Structural Analysis for US-APWR Reactor Coolant Pump Motor Flywheel

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Abstract

This technical report describes the evaluation of the reactor coolant pump (RCP) motor flywheel design and its conformance to U.S Regulatory Guide (RG) 1.14.

RG 1.14 describes the flywheel design requirements for the RCP motor.

This report includes the following analysis results:
- Ductile failure analysis
- Nonductile failure analysis
- Fatigue Crack growth analysis
- Excessive deformation analysis

It is confirmed that results of the above analyses satisfied the flywheel design requirements of RG 1.14.

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List of Acronyms

ASME	American Society of Mechanical Engineers
LBB	leak before break
LOCA	loss of coolant accident
RCP	reactor coolant pump
RG	Regulatory Guide
RT_{NDT}	reference nil ductility temperature

1.0 INTRODUCTION

The purpose of this report is to establish that the US-APWR reactor coolant pump (RCP) motor flywheel design satisfies the requirements of Regulatory Guide (RG) 1.14(Reference 1).

RG 1.14, Revision 1, Section C, Subsection 2 provides the following regulatory position for flywheel design. These guidelines are followed in the flywheel evaluation reported herein.

a) *The flywheel assembly, including any speed-limiting and antirotation devices, the shaft, and the bearings, should be designed to withstand normal conditions, anticipated transients, the design basis of loss-of-coolant accident, and the Safe Shutdown Earthquake loads without loss of structural integrity.*

b) *Design speed should be at least 125% of normal speed but not less than the speed that could be attained during a turbine overspeed transient. Normal speed is defined as the synchronous speed of the a.c. drive motor at 60 hertz.*

c) *An analysis should be conducted to predict the critical speed for ductile failure of the flywheel. The methods and limits of paragraph F-1323.1(b) in Section III of the ASME Code are acceptable. If another method is used, justification should be provided. The analysis should be submitted to the NRC staff for evaluation.*

d) *An analysis should be conducted to predict the critical speed for nonductile failure of the flywheel, justification should be given for the stress analysis method, the estimate of flaw size and location, which should take into account initial flaw size and flaw growth in service, and the values of fracture toughness assumed for the material. The analysis should be submitted to the NRC staff for evaluation.*

e) *An analysis should be conducted to predict the critical speed for excessive deformation of the flywheel. The analysis should be submitted to the NRC staff for evaluation. (Excessive deformation refers to any deformation such as an enlargement of the bore that could cause direct separation or an imbalance of the flywheel leading to structural failure or separation of the flywheel from the shaft. The calculation of deformation should employ elastic-plastic methods, unless it can be shown that stresses remain within the elastic range.)*

f) *The normal speed should be less than one-half of the lowest of the critical speeds calculated in regulatory positions C.2.C, d, and e above.*

g) *The predicted LOCA overspeed should be less than the lowest of the critical speeds calculated in regulatory positions C.2.c, d, and e above.*

2.0 FLYWHEEL DIMENSIONS AND MATERIAL PROPERTIES

Flywheel dimensions are shown in Table 2-1 and Figure 2-1.
These flywheels consist of two large steel discs that have three vertical keyways, which are positioned at 120 degrees interval, and are shrunk fit directly to motor shaft.
Upper Flywheel disk radius is 37.5 in., bore radius is 5.06 in., and keyway radial length is 0.906 in. The shrink fit between flywheel and shaft ranges from 7.87×10^{-4} in. to 1.57×10^{-3} in..
Average shrink fit is therefore 1.18×10^{-3} in.
US-APWR RCP motor flywheels are made of SA533 Grade B Class 1 steel.
Flywheel material properties which are used in the calculation are shown as follows.

