 (Reference 10.2-6). Five coupons will be taken from each LPT rotor. Four tensile test specimens and a minimum of eight Charpy V-notch test specimens, which includes a minimum of three Charpy V-notch test specimens at room temperature, are cut out from each coupon and tested in accordance with the requirement of ASTM A370 (Reference 10.2-6).

10.2.3.2 Fracture Toughness

Suitable material toughness is obtained through the use of materials described in Subsection 10.2.3.1 to produce a balance of material strength and toughness to provide safety while simultaneously providing high reliability, availability, and efficiency during operation. The restrictions on phosphorous (P), sulphur (S), aluminum (Al), antimony (Sb), tin (Sn), arsenic (As) and copper (Cu) in the specification for the rotor steel provide the appropriate balance of material strength and toughness. The Charpy V-notch energy and 50 percent FATT requirements are equal to or more rigorous than those given in ASTM A470, Grade C, Class 6.

Impact on R-COLA

There is no impact on the R-COLA.

Impact on PRA

There is no impact on the PRA

Impact on Technical/Topical Report

There is no impact on a Technical/Topical Report.

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

05/30/2013

US-APWR Design Certification

Mitsubishi Heavy Industries

Docket No. 52-021

RAI NO.:	**NO. 574-4633**
SRP SECTION:	**10.02.03 – Turbine Rotor Integrity**
APPLICATION SECTION:	**10.2.3**
DATE OF RAI ISSUE:	**4/20/2010**

QUESTION NO.: 10.02.03-11

In a letter dated March 10, 2009, MHI provided responses to RAI No. 199-2073, Questions 10.02.03-2 and 10.02.03-5 concerning the integrity of a non-bored (solid) turbine rotor.

MHI response to RAI No. 199-2073, Questions 10.02.03-2 provided some material test result comparisons between the rotor outer periphery and the rotor center core so that the mechanical properties at the rotor center core can be evaluated using the material at the outer periphery of the turbine rotor. Based on this comparison, chemical composition and mechanical testing of the core for non-bored rotors would not be performed. The NRC staff notes that the comparative material test results provided shows that the material at the center core of the turbine rotor has material properties that are less conservative (lower reduction of area, lower impact energy and higher 50 percent FATT temperature) than at the outer periphery, which is due to the different solidification rates of this large component. Therefore, the material properties cannot be accurately and consistently determined using only test specimens from the outer periphery of the turbine rotor.

In its response to RAI No. 199-2073, Question 10.02.03-05, MHI stated that ultrasonic inspection of the turbine rotor will be performed prior to gashing (final outside periphery machining) so that 100% ultrasonic inspection can be performed on the turbine rotor due to its drum shape.

However, it also states that as ultrasonic testing technology advances, potential defects at the center core region will be detected. Therefore, this implies that currently, ultrasonic inspection is not capable of ensuring the integrity of non-bored turbine rotors at the center region.

Therefore, the integrity of non-bored turbine rotors cannot be verified, since the non-destructive examinations (pre-service and in-service volumetric inspections) are not capable of detecting defects at the center core region, and destructive testing cannot be performed on non-bored rotors to confirm the material properties. Therefore, the non-bored rotor design should be deleted from the US-APWR FSAR, or provide the following:

- Specific destructive testing that can confirm the material properties at the core region, and/or more extensive test results.
- Specific non-destructive testing that can detect defects at the center core region, or provide specific in-service non-destructive examinations, including inspection types, inspection interval, acceptance criteria, etc. taking into consideration that material properties and the presence of internal defects of the as-built turbine rotor cannot be confirmed.

- Appropriate operating experience which justifies the integrity of the turbine rotor can be maintained.

ANSWER:

The content of S (Sulfur) and P (Phosphorous) that have adverse effects on inclusion and segmentation have been significantly reduced because of progress in steel making technology. Figure 11-1 shows the history of reduction in the content of S and P. Figure 11-2 also shows the material test record sample for rotors manufactured over the last 20 years. The test result shows that the mechanical properties at the center core of the rotor are stable enough to satisfy the specification requirements.

