Journal of KOSSE. (2017. 6) Vol. 13, No. 1 pp. 15-23
DOI: https://doi.org/10.14248/JKOSSE.2016.13.1.015
www.kosse.or.kr

ISSN (print) : 1738-480X
ISSN (online) : 2288-3592

Design Verification of APR1400 Reactor Vessel Through Re-engineering Approach

Mutegi Peter Mutembei, Ihn Namgung*
KINGS (KEPCO INTERNAL NUCLEAR GRADUATE SCHOOL

Abstract : This paper describes verification of APR1400 reactor vessel by applying the system engineering approach, in which the design re−engineering method is used to check the design parameters of APR1400 RV (reactor vessel). The RV is classified as safety class 1 and therefore must adhere strictly to the rules of ASME BPVC section III, subsection NB and seismic category I. This study explores designing the RV by following the ASME guidelines and making a comparative study with the current design. To meet this objective we apply system engineering methodologies to structure the process and allow for verification and validation of the major RV design parameters such as thickness of RV. The structural thicknesses of various part of RV are determined as well as reinforcements on the RV major nozzles. A 3D virtual reality model was created based on the design parameters using CATIA V5 and animation using Dassault Composer V2016. A comparison of re−engineered ARP1400 RV and standard APR1400 RV was done to show which design parameters were taken more conservative approach.

Key Words : Re−engineering, APR1400, Reactor Vessel, Nuclear Component

---

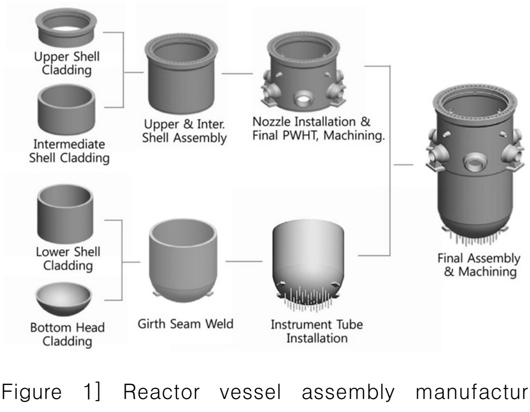
Received: November, 2016 / **Revised**: June 21, 2017 / **Accepted**: June 26, 2017

* Corresponding Author : Ihn Namgung, inamgung@kings.ac.kr

1. Introduction

The RV is classified as safety class 1 and therefore must adhere strictly to the rules of ASME BPVC section III, subsection NB. Figure 1 shows the RV and its subparts. The RV forms the primary pressure boundary of Nuclear Steam Supply System, supports reactor internals and core and provides coolant flow path. There are 4 inlet nozzles and 2 outlet nozzles for coolant flow, and 4 direct injection nozzles and 61 ICI nozzles (bottom mount nozzles). The RV is supported vertically by 4 columns attached to cold-leg and horizontally by 4 shear lugs at the bottom of outside bottom head. The 4 shear lugs and base plate of support columns allows expansion of RV due to temperature rise while restraining horizontal movement during seismic events.

Figure 1 shows manufacturing process of reactor vessel. All of the sub-parts of the reactor vessel are made of forgings from ring for shell part and plate for head part. These forged parts are then cladded and welded together to form reactor vessel. The core region is made out of one shell section to prevent adverse effect on the reactor vessel from welding process. Note also current RV manufacturing has been improved so that all weldings in RV are in circumferential weld and there are no longitudinal welds. The change of fabrication practice is to reduce the chances of stress corrosion cracking in the longitudinal weld.



[Figure 1] Reactor vessel assembly manufacturing process

The basic shape of RV is cylinder and sphere and openings for nozzle. Stresses in cylinder and sphere could be predicted accurately, but stresses rear by openning is not. The numerous nozzles/ openings that provide interface points to other systems and components form geometric discontinuities that create stress concentration. Henc there's a need to ascertain that proper structural compensation is made to ensure safety. The ASME BPVC section III, subsection NB provides guidelines for the design of vessel thickness and nozzles. The re-engineered design carried out in this study followed the ASME procedure. These ASME procedure is minimum guidelines to ensure safety of RV.