Poisson's ratio : 0.3
Material density : 0.283 lb/in.^{3}
Young's modulus : 30×10^6 psi

Table 2-1 Flywheel Dimensions

Outside Radius (inch)	Bore Radius (inch)	Keyway Radial Length (inch)	Comments
37.5	5.06	0.906	Upper Flywheel

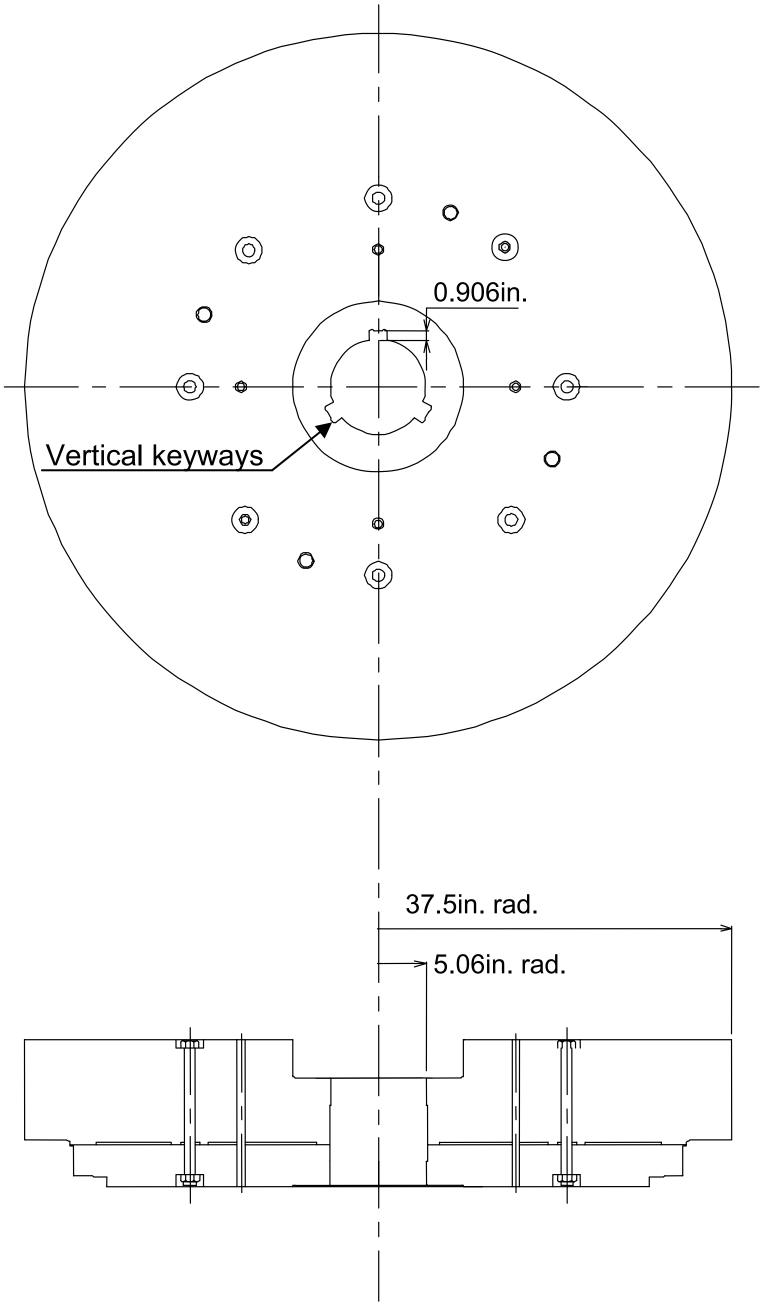

Figure 2-1 RCP Motor Flywheel

3.0 DUCTILE FAILURE ANALYSIS

This section describes the results of the ductile failure analysis.
The faulted condition stress limits for elastic analysis (P_m and $P_m + P_b$) are taken as 0.7 S_u and 1.05 S_u, where S_u is the minimum specified ultimate tensile stress of the material. As compared with P_m to $P_m + P_b$, 80 ksi is used for S_u which is the minimum specified value for SA533 Grade B, Class 1 steel in accordance with ASME Section II part D (Reference 2, 3). Stresses in the flywheel, neglecting local stress concentrations such as holes and keyways, can be calculated by the following equations (References 4):

$$\sigma_r = \frac{(3+v)}{8}\frac{\rho\omega^2}{386.4}\left(b^2 + a^2 - \frac{a^2b^2}{r^2} - r^2\right) \tag{1}$$

$$\sigma_\theta = \frac{(3+v)}{8}\frac{\rho\omega^2}{386.4}\left[b^2 + a^2 + \frac{a^2b^2}{r^2} - \left(\frac{1+3v}{3+v}\right)r^2\right] \tag{2}$$

where:
σ_r ; radial stress, psi
σ_θ ; circumferential, or hoop stress, psi
ν ; Poisson's ratio,
ρ ; flywheel material density, lb/in.^{3}
ω ; flywheel angular speed, rps
b ; flywheel outer radius, in.
a ; flywheel bore radius, in.
r ; flywheel radial location of interest, in.