Please note that there are similar figures to Figure 11-2 in the answer to Q10.02.03-1 and Q10.02.03-5 in RAI 199-2073 as “Figure 2-2” and “Figure 5-1”. However, the Figures in the response to the RAI 199-2073 need to be replaced by the updated Figure 11-2 in this response to RAI 574-4633, Question No. 10.02.03-11The illegible figures in the response to the RAI 199-2073 show the mechanical properties of the LPT rotors for fossil usage and are not suitable for the evaluation of the LPT rotors for nuclear usage for the following reasons;

- All the rotors listed in Figure 2-2 and Figure 5-1 in RAI 199-2073 rotate at full speed (3,000 or 3,600rpm) and the size of the rotors are much smaller than those usually used in nuclear power plants, which rotate at half speed (1,500 or 1,800rpm).
- There are also significant differences in the mechanical properties such as yield strength and tensile strength between the rotors for fossil and nuclear usage. Those differences could have serious impacts on the mechanical properties and homogeneity of the rotors, especially at and around the axial center of the rotors.

Figure 11-1 Reduction history of the content of S and P

Figure 11-2 Example of the LPT rotor material test result from last 20 year record (all the rotors from A through G are for nuclear usage)

Through past improvements in ultrasonic testing technology, it is possible to detect small defects at the center of the rotor from the rotor periphery. Figure 11-3 demonstrates that ultrasonic inspection from the rotor periphery can reliably detect flaws [ ] in length.

Figure 11-3 Minimum detectable flaw size at the center of the rotor by the ultrasonic inspection

Table 11-1 shows examples of a bore inspection record after long term operation. This record confirms that integrity of the turbine rotor has been maintained for more than [ ].

All the units included in the Table 11-1 are the ones for fossil usage and do not include the units for nuclear usage. But please note that the low pressure turbines for unit A, C and D are of half speed (1,800rpm) design like nuclear machines, and the rotor size and the material properties are the same as nuclear units. In addition, operating conditions such as inlet temperature and the number of starts/stops of fossil LP turbines is much more severe than nuclear steam turbines in terms of imposed stresses on the rotors. It can be concluded that the operating experience at fossil unit A, C and D bound the experience at nuclear units.

Table 11-1 Examples of bore inspection after operation (with-bored rotor)

Additional NRC Comment (Open Item 10.2.3-4):

Based on the above, the turbine rotor can be either a bored or non-bored rotor design. The applicant also stated that the homogeneity and quality of the material at the center core of a non-bored rotor is ensured through the steel making process. In addition, in its response to RAI 199-2073, Question 10.2.3-2, the applicant provided some material test result comparisons between the rotor outer periphery and the rotor center core so that the mechanical properties at the rotor center core can be evaluated using the material at the outer periphery of the turbine rotor. Therefore the applicant will not perform chemical composition and mechanical testing of the core for non-bored rotors.

The NRC staff notes that the comparative material test results provided show that the material at the center core of the turbine rotor has material properties (lower reduction of area, lower impact energy and higher 50 percent FATT temperature) that are less conservative than at the outer periphery, which is due to the different solidification rates of this large component. Therefore, the material properties cannot be accurately and consistently determined using only test specimens from the outer periphery of the turbine rotor. Since the material properties do vary from the outer periphery to the internal center core, and the internal core of each non-bored as-built turbine rotor cannot be verified, the applicant should delete the non-bored turbine rotor from its design, or provide specific destructive testing and nondestructive testing taking into consideration that the internal material properties and the presence of internal defects of the as-built rotor cannot be confirmed. In addition, appropriate operating experience should be provided which justifies that the integrity of the rotor can be maintained.

MHI Response to Additional NRC Comment

I. Internal material of the non-bored LPT rotors

1. Reasons for use of non-bored rotor

   MHIs response in the response to RAI No. 199-2073, Questions 10.02.03-2 and 10.02.03-5 explained that non-bored rotors are to be used in the US-APWR steam turbine for the following reasons:

(1) Inherent low tangential stress due to centrifugal forces at around the center of the rotor,

(2) Advancement of steel making process that realize homogeneity along the radial line of large size LPT rotors. Moreover, these advancements ensure that the mechanical properties at the center of the rotors can be reliably and stably kept within the limitations specified in MHI purchase specification.