2. System Engineering Process

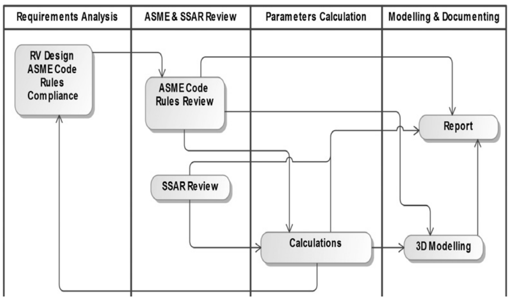
The system engineering approach takes on the design process of the system as a whole rather than focusing on individual components.

2.1 System Engineering Methodology

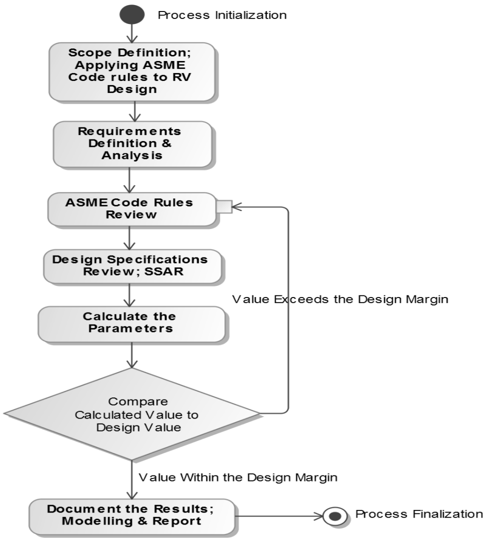
At the highest level, the systems engineering methodology focuses on several major steps including: problem statement, identification of objectives and requirements documentation, concept generation, analysis of alternatives and trade studies, selection of primary concept, system creation, including decomposition, design, development, integration, verification and validation, and system operation and life cycle disposal. The system is then physically reconstructed from its individual components into subsystems and eventually integrated into a complete system. These steps are typically combined together in a manner that decomposes the problem into subsystem and eventually component-level "pieces" that can be handled by individual engineers. Plans are created by the System Engineer to ensure that the subsystems and overall system perform as designed (verification) and ultimately meet the desired intent of the customer (validation) by performing the desired function.

Implementing the system engineering approach assesses the problem in a more efficient manner and makes the application of the desired codes for the RV design easy. When analyzing the RV structural design, and combining the desired codes, the output will be a design that satisfies the ASME code rules. This procedure is shown in Figure 2.

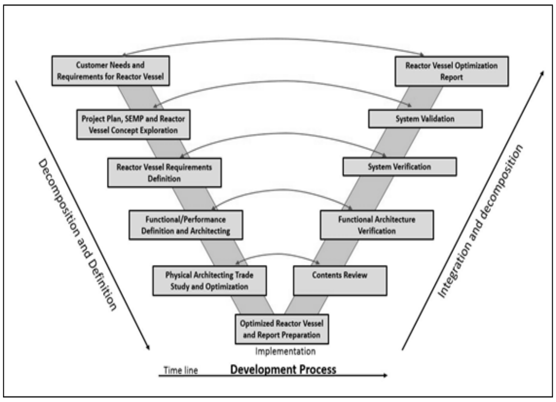
Figure 3 shows a flow chart representing the decision making process for the project. The re-engineering process is represented in the V-model shown in Figure 4 below. It is a systematic approach to understand and project requirements of the client and maps these requirements to process definitions. The V-model also performs reviews on multiple levels tracing all requirements through the entire project life cycle so as to ensure clear and unambiguous requirements.



[Figure 2] Process Activity Relationships



[Figure 3] Flow chart of the project process



[Figure 4] Project process V-model

2.2 Systems Engineering Requirements of ASME Design by Formula

In this study, ASME Section III Subsection NB code requirements are considered as minimum requirements. Any additional requirements by owner or regulatory body will be additional requirements which will increase conservatism in the design of RV.

ASME code requirement are mostly concerned about high pressure of primary system, and it contains two different procedures. One is for the design by stress analysis and the other is the design by formula. Since the procedure for the design by formula need to includes uncertainties, it is more conservative than the design by analysis. While design by analysis is more accurate and allows less conservative design, it requires detailed stress analysis and complete and lengthy documentation of the analysis result.

