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A STUDY ON THE APR1400 REACTOR PLATE-TYPE SUPPORT SYSTEM

Anh Tung Nguyen[1], Ihn Namgung[2]

[1] Graduate Student, Dept. of NPP, KEPCO International Nuclear Graduate School, Korea
[2] Professor, Dept. of NPP, KEPCO International Nuclear Graduate School, Korea

ABSTRACT

APR1400 Reactor Vessel is supported by column type support system that occupies the reactor cavity between reactor vessel and surrounding concrete wall. Due to the occupation of cavity space by the support column, it can hamper ex-vessel cooling capability in case of severe accident event. The column can acts as an elastic member that might amplify seismic motion that can adversely affect to the core. Another concern is about reactor closure head drop impact load may exceed load bearing capabilities of the support column.

Due to these reasons, other type of support system, a plate-type support, was proposed and evaluated of the adequacy of meeting the structural stiffness by Finite Element Analysis (FEA) approach. ASME Boiler and Pressure Vessel Code was used to verify the design. The modal analysis showed that the modal frequencies of plate-type support is higher than that of column-type support indicating higher rigidity of plate-type support. The FEM analysis results, which cover for design static load conditions, a thermal, pressure and mechanical loads, showed that stresses are within allowable limits in accordance with the design code. From the outcome of this research, the plate-type support can be an alternative to current column-type support design.

INTRODUCTION

The APR1400 is an advanced pressurized water reactor with design features inherited from OPR1000 including column-type support design. There are four vertical support columns at the cold leg of APR1400, see Fig. 1. The first twin unit APR1400, Shin-Kori 3 & 4, had already been built and in commercial operation. However, there is opportunity for an improvement of the design, since the column supports may increase dynamic load to the reactor core during seismic activity. The tall columns transfer amplified movement to the reactor, resulting in higher instability to the reactor core. The columns can be a hindrance to the external reactor vessel cooling (ERVC) during severe accident mitigation, since it occupies a large space of cavity and inhibit evaporated steam flow. In another scenario, such as reactor closure head drop case, the impact load may exceed acceptable limit of a column load bearing capacity. A plate-type support proposed in this paper is to improve support rigidity and stability.

Other commercial reactors of pressurized water reactors have different support configuration. AP1000 reactor by Westinghouse has supports on cold leg and the length is very short so it is not a column design (Westinghouse 2011). It incorporates unique design features in that ERVC strategy is incorporated in the design. The outside annulus of reactor vessel is stream lined to give better cooling ability, while core catcher concept was not incorporated in the design.

EPR (European Pressurized water Reactor) by Areva has ring type support system that support reactor at the main pipe nozzles as shown in Figure 3. The design allows radial expansion so that the reactor thermal expansion can be accommodated. The EPR design incorporated core catcher design for severe accident mitigation measures.

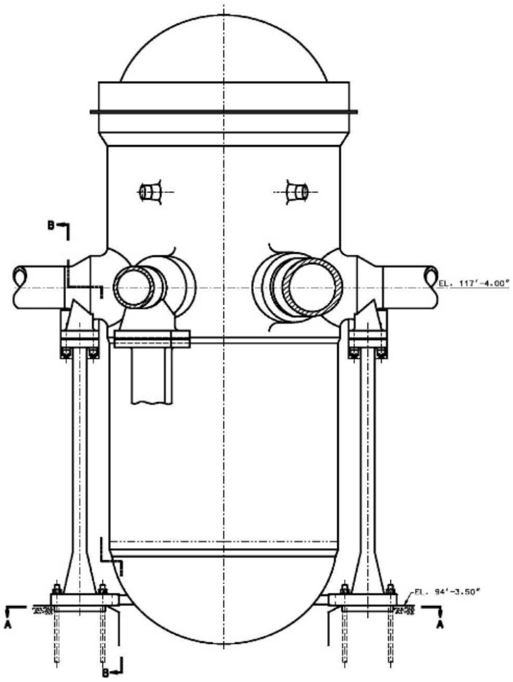


Figure 1. APR1400 Reactor column support system (KHNP, 2014)

The VVER-1000 by Rosatom has separate support system for vertical and horizontal direction. The vertical support is near the core region of the reactor vessel shell just above the core region as shown in Figure 4. The horizontal support is at the reactor vessel ledge by an 'S' shaped bellows.