2. Mechanical properties at the center of LPT rotors;

   Measured mechanical properties at the center bore core of the full integral rotor with drum diameter of [ ] are shown in Figure 11A-1. The figure shows that all the mean values of the mechanical properties ± 3σ (99.7% reliability) are secured to satisfy the minimum required values of the purchase specification. As the LPT rotor size of the US-APWR is almost the same as the rotors listed in Figure 11A-1 (this implies that the drum diameter of the US-APWR LPT rotors is expected to be the same as the maximum diameter of the above range), it is concluded that the mechanical properties including "Absorbed Energy" and "50 percent FATT" are maintained at a reliability higher than 99.7 percent within the allowable ranges that are specified in the MHI purchase specification.

3. Turbine missile probability

   It was concluded that non-bored LPT rotors keep the turbine missile probability less than the criteria specified in the SRP without destructive testing at the center bore core for the following three reasons:

   (1) Inherent low tangential stress around the center of the rotor,

   (2) The mechanical properties at the rotor center stay at a reliability higher than 99.7 percent of the allowable range,

   (3) The fracture toughness (KIC) applied in technical report "Probability of Missile Generation from Low Pressure Turbines, MUAP-07028" is [ ]. is calculated based on the minimum requirement of the Charpy V-notch energy (USE) and 50 percent FATT that are specified in the purchase specification of the Low Pressure Turbine rotors.

II. Inspection of the internal defects of non-bored LPT rotors

As is explained in the DCD Section 10.2.3.3 "Preservice Inspection", each LPT rotor forging is subject to a 100 percent volumetric examination (UT inspection). 100% UT inspection after periphery machining of the as-built rotors will be carried out to define the initial internal defect size and location, including the ones around the center of the rotors. This UT inspection can detect the defects as small as [ ] at the center of the rotors, while we assumed initial crack size is [ ] in the turbine missile analysis conservatively to compensate for the possible inclined cracks. Therefore, the UT inspection from the rotor outer periphery performed as part of the preservice inspection is enough to keep the turbine missile probability caused by low cycle fatigue less than the criteria specified in the SRP.

The LPT rotor outer surface is exposed to wet steam and material degradation could occur due to the corrosive environment. The center of the rotor is isolated from the steam environment and there is no possibility of material degradation such such environmental effects. Therefor the initial 100 percent UT inspection of the rotor and the turbine missile probability analysis using the initial crack size and location of the as built-rotor is sufficient to establish that the turbine missile probability is less than the criteria for the plant life time. This means that it is not necessarily mandatory to do the UT inspection around the center of the rotors during periodical inspection.

Figure 11A-1 Test results of mechanical properties at the center bore core of full integral LPT rotors for nuclear usage

(Refer to the Notes on the next page)

Notes for Figure 11A-1 (Figure of the previous pages):

Note 1: All the data in Figure 11A-1 is for the center bore core of full integral rotors with drum diameters between [ ] inches. The drum diameter of the US-APWR LPT rotors is expected to be almost same as the maximum of the above range.

Note 2: The steel forging manufacturer of all the rotors listed in this figure is suppling the LPT rotor forgings for US-APWR.

Note 3: The positions of the test coupons from B1 through B3 are shown below:

Note 4: Blue dotted lines show the range of $\pm 3\sigma$ (99.7 percent reliability).
All the mechanical properties including "Charpy V-notch energy" and "50 percent FATT" are confirmed to be in the reliability higher than 99.7 percent.

Note 5: Minimum yield strength requirement of the LPT rotors of Unit C and D changed from [ ] to [ ] to keep the Stress Corrosion Cracking (SCC) sensitivity as low as possible depending on the safety margin of the rotors against centrifugal forces. Tensile strength of the same rotors also reduced along with the reduction of yield strength.

Impact on DCD

The 2nd paragraph from the last of the US-APWR, Tier 2, Section 10.2.3.4 will be revised as follows:

The non-bored design of the high-pressure and low-pressure turbine rotor provides the necessary design margin by virtue of its inherently lower centerline stress. Metallurgical processes permit fabrication of the rotors without a center borehole. The use of solid rotor forgings was verified by an evaluation of the material removed from center-bored rotors for nuclear power plants. This evaluation demonstrated that the material at the center of the rotors satisfied the rotor material specification requirements. Forgings for no-bore rotors are provided by suppliers who have been qualified based on bore material performance.

Impact on R-COLA

There is no impact on the R-COLA.

Impact on PRA

There is no impact on the PRA.

Impact on Technical/Topical Report

There is no impact on a Technical/Topical Report.