Assuming that the stress in the thickness direction (σ_x) is negligible, and that the radial stress (σ_θ) always falls between σ_x and σ_θ, the maximum stress intensity at any point in the flywheel is equal to the circumferential stress, σ_θ.
Note that the circumferential stress peaks at the flywheel bore and keyway locations, and decreases approximately linearly thereafter in the radial direction. In order to apply the faulted stress limits to a nonlinear stress distribution, the actual stress distribution must be resolved into its membrane and bending components:

$$P_m = \frac{1}{(b-a)}\int_a^b \sigma_\theta \, dr \tag{3}$$

$$P_b = \frac{6}{(b-a)^2}\int_a^b \sigma_\theta \,(r_m - r)\, dr \tag{4}$$

where r_m is the flywheel mean radius defined as (a + b)/2.
Substituting the circumferential stress term from Equation (1) and (2), shown above and carrying out the integrations in Equation (3) and (4) yields:

$$P_m = \left(\frac{3+\nu}{8}\right)\frac{\rho\omega^2}{386.4\,(b-a)}(b^3-a^3)\left[1-\frac{1}{3}\left(\frac{1+3\nu}{3+\nu}\right)\right] \tag{5}$$

$$P_b = \left(\frac{3+\nu}{8}\right)\frac{6\rho\omega^2}{386.4\,(b-a)^2}\left[\frac{b^4}{12}\left(\frac{1+3\nu}{3+\nu}\right)+\frac{b^3a}{2}[1-\frac{1}{3}\left(\frac{1+3\nu}{3+\nu}\right)]\right.$$

$$\left. -a^2b^2\ln(\frac{b}{a})-\frac{ba^3}{2}[1+\frac{1}{3}(\frac{1+3\nu}{3+\nu})]-\frac{a^4}{12}(\frac{1+3\nu}{3+\nu})\right] \tag{6}$$

It is assumed that there is no cracking and local stress effects from holes and keyways is ignored. Limiting speeds were also calculated considering the reduced cross sectional area resulting from the keyway, and that cracks may exist, emanating radially from the maximum radial location of the keyway, through the full thickness of the flywheel (Reference 4). The results of these calculations are provided in the following table.

Table 3-1 Ductile Failure Limiting Speed

Assuming No Cracks		Crack Length (as measured from the maximum radial location of the Keyway)	
Neglecting Keyway Radial Length	Considering Keyway Radial Length	0.25 inches Crack	0.50 inches Crack
3524 rpm	3500 rpm	3493 rpm	3486 rpm

With respect to RG 1.14, Revision 1, Section C, item 2f, normal speed should be less than one-half of the lowest critical speed as calculated for ductile failure, nonductile failure, and excessive deformation. In accordance with the table above, normal speed must be less than 1762 rpm, because of the minimum calculated limiting speed of 3524 rpm (assuming no cracks). Therefore, since the normal operating speed for the RCP motor is 1200 rpm, item 2f of RG 1.14 is satisfied for ductile failure without cracking. Assuming a rather large crack of 0.50 inches in depth, item 2f is still satisfied for ductile failure because one-half of the lowest calculated critical speed (3486 rpm) is 1743 rpm, which is higher than the normal operating flywheel speed of 1200 rpm.

Per item 2g of Section C of RG 1.14, the predicted loss of coolant accident (LOCA) overspeed should be less than the lowest of the critical speeds calculated for ductile failure, non-ductile failure, and excessive deformation, since the predicted LOCA overspeed is in all cases less than 1500 rpm (125% of normal speed) because leak before break (LBB) is applied. And the minimum calculated limiting velocity for ductile failure is 3500 rpm, item 2g of RG 1.14 is satisfied for ductile failure, assuming there is no crack. Assuming that a rather large crack of 0.50 inches in length is present, item 2g is still satisfied for ductile failure, since the lowest calculated critical speed (3486 rpm) is higher than 1500 rpm.