In this paper, a plate-type support, or edge support, is investigated as an alternative option for the current column-type support system. A plate-typed support concept is simplest in shape to manufacture and installation. The focus is to investigate the validity and to check basic requirement to meet ASME core limits in order to propose a possible alternative for the reactor support system. The proposed design change is analyzed using ANSYS V17.0. The work covers steady-state thermal analysis and static structural analysis for the design condition. From the analysis result, primary membrane and bending stress intensity (Pm and Pb) are evaluated to verify with allowable design limits. In addition, modal analysis of both the column support system and plate support system were compared to assess the rigidity and stability of support system.

MODAL ANALYSIS OF COLUMN-TYPE SUPPORT SYSTEM

Dynamic behaviour of support system is one of important characteristics in determining the design parameters. Understanding the dynamic behaviour of column support system of APR1400 reactor is done by modal analysis. Since a full seismic analysis requires modelling of all connected systems having significant mass and stiffness, a modal analysis of reactor with support system is a simple indicator how system behaves before doing a seismic analysis. A proper seismic analysis would requires to includes steam generators, RC pumps and RCS main pipes since they are connected rigidly and have large masses. A 3D modelling of such system is not considered in this investigatory study of plate-type support system. Fig. 2 shows the model of the column support system used for modal analysis, in the model the mass for core and internals as well as closure head were represented as mass points and connected to the support ledge of reactor vessel.

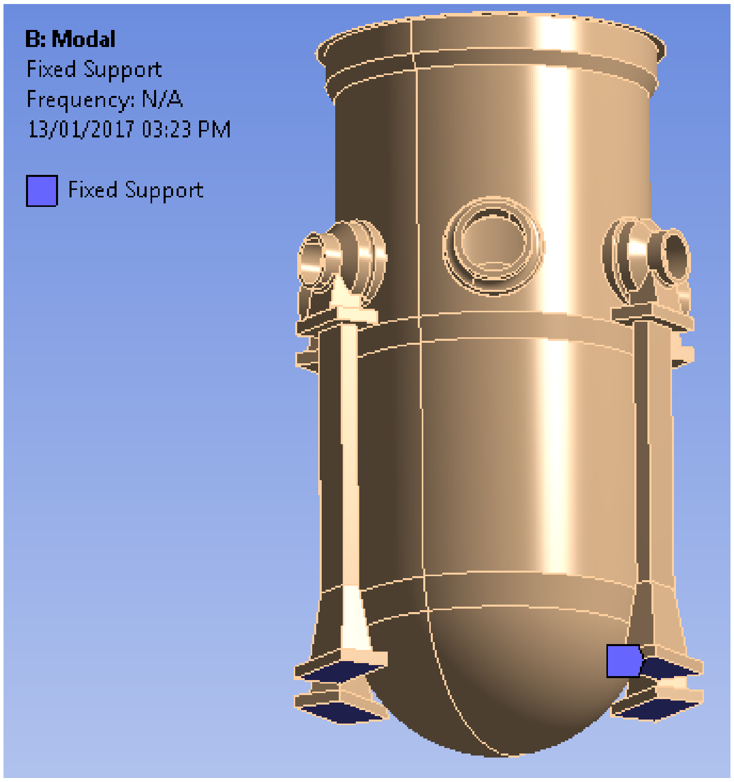


Figure 2. Modal analysis model for column support system

Table 1 presents the results of natural frequencies of the column support model and Fig. 3 shows the mode shapes of corresponding frequencies. From the Fig. 3, the natural vibration is governed mostly by column vibration and the modal frequencies are spread from low frequencies. This is due to the large mass of reactor vessel and high stiffness compared to columns. Therefore, reactor vessel acts as if a lump of mass and support columns acts as beams. The deformation is pronounced for higher frequencies reflecting beam bending is the dominant factor in increasing the deformation as modal frequencies increases. A comprehensive seismic response requires all connected systems modelled together to address the impact of high frequency response properly.