10.2.3.1 Materials Selection

Fully integral turbine rotors are made from ladle refined, vacuum deoxidized Ni-Cr-Mo-V alloy steel by processes that maximize the cleanliness and toughness of the steel. The lowest practical concentrations of residual elements are obtained through the melting process. ~~The turbine rotor material complies with the chemical property limits of ASTM A470 (Reference 10.2-5). The specification for the rotor steel has lower limitations than indicated in the ASTM standard (Reference 10.2-5) for phosphorous, sulphur, aluminum and antimony.~~The LP turbine rotor material is similar to ASTM A470, Grade C, Class 6 (Reference 10.2-5) as specified in the turbine missile analysis (Reference 10.2-9). This material has the lowest fracture appearance transit temperatures (FATT) and the highest Charpy V-notch energies obtainable on a consistent basis from water-quenched Ni-Cr-Mo-V material at the sizes and strength levels used. Mechanical properties such as tensile strength, yield strength, elongation, reduction of area, ~~absorbed energy at Charpy test~~Charpy V-notch energy at room temperature, upper shelf energy and 50 percent FATT are equal to or more conservative than those of ASTM A470, Grade C, Class 6. Charpy tests and tensile tests are conducted in accordance with ASTM, A370 (Reference 10.2-6). ~~A minimum of three Charpy test specimens are tested using the impact test criteria that satisfy ASTM A470 Grade C (Class 6).~~Five coupons will be taken from ~~one~~each LPT rotor. Four tensile test specimens and a minimum of eight Charpy V-notch ~~(C_v)~~ test specimens, ~~which includes~~including a minimum of three ~~C_v~~Charpy V-notch test specimens at room temperature, are cut ~~out~~ from each coupon and tested in accordance with the requirement of ASTM A370 (Reference 10.2-6). DCD_10.2.3-10 S01 DCD_10.2.3-10 S01 DCD_10.02.03-10 S02 DCD_10.02.03-10 S02

The production of steel for the turbine rotors starts with the use of high-quality, low residual element scrap. An oxidizing electric furnace is used to melt and dephosphorize the steel. Ladle furnace refining is then used to remove oxygen, sulphur, and hydrogen from the rotor steel. The steel is then further degassed using a process whereby steel is poured into a mold under vacuum to produce an ingot with the desired material properties. This process minimizes the degree of chemical segregation since silicon is not used to deoxidize the steel.

10.2.3.2 Fracture Toughness

Suitable material toughness is obtained through the use of materials described in Subsection 10.2.3.1 to produce a balance of material strength and toughness to provide safety while simultaneously providing high reliability, availability, and efficiency during operation. The restrictions on phosphorous (P), sulphur (S), aluminum (Al), antimony (Sb), tin (Sn), arsenic (As) ~~argon,~~ and copper (Cu) in the specification for the rotor steel provides ~~for~~ the appropriate balance of material strength and toughness. The ~~impactabsorbed~~Charpy V-notch energy and 50 percent FATT~~transition temperature~~ requirements are equal to or more rigorous than those given in ASTM A470, Grade C, Class 6 ~~or 7 and their equivalents~~. DCD_10.2.3-10 S01 DCD_10.02.03-10 S02

Stress calculations include components due to centrifugal loads and thermal gradients where applicable. Fracture toughness will be at least 200ksi·in$^{1/2}$ (220MPa·m$^{1/2}$). For the purpose of conservative evaluation, fracture analysis is to be done using ~~a~~ fracture toughness with margin against minimum expected values on the rotors. The material DCD_10.02-3

The rotor is evaluated for fracture toughness by criteria that include the design duty cycle stresses, number of cycles, ultrasonic examination capability and growth rate of potential flaws. Conservative factors of safety are included to account for the amount of uncertainty in the potential or reported ultrasonic indications of flaws, rate of flaw growth (da/dN versus dK) and the duty cycle stresses and number.

Reported rotor forging indications are adjusted to account for the amount of uncertainty and interaction. A rotor forging with a reported indication that would grow to a critical size in the applicable duty cycles is not accepted. The combined rotation and maximum transient thermal stresses used in the applicable duty cycles are based on the brittle fracture and rotor fatigue analyses described below.

Maximum transient thermal stresses are determined from historical maximum loading rates for nuclear service rotors.