Therefore, RG1.14 acceptance criteria for ductile failure of the flywheels are satisfied.

4.0 NONDUCTILE FAILURE ANALYSIS

A solution for the stress intensity factor for a radial, fulldepth such as through the full thickness of the flywheel plate, crack emanating from the bore of a rotating disk is given by the following equation (Reference 4):

$$K_J = \frac{\rho\omega^2}{386.4} b^{5/2} \Phi \left[\frac{\pi\left(\frac{c}{b} - \frac{a}{b}\right)}{(1 - v^2)} \right]^{1/2} \tag{7}$$

where:

$$\Phi = \frac{(3+\nu)}{32} \left[3\left(1 + \frac{a^2}{b^2}\right) + 3\left(\frac{a}{b}\right)\left(\frac{b}{c}\right) + \left(1 + \frac{a}{b} + \frac{a^2}{b^2}\right) \frac{\left(1 - \frac{a}{b}\right)}{\left(1 - \frac{c}{b}\right)} \right]$$

$$- \left(\frac{1+3\nu}{32}\right) \left[\frac{\left(\frac{c}{b}\right)^3 - \left(\frac{a}{b}\right)^3}{\left(\frac{c}{b} - \frac{a}{b}\right)} + \frac{1}{3} \frac{\left(1 - \frac{a}{b}\right)^3}{\left(1 - \frac{c}{b}\right)} \right] \tag{8}$$

where:
ρ ; flywheel material density, lb/in.^{3}
ω ; flywheel angular speed, rps
b ; flywheel outer radius, in.
a ; flywheel inner radius, in.
c ; radial location of crack tip, in.
ν ; Poisson's ratio

For ferritic steels, on the other hand, ,fracture toughness can be calculated by the following equation from the ASME Section XI (Reference 5):

$$K_{IC} = 33.2 + 20.734 \exp\left[0.02(T - RT_{NDT})\right] \tag{9}$$

Therefore, minimum fracture toughness of reference nil ductility temperature (RT_{NDT}) value of 10°F, at the lowest operating temperature of 70°F is 102.0 ksi sqrt in. This ambient temperature is a much lower temperature than can be excepted in the containment during normal operating conditions.

The results of these calculations are provided in the following table.

Table 4-1 Nonductile Failure Limiting Speed

Crack Length (as measured from the maximum radial location of the Keyway)	
0.25 inches Crack	0.50 inches Crack
2596 rpm	2489 rpm

Assuming a large crack of 0.50 inches in depth, item 2f is still satisfied for ductile failure because one-half of the lowest calculated critical speed (2489 rpm) is 1244 rpm, which is higher than the normal operating flywheel speed of 1200 rpm.

Therefore, assuming that a rather large crack of 0.50 inches in length is present, item 2g is still satisfied for ductile failure, since the lowest calculated critical speed (2489 rpm) is higher than 1500 rpm.

Therefore, RG1.14 acceptance criteria for ductile failure of the flywheels are satisfied.

Note that the flaw length of 0.50 inches can be found by inspection, and that the ambient temperature has the margin for the expected operating conditions.

5.0 FATIGUE CRACK GROWTH

In order to estimate the magnitude of fatigue crack growth during plant life, an initial radial crack length of 0.5 inches through the flywheel is assumed (from the maximum keyway radial location to the flywheel outer radius). Fatigue crack growth rate is characterized in terms of range of applied stress intensity factor, and is shown as the following equation (Reference 5)

$$\frac{da}{dN} = C_0 \, (\Delta K_I)^n \qquad (10)$$

where: da/dN ; crack growth rate, in./cycle
n ; slope of the log (da/dN) versus log (ΔK_I)
C_0 ; scaling constant