Table 1: Modal analysis result of column-type support system with first 10 modal frequencies

Mode	Natural Frequency (Hz)	Maximum deformation location	Maximum deform. (mm)	Column behaviour
1	3.5966	Reactor vessel	0.051	Bending and Twisting
2	4.9944	Reactor vessel	0.054	Bending and Twisting
3	7.1247	Reactor nozzles	0.071	Twisting
4	15.692	Reactor bottom	0.099	Bending and Twisting
5	27.01	Reactor bottom	0.099	Bending and Twisting
6	33.271	Reactor vessel	0.077	Bending
7	34.477	Reactor vessel	0.090	Bending and Twisting
8	37.575	Column mid span	0.067	Mid span buckling
9	51.483	Column mid span	0.270	Mid span buckling
10	51.982	Column mid span	0.260	Mid span buckling

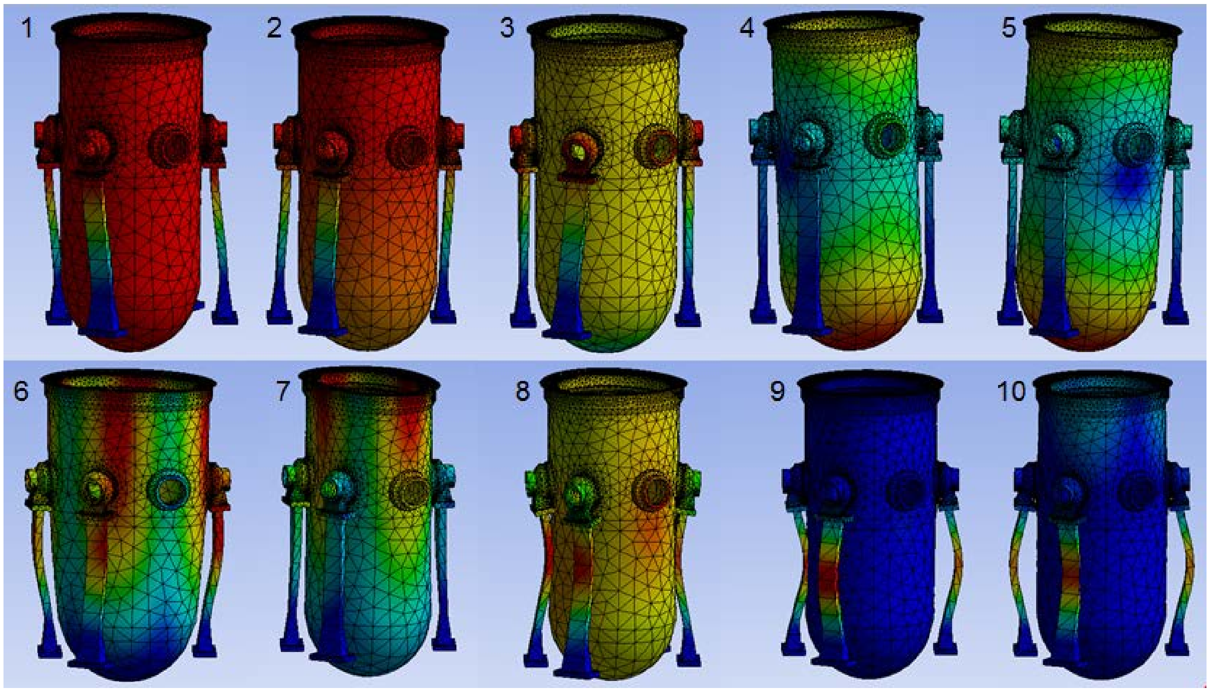
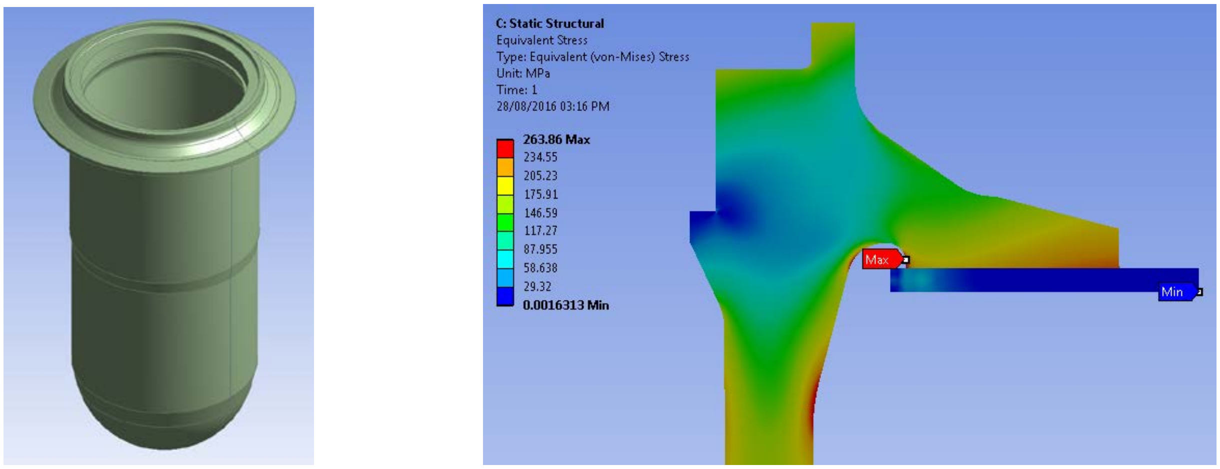