10.2.3.2.1 Brittle Fracture Analysis

DCD_10.02.03-9 S02

A brittle fracture analysis is performed on the turbine rotor to provide confidence that small flaws in the rotor, especially near the centerline, do not grow to a critical size with unstable growth resulting in a rotor burst. The brittle fracture analysis process includes determining the stresses in the rotor resulting from rotation, steady-state thermal loads, and transient thermal loads from startup and load change. These stresses are combined to generate the maximum stresses and locations of maximum stress for the startup and load change transients. A fracture mechanics analysis is performed at the location(s) of maximum stress to verify that an initial flaw, equal to the minimum reportable size, will not grow into critical crack size over the lifetime of the rotor under the cumulative effects of startup and load change transients.

A fracture mechanics analysis is done at the location(s) of maximum stress to determine the critical crack size and the initial flaw area that would grow just to the critical size when subjected to the number of startup and load change cycles determined to represent the lifetime of the rotor. This initial flaw area is divided by a factor of safety to generate an allowable initial flaw area. The minimum reportable flaw size is multiplied by a conservative factor to correct for the imperfect nature of a flaw as an ultrasonic reflector, as compared to the calibration reflector. The resulting area is the corrected flaw area. For an acceptable design, the allowable initial flaw area must be greater than or equal to the corrected flaw area.

For rotor contour, a surface connected elliptical crack is assumed. The flaw is assumed to be orientated normal to the maximum principle stress direction.

The beginning-of-life FATT for the high pressure and low pressure rotor is specified in the material specification for the specific material alloy selected. Both high pressure and low-pressure turbines operate at a temperature at which temperature embrittlement is insignificant. The beginning-of-life FATT is not expected to shift during the life of the rotor due to temperature embrittlement.

Minimum material ~~toughness is provided by specification of the maximum FATT and minimum upper shelf impact energy for the specific material alloy selected. There is not a~~ DCD_10.02.03-9 S02

~~separate material toughness (K_{IC}) requirement for US-APWR rotors.~~fracture toughness of the turbine rotors is provided by specifying the minimum yield strength, the maximum 50 percent FATT, and the minimum USE for the selected material. DCD_10.02.03-9 S02

10.2.3.2.2 Rotor Fatigue Analysis

A fatigue analysis is performed for the turbine rotors to show that cumulative usage is acceptable for expected transient conditions including normal plant startups, load following cycling, and other load changes. A margin is provided by assuming a conservatively high number of turbine start and stop cycles. The turbine rotors in operating nuclear power plants were designed using this methodology and have had no history of fatigue crack initiation due to duty cycles.

In addition to the low cycle fatigue analysis for transient events, an evaluation for high cycle fatigue is performed. This analysis considers loads due to gravity bending and bearing elevation misalignment. The local alternating stress is calculated at critical rotor locations considering the bending moments due to the loads described above. The maximum alternating stress is less than the smooth bar endurance strength modified by a size factor.

The T/G is supported by a reinforced concrete foundation, which is designed so that the vertical deflection of beams, girders and columns/column-wall should not impose additional alternating stress on the T/G or shaft train considering the following factors:

- Condenser vacuum load
- Normal torque load
- Thermal load due to machine expansion-contraction
- Load due to temperature increase of the deck
- Piping load

The dynamic response of the T/G foundation including vibration amplitude and natural frequency analysis are analyzed to confirm that no additional alternating stress is imposed on the T/G shaft train.

10.2.3.3 Preservice Inspection

Preservice inspections for turbine rotors include the following:

- Rotor forgings are rough machined with a minimum stock allowance prior to heat treatment.
- Each rotor forging is subjected to a 100-percent volumetric (ultrasonic) examination. Each finish-machined rotor is subjected to a surface magnetic particle and visual examination. Results of the above examination are evaluated by use of criteria that are more restrictive than those specified for Class 1 components in ASME Code, Section III and V (Reference 10.2-7 and 10.2-8). These criteria include the

requirement that subsurface ultrasonic indications are either removed or evaluated to verify that they do not grow to a size which compromises the integrity of the unit during the service life of the unit.

- Finish-machined surfaces are subjected to a magnetic particle examination. No magnetic particle flaw indications are permissible in highly stressed regions.
- Each fully bladed turbine rotor assembly is spin tested at 120 percent overspeed, the maximum anticipated design overspeed at a load rejection from full load.