In this study, design by formula is taken as re-engineering design of RV. In essesce the cylindrical shell thickness of RV and bottom head thickness to determin.

- Cylindrical Shells (NB-3324.1)

$$t = \frac{PR}{S_m - 0.5P} \quad \text{or} \quad t = \frac{PR_o}{S_m + 0.5P}$$

- Spherical Shells (NB-3324.2)

$$t = \frac{PR}{2S_m - P} \quad \text{or} \quad t = \frac{PR_o}{2S_m}$$

where

P = Design Pressure

R = inside radius of shell or head

R_o = outside radius of shell or head

S_m = design stress intensity values (Sec. II, Part D, Subpart 1, Tables 2A and 2B)

t = thickness of shell or head

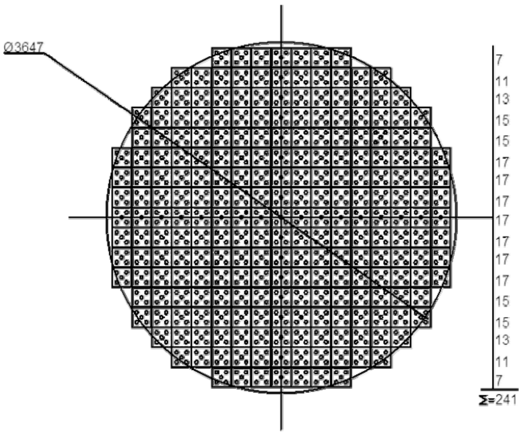
Other requirements are related to nozzle openings. Since opening in vessel weaken the strength, it has to be reinforced. The Opening Reinforcement is defined in NB-3332. This reinforcement are also limited to the vicinity of openings in order to effectively reinforce the openings. The limit of reinforcement is defined in NB-3334. The strength of reinforcing matrerial is defined in NB-3336, and requirements on multiple opennings are defined in NB-3335. Also special vessel requirements are define in NB-33360.

In the design of vessel, these requirements shall be meet as minimum. Any specific owner requirement and regulatory requirements are additional requirements.

3. Sizing Calculation Methodology

3.1 Core and Reactor Internals Design Data

Since the design re-engineering is based on APR1400 reactor design, the core design of APR1400 is used to determine the inner diameter of reactor vessel. Figure 5 shows the APR1400 core arrangement.



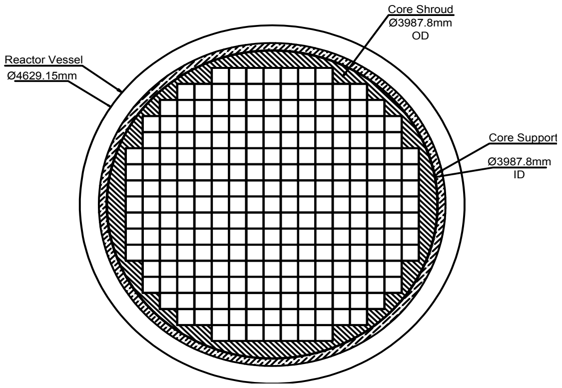
[Figure 5] Core Arrangement of APR1400

With reference to APR 1400 SSAR, we get the parameters of Core Support Barrel and Core Shroud as shown in Table 1 below.

The arrangement of ractor core is shown in Figure 6 with design parameters given in Table 1 is used.

<Table 1> Core Support Barrel and Core Shroud parameters

Components	Parameter
Core Shroud	OD: 3987.8 mm (157 in)
CSB	ID: 3987.8 mm (157 in)
Reactor Vessel	ID: 4629.15 mm (182.25 in)



[Figure 6] Reactor Core Cross Section

3.2 Reactor Vessel Sizing

3.2.1 Operating Parameters and Materials

APR1400 intrinsic material properties and operating conditions are tabulated in Table 2 and 3, and Figure 7.