Figure 3. Mode shapes of the column support system for the first 10 natural frequencies

PLATE-TYPE SUPPORT CONCEPT FOR APR1400 REACTOR

The purpose of a columnless support is to allow uninhibited cooling of reactor vessel in case of severe accident and increasing the rigidity of support system in case of dynamic event such as seismic activity. In order to increase ex-vessel cooling water contact area with RV outer surface and coolant volume, the support position was chosen at the location of reactor vessel ledge. It is important that the support must allow thermal expansion of the vessel during heat-up and cooldown. From these requirements, a number of concepts were developed. Each concept possesses a set of unique parameters which defines the cross section geometry. By using parameter set function in ANSYS, the iterative process of design optimization was automated. A table of different design parameters produces different stress results, and allows finding optimum design parameter for the specified design. For a table of design parameters, the resulting equivalent stresses are evaluated following re-meshing and recalculating the stresses at specified locations. The optimum value of design parameter for each different design can be observed and found by this process. Upon find near optimum design parameters, a fine tuning of design parameter is done to find near optimum value of design parameters.

In the proposed design, support location is changed from cold-leg to reactor vessel flange to have larger cavity volume. This change may requires the relocation of steam generator support location and RC pump support location as well if this design change would be incorporated. The reactor vessel ledge is modified to have higher strength by thick flange to transfer load to the concrete structure. Fig. 4 presents proposed plate-type support where Fig.3-a shows 3D image of support and reactor vessel and Fig.3-b shows stress analysis results of axisymmetry model. In Fig. 3-b, stress contours for design loading condition is given. The plate-type support proposed in this study is designed in such a way that a thermal expansion is allowed in radial direction by sliding and horizontal movement is prohibited much like current horizontal support of RV at the bottom head. With proposed plate-type support system, a horizontal support is still required at the bottom head. With this arrangement, RV thermal expansion is allowed in radial and vertical direction; however, horizontal translation is limited.



a) 3D view of RV plate-type support b) axisymmetry modelling of plate-type support system

Figure 4. Plate-type support concept

ASME CODE ANALYSIS OF THE PLATE-TYPE SUPPORT

The design limits are defined in ASME Section III Article NF-3000 Design. The support is categorized as plate-type support and shall follow the “Design rules for plate- and shell-type supports” as stated in Article NF-3200. Since this is the reactor vessel support, the support class is defined as Class 1 and shall conform to Article NF-3220 “Design by analysis for Class 1”. In accordance with Article NF-3220, the stress intensity limits that must be satisfied for design loadings are:

a. *General primary membrane stress intensity* Pm

b. *Primary membrane plus primary bending stress intensity* Pm + Pb

The allowable value for requirement a. is Sm at design temperature and b. is 1.5Sm where Sm is material stress intensity. The material of the support is selected to be the same material with the reactor vessel, which is SA-508 Grade 3 Class 1. From ASME Section II Part D, the Sm value is found to be 184 MPa and Table 2 lists the allowable stress intensities.

Table 2: Allowable stress intensity limits of SA508 Grade 3 Class 1

Stress category	Allowable stress intensity (MPa)
P_m	184
$P_m + P_b$	276

The support base shall be anchored onto concrete structure in accordance with Regulatory Guide 1.199 of U.S.NRC. The attachment of support plate to the concrete structure is bonded in the analysis and assumes there is no displacement of support plate relative to the concrete wall attachment. The base plate is positioned under the reactor flange support face.

Since thermal and structural analyses of the supports in this research are performed by 2D axisymmetric method, a 3D model of the concept is demonstrated in Fig.5 to give an easy visualization. In this visualization, lateral restraints are not shown for simplification and it should be similar in concept to the lateral restraint of support column.