Rotor areas which require threaded holes are not subjected to a magnetic particle examination of the threaded hole. The number of threaded holes is minimized, and threaded holes are not located in high stress areas.

10.2.3.4 Turbine Rotor Design

The turbine assembly is designed to withstand normal conditions and anticipated transients, including those resulting in turbine trip, without loss of structural integrity. The design of the turbine assembly meets the following criteria:

- The design overspeed of the turbine is 5% above the highest anticipated speed resulting from a loss of load.
- The combined stresses of the low-pressure turbine rotor at design overspeed due to centrifugal forces and thermal gradients do not exceed 0.75 of the minimum specified yield strength of the material at design overspeed.
- The turbine shaft bearings are able to withstand any combination of the normal operating loads, anticipated transients, and accidents resulting in turbine trip.
- The natural critical frequencies of the turbine shaft assemblies existing between zero speed and 20% overspeed are controlled in the design and operation so as to cause no distress to the unit during operation.
- The turbine rotor design facilitates an inservice inspection of all high stress regions. All the turbine rotors use the mono-block rotor design instead of the conventional shrunk-on disk design.
- Tangential stresses will not cause a flaw, which is assumed to be twice the corrected ultrasonic examination reportable size, to grow to critical size in the design life of the rotor (refer to Subsection 10.2.3.2).

The low-pressure turbine has fully integral rotors forged from a single ingot of low alloy steel. This design is inherently less likely to have a failure resulting in a turbine missile than designs with shrunk-on discs. A major advantage of the fully integral rotor is the elimination of disc bores and keyways, which can be potential locations for stress risers and corrosive contaminant concentration. This difference results in a substantial reduction of rotor peak stresses, which in turn reduces the potential for crack initiation. The reduction in peak stress also permits selection of a material with improved ductility, toughness, and resistance to stress corrosion cracking.

The non-bored design of the high-pressure and low-pressure turbine rotor provides the necessary design margin by virtue of its inherently lower centerline stress. Metallurgical processes permit fabrication of the rotors without a center borehole. The use of solid rotor forgings was verified by an evaluation of the material removed from center-bored rotors for ~~fossil~~nuclear power plants. This evaluation demonstrated that the material at the center of the rotors satisfied the rotor material specification requirements. Forgings for no-bore rotors are provided by suppliers who have been qualified based on bore material performance. DCD_10.2.3-11 S01

All the low-pressure turbine rotating blades are attached to the rotor using christmas tree, side entry type root.

10.2.3.5 Inservice Inspection

The inservice inspection program for the LP turbine provides assurance that rotor flaws that might lead to brittle failure of a rotor at speeds up to design speed will be detected. This inspection includes disassembly of the turbine at equal or less than 10-year intervals during plant shutdowns coincident with the inservice inspection schedule required by IWA-2430 of the 2007 Edition with 2008 Addenda of Section XI, Division 1 ASME Boiler & Pressure Vessel Code. Inspection of parts that are normally inaccessible when the turbine is assembled for operation (couplings, coupling bolts, turbine rotors, and low pressure turbine blades) is conducted.

The maintenance and inspection program plan for the turbine assembly and valves is based on turbine missile probability calculations, operating experience of similar equipment and inspection results. The turbine missile generation probability due to rotor material failure below design overspeed was submitted in Reference 10.2-9. The analysis of missile generation probability due to failure of the overspeed protection system is used to determine turbine valve test frequency and is described in Reference 10.2-10. The maintenance and inspection program includes the activities outlined below:

- This inspection consists of visual, surface, and volumetric examinations as indicated below:
    - Each rotor, stationary and the rotating blade path component is inspected visually and by magnetic particle testing on its accessible surfaces. Ultrasonic inspection of the side entry blade grooves is conducted. These inspections are conducted at intervals equal or less than 10 years for both high-pressure and low-pressure turbines.
    - A 100 percent surface examination of couplings and coupling bolts is performed.
    - The fluorescent penetrant examination is conducted on nonmagnetic components.
- At least one main steam stop valve, one main steam control valve, one reheat stop valve, and one intercept valve are dismantled approximately every 4 years during scheduled refueling or maintenance shutdowns. A visual and surface examination of the valve internals is conducted. If unacceptable flaws or excessive corrosion are