<Table 2> APR 1400 RCS Design parameters

Parameter	Value
Design thermal power, MWt	4000
Design pressure, kg/cm2A(psia)	175.8 (2500) or 17.237 MPa
Design temperature, oC(oF)	343.3 (650)

<Table 3> Reactor Vessel Materials

Reactor Vessel	Material Specification
• Forging part	SA - 508, Grade 3 Class 1
• Plate part	SA-533 Type B Class 1

3.2.2 Sizing Calculations

The procedural application of appropriate ASME code for determining the major design parameters of the reactor vessel is as follows,

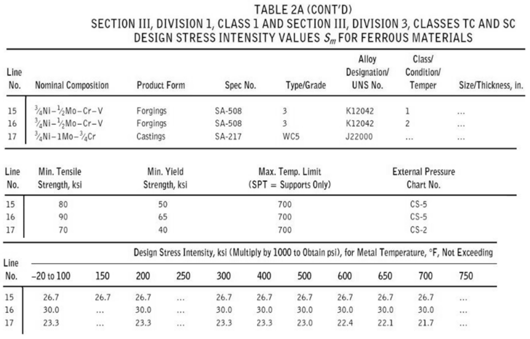


TABLE 2A (CONT'D)
SECTION III, DIVISION 1, CLASS 1 AND SECTION III, DIVISION 3, CLASSES TC AND SC
DESIGN STRESS INTENSITY VALUES S_m FOR FERROUS MATERIALS

Line No.	Nominal Composition	Product Form	Spec No.	Type/Grade	Alloy Designation/ UNS No.	Class/ Condition/ Temper	Size/Thickness, in.
15	¾Ni–½Mo–Cr–V	Forgings	SA-508	3	K12042	1	...
16	¾Ni–½Mo–Cr–V	Forgings	SA-508	3	K12042	2	...
17	¾Ni–1Mo–¾Cr	Castings	SA-217	WC5	J22000	...	...

Line No.	Min. Tensile Strength, ksi	Min. Yield Strength, ksi	Max. Temp. Limit (SPT = Supports Only)	External Pressure Chart No.
15	80	50	700	CS-5
16	90	65	700	CS-5
17	70	40	700	CS-2

Line	Design Stress Intensity, ksi (Multiply by 1000 to Obtain psi), for Metal Temperature, °F, Not Exceeding										
No.	–20 to 100	150	200	250	300	400	500	600	650	700	750
15	26.7	26.7	26.7	...	26.7	26.7	26.7	26.7	26.7	26.7	...
16	30.0	...	30.0	...	30.0	30.0	30.0	30.0	30.0	30.0	...
17	23.3	...	23.3	...	23.3	23.3	23.0	22.4	22.1	21.7	...

[Figure 7] ASME RV Material Specifications

a. Reactor Vessel thickness of active core region:

Thickness of Reactor Vessel; ASME Code NB- 3324.1 Cylindrical Shells

$$t = \frac{PR}{S_m - 0.5P}$$

Where:

P = 17.237 MPa: pressure inside of RV

S_m: Design stress intensity values (Section II, Part D, Subpart 1, Tables 2A and 2B),

Sm= 26.7 ksi or 184 MPa

R: Inner radius of RV, dRV = 4629.15

$$t = \frac{PR}{S_m - 0.5P} = \frac{17.237 \times 4629.15}{2 \times (184 - 0.5 \times 17.237)} = 227.48mm$$

b. Reactor Vessel lower head thickness:

The reactor vessel lower head thickness is determined by using ASME Code NB-3324.2 for spherical shells; NB-3324.2 Spherical Shells

$$t = \frac{PR}{2S_m - P} = \frac{17.237 \times 4629.15}{2 \times (184 - 17.237)} = 113.7mm$$

c. RV lower head radius:

To ensure continuity of reactor vessel design, we choose radius of RV lower head part equal

<Table 4> Diameter of Hot-leg and Cold-leg

Components	Parameter
Hot-leg inner dia., mm (in)	1066.8 (42)
Cold-leg inner dia., mm (in)	762 (30)

with the inner radius of RV, 2314.575 mm

d. Hot-leg and Cold-leg Sizing

i. Hot-leg and Cold-leg Thickness

According to ASME NB-3324.1 for Cylindrical Shells

$$t = \frac{PR}{S_m - 0.5P}$$

Where:

- P: Design Pressure = 17.237 MPa
- R = 1066.8: Inside radius of shell
- S_m: design stress intensity values (Section II, Part D, Subpart 1, Tables 2A and 2B)
- t: Thickness of shell