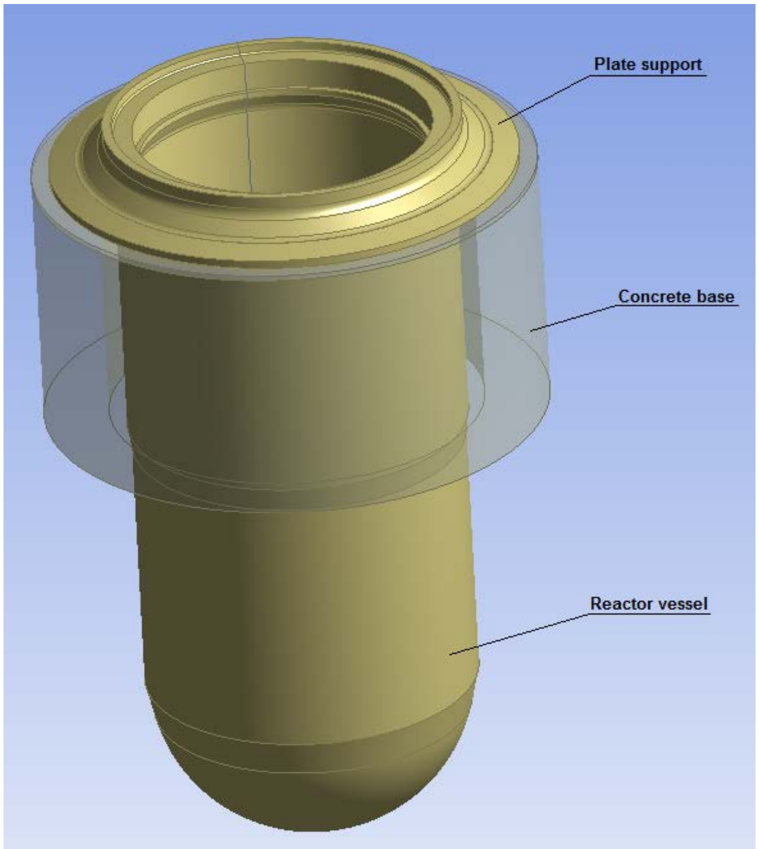


Figure 5. 3D model of the plate-type support

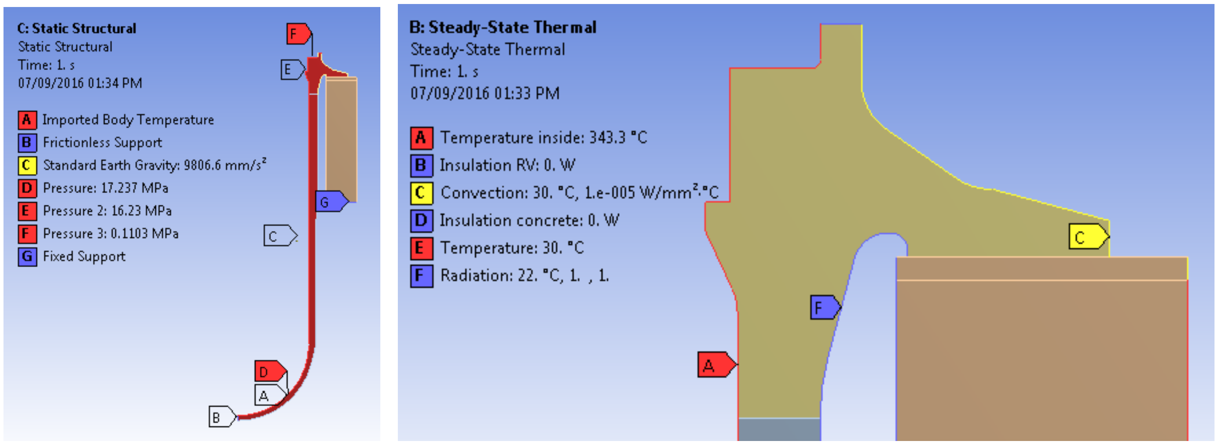
The plate support is desired to be placed on low friction surface to allow thermal expansion. The contact element between support plate and reactor support flange makes the problem nonlinear in contact geometry and the thermal expansion exceed the elastic range which makes it large deflection problem.