Fatigue crack growth behavior is affected by the R ratio (K_{min}/K_{max}, where $0 \leq R < 1.0$) and the environment. Fatigue crack growth behavior of carbon and low alloy ferritic steels exposed to an air environment is provided by the above equation with n = 3.07 and $C_0 = 1.99 \times 10^{-10}$ S.

$$S = 25.72 \, (2.88 - R)^{-3.07} \qquad (11)$$

where: S ; scaling parameter

In this case, the maximum stress intensity range occurs between RCP shutdown (zero rpm) and the normal operating speed of approximately 1200 rpm. Therefore, the R ratio is zero, and S = 1.0. The fatigue crack growth rate for the flywheels is calculated by:

$$\frac{da}{dN} = 1.99 \times 10^{-10} \, (\Delta K_I)^{3.07} \qquad (12)$$

It is assumed that 3000 cycles of RCP starts and stops for a 60 years design life in US-APWR, the estimated radial crack growth is as shown below in accordance with the above equation. Crack growth is negligible over a 60 years design life of the flywheel, even when assuming a large initial crack length.

Table 5-1 Fatigue Crack Growth Assuming 3000 Cycles of RCP Starts and Stops

Assumed Initial Crack Length (inch)	K_I (ksi Sqrt inch)	Crack Growth After 3000 Cycles (inch)
0.5	37	0.039

6.0 EXCESSIVE DEFORMATION ANALYSIS

The extension in the bore radius (a) and the outer radius (b) of the flywheel by centrifugal force at the overspeed condition is estimated by the following equations (Reference 6, 7)

$$\Delta a = \frac{1}{4}\frac{\rho\omega^2}{386.4}\frac{a}{E}\left[(3+\nu)b^2+(1-\nu)a^2\right] \qquad (13)$$

$$\Delta b = \frac{1}{4}\frac{\rho\omega^2}{386.4}\frac{b}{E}\left[(1-\nu)b^2+(3+\nu)a^2\right] \qquad (14)$$

where:
a ; bore radius, in.
b ; outer radius, in.
ρ ; flywheel material density, lb/in.^{3}
ω ; flywheel angular speed, rps
E ; Young's modulus, psi
ν ; Poisson's ratio

At the flywheel overspeed condition of 1500 rpm (157.08 rps), the extension in the bore radius and the outer radius is calculated as shown below:

Table 6-1 Flywheel Deformation at 1500 rpm

Change in Bore Radius (inch)	Change in Outer Radius (inch)
0.004	0.007

As shown in the table above, a maximum flywheel deformation of only 0.007 inches is anticipated for the flywheel overspeed condition. This increase will not be an important issue, such as excessive vibrational stress leading to crack propagation, since deformations as calculated are negligible.

Note that flywheels are designed to lose their shrink fit at operating speed. However, the three keyways, which are positioned at 120 degrees interval, maintain the centering of the flywheels, and therefore maintain balance of the flywheel .

One concern is for excessive deformation in the RG 1.14. Excessive deformation is defined as "any deformation such as an enlargement of the bore that could cause separation directly or could cause an imbalance of the flywheel leading to structural failure or separation of the flywheel from the shaft." Therefore, concern about excessive deformation is not related to the loss of shrink fit, but instead relates to the amount of deformation which could cause imbalance or failure.

Excessive deformation, which described on RG 1.14 and cause imbalance or failure, are greater than or equal to the limiting flywheel speed for ductile failure. Therefore, by the result of section 3.0, there is no problem with excessive deformation.

7.0 CONCLUSION

Evaluation of the flywheel design is performed to confirm that requirements of RG 1.14 are satisfied. The results are shown as follows:

(1) It is confirmed that the normal speed was less than one-half of the lowest critical speed as calculated for ductile failure, and that the predicted LOCA speed should be less than the lowest critical speed.

(2) It is confirmed that the normal speed was less than one-half of the lowest critical speed as calculated for nonductile failure, and that the predicted LOCA overspeed should be less than the lowest critical speed.

(3) It is confirmed that flaw growth during plant operation was negligible.

(4) It is confirmed that there is no problem about excessive deformation as same as the result of ductile failure analysis.

Therefore, RG 1.14 acceptance criteria for design of the flywheel are satisfied.

8.0 REFERENCE

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