SA-508 Design Stress Intensity Value: Sm = 184 MPa

$$t_{hotleg} = \frac{PR}{S_m - 0.5P} = \frac{17.237 \times 1066.8}{184 - 0.5 \times 17.237} = 104.8\,mm$$

$$t_{coldleg} = \frac{PR}{S_m - 0.5P} = \frac{17.237 \times 762}{184 - 0.5 \times 17.237} = 74.89mm$$

ii. Hot-leg Reinforcement

According to NB3332.2 Required Area of Reinforcement:

The total cross-sectional area of reinforcement A, requires in any given plane for a vessel under internal pressure, shall not be less than

$$A = d \times t_r \times F = A_1 + A_2$$

Where:

d = finished diameter of a circular opening or finished dimension (chord length) of an opening on the plane being considered for elliptical and around openings in corroded condition. (in this case d = 1066.8 mm)

F = a correction factor which compensates for the variation in pressure stresses on different planes with respect to the axis of a vessel. In this case, we choose F= 0.5

tr =230 mm, the thickness which meets the requirements of NB-3221.1 in the absence of the opening.

Substituting these values to the equation returns the required area as,

A = 1,066.8 x 230 x 0.5 = 122,682 mm^2

According to NB-3334.1 Limit of Reinforcement along the Vessel Wall:

(a) One hundred percent of the required reinforcement shall be within a distance on each side of the axis of the opening equal to the greater of the following:

(1) The diameter of the ?nished opening in the corroded condition;

L_{limit}- > $D_{Hot-leg}$ = 1066.8 mm

(2) The radius of the ?nished opening in the corroded condition plus the sum of the thicknesses of the vessel wall and the nozzle wall.

L_{limit} > $r_{Hot-leg}$ + t_v + $t_{Hot-leg}$ = 533.4 + 230 + 112.5= 875.9 mm

Comparing the 2 cases, one hundred percent of the required reinforcement shall be within a distance on each side of the axis of the opening:

$L_{limit-1}$ = 1,066.8 mm

Required Area of Reinforcement not less than a half of the required material shall be on each side of the center line. It's mean: A_v > 0.5A= 0.5 x 122682 = 61341 mm^2, so the thickness of material add along the vesssel wall is:

$$A_V = t_V \bullet L_{limit-1} \Rightarrow t_V = \frac{61341}{1066.8} = 57.5\,mm$$

(b) Two-thirds of the required reinforcement shall be within a distance on each side of the axis of the opening equal to the greater of the following:

(1) $r+0.5\sqrt{Rt}$, where R is the mean radius of shell or head, t is the nominal vessel wall thickness, and r is the radius of the finished opening in the corroded condition;

$$R_V = 2314.575 + 0.5t_V = 2,429.575mm$$

$$L_{\lim} > r_{Hotleg} + 0.5\sqrt{R_V t_V} = 533.4 + 0.5\sqrt{2429.575 \times 230} = 907.16mm$$

(2) The radius of the finished opening in the corroded condition plus two-thirds the sum of the thicknesses of the vessel wall and the nozzle wall.

$$L_{limit} > r_{Hotleg} + \frac{2}{3}(t_V + t_{Hotleg})$$

$$L_{limit} > 533.4 + \frac{2}{3}(230 + 112.5) = 761.7$$

Combine 2 cases, Two-thirds of the required reinforcement shall be within a distance on each side of the axis of the opening

$L_{limit-2}$ = 907.16 mm

So the thickness of two third of the required reinforcement is:

$$\frac{2}{3}A_V = t_{V2} \cdot L_{limit-2} \Rightarrow t_{V2} = \frac{3 \times 61341}{2 \times 907.16} = 45.07mm$$

Hence, $t_{V2} < t_1 = 57.5mm$

According to NB-3334.2 Limit of Reinforcement; Normal to the Vessel Wall

$$L_{limit} = 0.5\sqrt{r_m t_n} + 0.5r_2$$

where,

r_i: inside radius of nozzle

r_m: mean radius = r_i+0.5t_n= 533.4+0.5t_n

r_2: transition radius, between nozzle and wall (choose 50 mm)

t_n: nominal nozzle thickness, as indicated

t_n = t_0+$t_{reinforcement}$. Where t_0 = 104.8 mm

By iteration methodology we apply values of treinforcement from 0, 10, 20.... to find $L_{limit-2}$

We get the value of thickness of reinforcement: $t_{reinforcement}$ = 150 mm and the long of reinforcement is: $L_{Limit-2}$ = 233.8 mm

At that point, the thickness of Hot-leg after reinforcement is: t_n = 262.5 mm

iii. Cold-leg reinforcement

The radius and thickness of cold-leg had been calculated previously.