The design loads shown in Table 3 are used for external loads of static structural analysis and thermal analysis. Fig. 6-a shows static structural analysis BC in which the weight of internals including core weight are applied to the reactor vessel upper flange. Design pressure was applied to inner surface of reactor vessel and gravity was added and the closure head and integrated head area weight were applied to the reactor vessel flange contact area. Fig. 7-b shows thermal analysis BC in which reactor vessel inner surface temperature

Two cases of analysis were done in which one is frictionless between support plate and reactor vessel flange, and the other is frictional. This is to observe the effect of friction. In both cases, the support plate is bonded to the concrete shielding wall to represent anchoring of support plate to the concrete wall.

Table 3: Design loads

Load	Value	Unit
Thermal condition		
Design temperature	343.3	C
Convection	0.00001	W/mm^{2}C
Static structural		
Reactor internals weight*	16.23	MPa
Closure head weight*	0.1103	MPa
Design pressure	17.237	MPa



a) BC of static structural analysis b) BC of steady state thermal analysis

Figure 6. Boundary conditions of static structural and steady state thermal analysis

In order to assess stresses according to ASME code criteria, stresses are separated into membrane stresses and bending stresses. This separation was done along a linearized stress paths as shown in Fig.8. Fig. 7 shows linearized stress paths that caused dominant stress concentration and produces highest linearized stresses. The resulting primary membrane and primary bending stress intensities are summarized in Tables 4, 5 and 6 for frictionless, frictional with f=0.3 for dry friction cases and fixed case for simulating bolted condition, respectively. A bonded case, where the reactor upper flange and the support are fixed together, is also analysed to get how much stress concentration occurs in the geometric discontinuities in the reactor upper flange region.

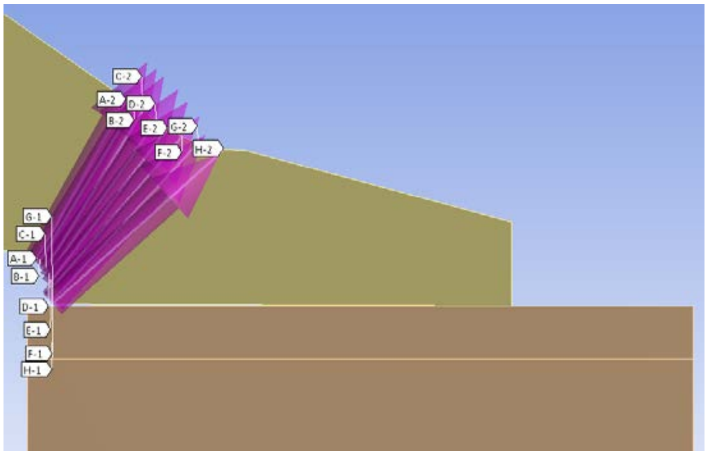


Figure 7. Linearized stress paths for primary membrane and bending stress intensity evaluation

Table 4: Stress intensities for frictionless case

Stress path	P_m (MPa)	$P_m + P_b$ (MPa)	SA-508 S_m (MPa)	SA-508 1.5S_m (MPa)
1-A	155.8	186.23	184	276
2-B	159.17	190.80	184	276
3-C	164.77	211.85	184	276
4-D	170.06	226.01	184	276
5-E	174.39	238.22	184	276
6-F	178.24	248.23	184	276
7-G	183.37	259.60	184	276
8-H	185.03	257.65	184	276

