

# PRELIMINARY CONCEPTUAL DESIGN OF THE INNOVATIVE NEXT GENERATION SMART PLUS

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## INTRODUCTION

In 2019, the Korea Atomic Energy Research Institute (KAERI) and the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) had established the Korea-Saudi Arabia Joint Nuclear Research Centre. Several joint research projects were conducted under the support of the centre, among which a project to propose a preliminary conceptual design of the innovative next generation SMART (System-integrated Modular Advanced Reactor) Plus was successfully completed.

In the present study, the achievements on the preliminary conceptual design of SMART Plus will be briefly reported.

## OBJECTIVES AND SCOPE

The main goal of this project is to propose a preliminary conceptual design of the innovative next generation SMART Plus to enhance its economic efficiency and safety by introducing innovative element technologies. To enhance the competitiveness of SMART (2019), several element technologies had been suggested such as Printed Circuit Steam Generator (PCSG), In-Vessel Control Rod Drive Mechanism (IV-CRDM), an improved Reactor Vessel (RV) module, and so on. The most important and promising one of those is to utilize a Printed Circuit Heat Exchanger (PCHE) as a Steam Generator (SG), and to develop an improved RV module adopting the PCSG, which can enhance the economic efficiency of SMART Plus.

Several configurations of conceptual design candidates of SMART Plus were investigated thoroughly in the present study to find out the most effective reactor configuration for economic enhancement without drastic degradation of safety. There are five conceptual designs for arrangement of an RV and Steam Generator Vessels (SGVs), i.e., integral, 1-SGV modular, 2-SGV modular, 3-SGV modular, and 4-SGV modular arrangement. Advantages and disadvantages for each candidate will be compared in terms of safety and economic efficiency.

## PRELIMINARY CONCEPTUAL DRAWINGS

In this study, preliminary conceptual drawings of the RV for SMART Plus are provided. The RV indicates the combined structure of the Reactor Pressure Vessel (RPV) and the Reactor Closure Head (RCH). The RPV indicates all the structures belonging to the RV, except the RCH. In a single RPV, a core is installed at the bottom, and an IV-CRDM is placed above the core.

In the design of SMART Plus, PCSGs are adopted as SGs. PCSGs are well known of their great thermal density (high heat transfer rate for the given volume) due to its compact channels. A PCSG block is a rectangular parallelepiped block, fabricated by diffusion bonding among many metal plates having chemically etched primary side or secondary side flow paths of hydraulic diameter in the order of a millimetre. A PCSG module is a set, or an assembly of a number of PCSG blocks, arranged horizontally and stacked vertically. The PCSG region is where the PCSG blocks are installed horizontally and stacked vertically along with primary side flow paths (raising hot side coolant at the centre of the vessel, and descending cold side coolant at the circumferential area between the PCSG

module and pressure vessel) and the feedwater and main steam common lines penetrating the reactor pressure vessel.

Concerning the transportability to in-land sites, the maximum acceptable outer diameter of the RV was limited to 4,000 mm excluding the flanges and nozzles. Figures are for information only, and many detailed reactor internal and external structures are omitted since they have not been designed in detail yet.

## RESULTS AND DISCUSSION

### *Integral Configuration*

An integral reactor, such as SMART (2019), contains all the Reactor Coolant System (RCS) loop and relative components including SGs inside a single pressure vessel. In this configuration, the core, SGs, pressurizer (PZR), Reactor Coolant Pump (RCP), and other reactor internal structures are all integrated in a single RV, resultantly to eliminate large primary loop pipes and the possibilities of Large-Break Loss Of Coolant Accident (LBLOCA).

Figure 1 shows a conceptual drawing of the RV of the integral design of SMART Plus. In the fluid systems design viewpoint, the height difference between the core and SGs in the integral SMART Plus has positive effects on natural circulation flow rate. Also, compared to the other configurations, the integral SMART Plus is the most favourable one regarding reactor engineering, since the RCS flow path is nearly symmetric in all directions, and it is relatively easier to design detailed flow paths for uniform core flow distribution and SG flow distribution.

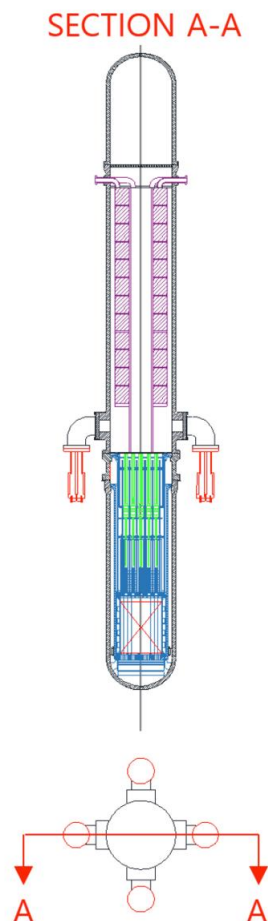


Figure 1. Conceptual drawing of an integral SMART Plus

However, the height of PCSG module (in other words, the number of PCSG block layers) is excessive and it may cause severe non-uniformities in the flow rates through each layer of PCSG blocks, both in the primary and secondary sides. Also, the excessive height of the integral SMART Plus yields several design difficulties, mainly related to mechanical and fabrication issues. Therefore, this configuration is not recommended for SMART Plus.