$t_{cold-leg}$ =74.89 mm $R_{Cold-leg}$=381 mm

According to NB3332.2 Required Area of Reinforcement:

The total cross-sectional area of reinforcement A, requires in any given plane for a vessel under internal pressure, shall not be less than

$$A = d \times t_r \times F = A_1 + A_2 = 382 \times 2 \times 230 \times 0.5 = 87,860mm$$

- According to NB-3334.1 Limit of Reinforcement along the Vessel Wall:

(a) One hundred percent of the required reinforcement shall be within a distance on each side of the axis of the opening equal to the greater of the following:

(1) The diameter of the finished opening in the corroded condition;

L_{limit} > $D_{Cold-leg}$ = 762 mm

(2) The radius of the finished opening in the corroded condition plus the sum of the thicknesses of the vessel wall and the nozzle wall.

L_{limit} > $r_{Hot-leg}$ + t_v + $t_{Hot-leg}$ = 381 + 230 + 80 = 691 mm

Comparing the 2 cases, One hundred percent of the required reinforcement shall be within a distance on each side of the axis of the opening:

$L_{limit-1}$ = 762 mm

Required Area of Reinforcement not less than a half of the required material shall be on each side of the center line. It's mean:

$A_V > 0.5A = 0.5 \times 87{,}860 = 43{,}930\,mm^2$, so the thickness of material add along the vesssel wall is:

$$A_V = t_{V1} \cdot L_{limit-1} \Rightarrow t_{V1} = \frac{43{,}930}{762} = 57.6\,mm$$

(b) Two-thirds of the required reinforcement shall be within a distance on each side of the axis of the opening equal to the greater of: $r+0.5\sqrt{Rt}$, where R is the mean radius of shell or head, t is the nominal vessel wall thickness, and r is the radius of the finished opening in the corroded condition;

$$R_V = 2314.575 + 0.5t_V = 2429.575\,mm$$

$$L_{limit} > r_{Coldleg} + 0.5\sqrt{R_V t_V} = 381 + 0.5\sqrt{2429.575 \times 230} = 754\,mm$$

Two-thirds of the required reinforcement shall be within a distance on each side of the axis of the opening

$L_{limit-2}$ = 754 mm

So the thickness of two third of the required reinforcement is:

$$\frac{2}{3}A_V = t_{V2} \cdot L_{limit-2} \Rightarrow t_{V2} = \frac{2 \times 43930}{3 \times 754} = 38.8\,mm$$

$t_{V2} < t_{V1}$; So the thickness of material added along to the vessel will be 57.6 mm

- Limit of Reinforcement of Cold-leg Normal to the Vessel Wall

$$L_{limit} \geq 0.5\sqrt{r_m t_n} + 0.5r_2$$

Where:

r_i: inner radius

r_m: mean radius = r_i + $0.5t_n$ = 381+0.5 x t_n

r_2: transition radius, between nozzle and wall (choose 50mm)

t_n: nominal nozzle thickness, as indicated = $t_{cold-leg}$ + $t_{reinforcement}$

We can find the value of $t_{reinforcement}$ by iteration. The iteration was done for initial value of $t_{reinforcement}$ from 0, 10, 20 and found the final value of $L_{limit-2}$.

We get the value of thickness of reinforcement : $t_{reinforcement}$ = 120 mm and the length of reinforcement is: $L_{Limit-2}$ = 209 mm

Considering the limit of reinforcement and thickness for various cases, the resulting thickness of Hot-leg after reinforcement is: t_n = 210 mm.