Table 5: Stress intensities for case with friction coefficient of f=0.3

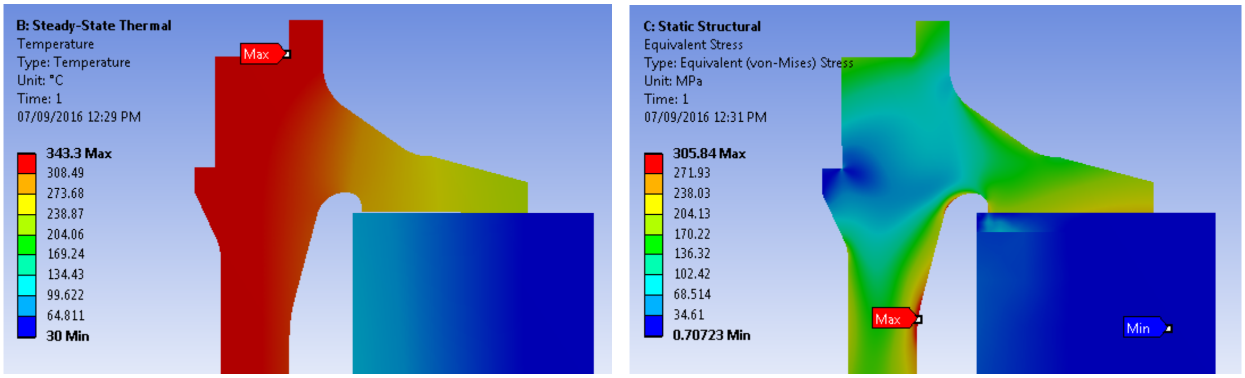
Stress path	P_m (MPa)	$P_m + P_b$ (MPa)	SA-508 S_m (MPa)	SA-508 $1.5S_m$ (MPa)
1-A	106.82	122.10	184	276
2-B	101.39	127.05	184	276
3-C	98.62	128.71	184	276
4-D	90.82	127.50	184	276
5-E	86.20	124.21	184	276
6-F	82.36	138.84	184	276
7-G	79.58	150.27	184	276
8-H	82.27	156.03	184	276

Table 6: Stress intensities for bolted case

Stress path	P_m (MPa)	$P_m + P_b$ (MPa)	SA-508 S_m (MPa)	SA-508 $1.5S_m$ (MPa)
1-A	125.62	466.34	184	276
2-B	131.87	467.27	184	276
3-C	138.06	450.54	184	276
4-D	146.66	431.38	184	276
5-E	151.95	398.92	184	276
6-F	156.63	347.87	184	276
7-G	154.01	257.09	184	276
8-H	176.45	266.06	184	276

The results show that the stress intensities for frictionless and frictional case are well within allowable limit both for primary membrane stress limit and primary membrane plus bending stress limits, Table 4 and 5, while the primary membrane plus bending stress for bolted case exceeds allowable stress limit, Table 6. It is interesting to note that the stress intensities of frictional case are lower than that of frictionless case. This is because the thermal stress works against the direction of mechanical load of weight. The heavy weigh produces large bending stress on the reactor flange area and the thermal expansion produces stresses bending in opposite direction. A typical case of stress is shown in Fig. 8-a for temperature distribution and Fig. 8-b for equivalent stress intensity of frictionless case.

From the temperature distribution of thermal analysis, the temperature at the contact surface of concrete structure is less than 150°C. Since analysis took a conservative approach by taking into account the direct radiation from the RV inside, if there is insulation in the cavity, the temperature can be lowered.



a) Temperature distribution for design condition
b) Stress distribution for design condition

Figure 8. Analysis result for frictionless case

MODAL ANALYSIS OF REACTOR WITH PLATE-TYPE SUPPORT SYSTEM

Modal analysis was conducted for the plate-type support case to find the natural frequencies. Fig 4-a shows the model of the plate-type support used for modal analysis. Fixed support condition is applied at the bottom surface of the support for the modal analysis that requires system to be linear. Table 7 presents the results of the natural frequencies found for the model. Fig. 9 shows the mode shape of reactor with plate-type support system.

Table 7: Modal analysis result of plate-type support system

Mode	Frequency (Hz)	Maximum deformation location	Maximum deformation (mm)	Support behavior
1	56.578	Reactor vessel	0.108	Radial deformation
2	56.579	Reactor vessel	0.108	Radial deformation
3	65.752	Reactor vessel	0.078	Side-to-side bending
4	65.958	Reactor vessel	0.079	Side-to-side bending
5	82.701	Reactor vessel	0.089	Twisting
6	85.841	Reactor vessel	0.123	Stable
7	85.853	Reactor vessel	0.124	Stable
8	101.02	Reactor vessel	0.083	Vertical deformation
9	124.57	Reactor vessel	0.107	Radial deformation
10	124.57	Reactor vessel	0.107	Radial deformation

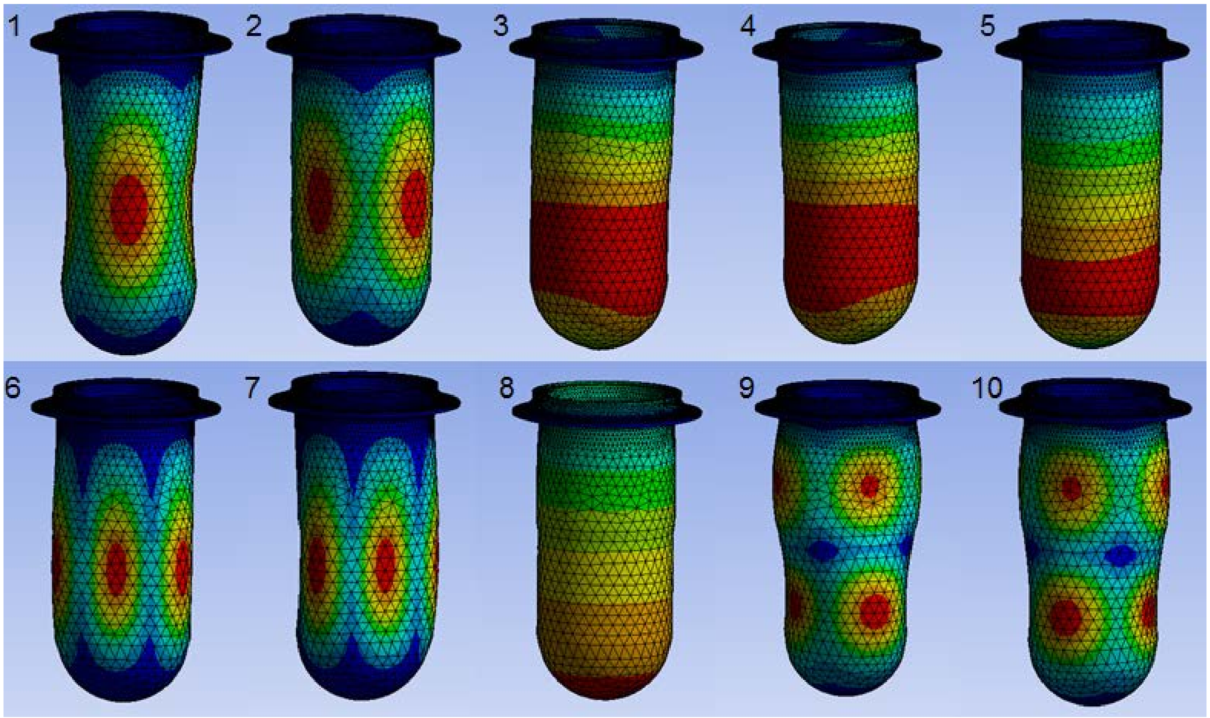


Figure 9. Mode shape of plate-type support system for the first 10 modal frequencies

RESULTS AND DISCUSSIONS

The analysis result shows that stress condition in frictionless and frictional contact between the support plate and the reactor upper flange are within allowable stress limit and satisfy design load condition. The maximum equivalent stress is located at the corner between the flange and the Reactor

Vessel main shell, which is also the location where failure would most likely to occur. Linearized stress intensity was investigated across the connection region between the support and the body to show that the stress value stay within the allowable limit. Allowable limits were identified in accordance with ASME codes.

The frictional case produces a more realistic model and may represent more accurate result. The stress difference between frictional and frictionless cases can be explained by the frictional force on the bottom surface of the reactor upper flange acts as a reaction force that reduces the resultant bending stresses. The reactor upper flange deforms under the heavy weight load of the reactor vessel causes flange to deform at some degree and produces higher bending stress within the support.

The stress level in fixed support case is significant. The fixed support prevents thermal expansion movement therefore an extreme stress was observed. This indicates that the fixed support will not satisfy the design requirement and is not suitable in this case.

Comparing the modal analysis between the column support system and the plate-type support, it is observed that the natural frequencies of plate support system is much higher, see Table 1 and 7. This indicates much higher rigidity of plate-type support system, and will results in different seismic input spectra at the RV support location. Since rigid system tends to store less seismic energy, it can be predicted that the plate-type support may reduce seismic load to the reactor internals and core.

CONCLUSIONS

A plate-type support was investigated for the adequacy of reactor support. Thermal and static structural analysis was conducted for three cases including frictionless, frictional and fixed support for the design loading condition. The analysis result was evaluated according to the ASME code limits to verify the validity of the design. Analysis showed that dry friction case exhibit lowest stress intensity value.

Modal analysis of the column support system and the proposed plate-type support system were conducted to compare the behaviors of dynamic response. The results show that the plate-type support is considerably more stable than the column support and exhibit much higher rigidity.

Overall, the paper has verified a highly potential replacement for the current column support system with very simple shape of support design of plate-type support.

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