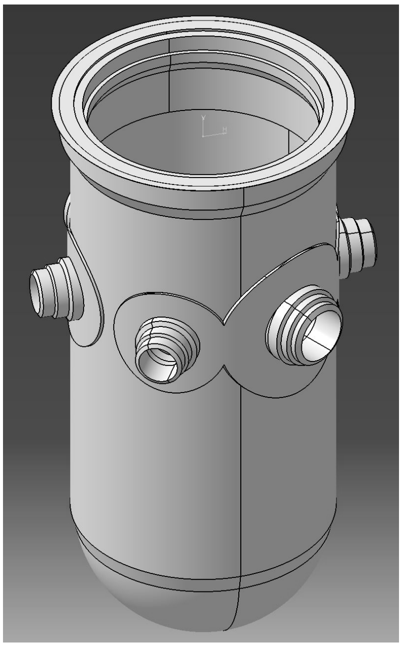
4. Sizing result and 3D Design of RV

In the previous chapter, important design parameters were shown how to drive them. Table 5 below summarize the results.

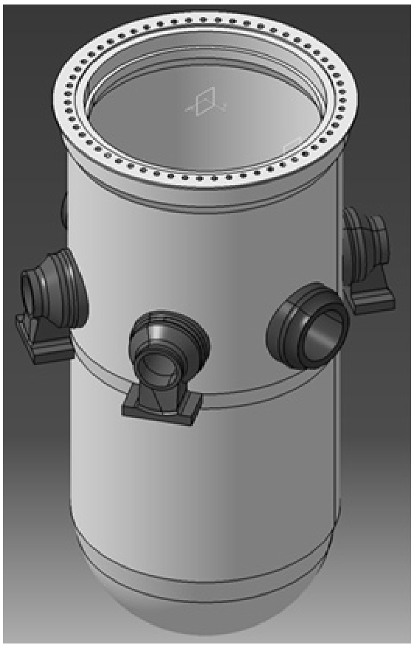
Figure 7 and 8 show the 3D design result that was carried out using CATIA V5.

No.	Parameter	Re-eng. (mm)	Standard (mm)
1	RV active core region thickness	227	230
2	RV nozzle region thickness (not including the reinforced section)	227	285
3	RV bottom head thickness	114	165
4	RV bottom head inner radius	2315	2330
5	RV Inner radius	2315	2330
6	Hot leg thickness	105	112.5
7	Cold-leg thickness	75	80
8	Hot-leg reinforcement thickness along the vessel wall	58	55
9	Hot-leg reinforcement length along the vessel wall	1067	ext. nozzle region
10	Hot-leg reinforcement thickness normal to the vessel wall	150	195
11	Hot-leg reinforcement length normal to the vessel wall	236	355
12	Cold-leg reinforcement thickness along the vessel wall	58	55
13	Cold-leg reinforcement length along the vessel wall	762	ext. nozzle region
14	Cold-leg reinforcement thickness normal to the vessel wall	150	235
15	Cold-leg reinforcement length normal to the vessel wall	194	450

<Table 5> Re-engineered design parameters and APR1400 RV design parameters



[Figure 7] ASME Code specification RV geometrical model



[Figure 8] Current design specification RV geometrical model

5. Conclusion

In this study only the major mechanical design parameters of the RV was explored whereas thermal-hydraulic functionality considerations were referred directly to the SSAR. The calculated design parameters, namely the thickness of reactor vessel parts, were lower compared to those of the standard APR1400 design. It showed that the APR1400 standard design parameters of RV exceed the ASME margins; this indicates a conservative structural design approach in the APR1400 reactor vessel. Thus ensuring structural integrity for the component.

Acknowledgements

This work was supported by the 2016 Research fund of the KEPCO International Nuclear Graduate School (KINGS), Republic of Korea. The authors would like to express appreciation toward KINGS.

References

1. Kossiakoff, A. and W.N. Sweet, Systems Engineering: Principles and Practice, Wiley-Interscience, Hoboken, NJ, pp. 69-109, 2011.
2. INCOSE, “Systems Engineering Handbook”, version 3.2.2., INCOSE TP-2003-002-03.2.2., pp. 61-218, October 2011.
3. ASME, 2010. “Section III, Division 1 - NB. Article NB-3000 Design”
4. Ihn Namgung, Conceptual Design of PWR600 Reactor Pressure Vessel Mechanical Design, KINGS textbook, 2015
5. Korea Electric Power Corporation and Korea Hydro & Nuclear Power Co., Ltd., 2001, “APR1400 SSAR (Standard Safety Analysis Report)”, Republic of Korea, Chapter 4 Reactor.