### *1-SGV Modular Configuration*

Figures 2 and 3 illustrate a conceptual drawing of the RV-SGV assembly of the 1-SGV modular SMART Plus. As in the integral design, PCSGs are adopted. However, in this configuration, the PCSG module is located in a separated pressure vessel other than the RV. This pressure vessel is called Steam Generator Vessel (SGV), and connected to the RV via a Cross Vessel (CV) providing primary coolant flow paths for both the hot side through the centre and cold side through the circumferential space. As in the integral design, the maximum acceptable outer diameter of the RV and SGV was limited to 4,000 mm without the flanges and nozzles.

The pressurizer (PZR) can be placed either at the upper space within the SGV (PZR in SGV), or at the upper space within the RV (PZR in RV). In the 1-SGV modular configuration (PZR in SGV) of Fig. 2, the height of the RV can be reduced slightly. The height can be modified during the detailed

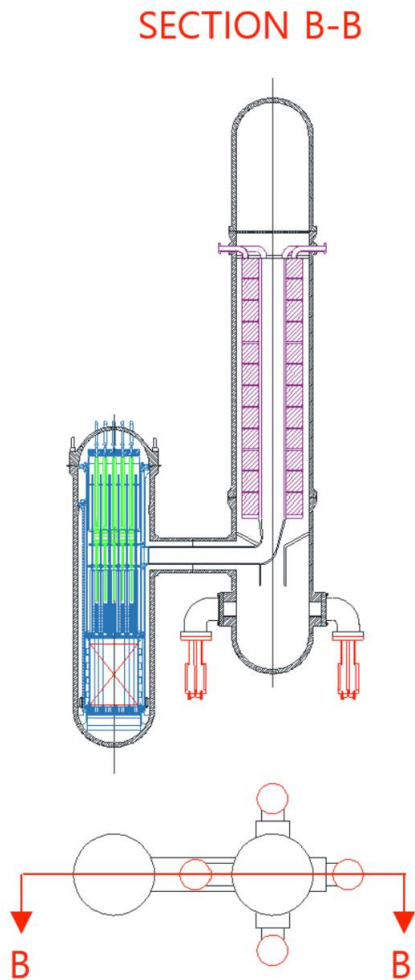


Figure 2. Conceptual drawing of an 1-SGV modular SMART Plus (PZR in the SGV)

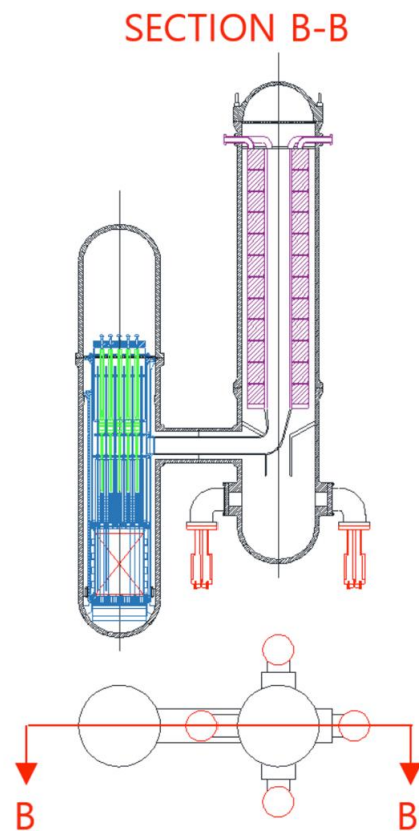


Figure 3. Conceptual drawing of an 1-SGV modular SMART Plus (PZR in the RV)

design procedures. The conceptual drawings shown in Figs. 2 and 3 are for information only, and many detailed reactor internal and external structures are omitted since they have not been designed in detail.

Although some of the design concerns such as excessive height of the RV are relieved by a small amount in the 1-SGV modular SMART Plus, the horizontal area requirement is greatly increased and the resulting overall manufacturing and construction cost is expected to increase. The asymmetric design of the RV-SGV assembly causes a number of critical problems regarding the RCS and reactor engineering. None of the problems can be solved easily. And, one of the conditions to be satisfied prior to adopt the modular configuration is that the possibilities of the LBLOCA shall be excluded, since it is one of the key advantages of the modular configuration compared to loop-type design. However, referring to Figs. 2 and 3, the length of the CV is not short enough. Since the CV shall be designed so that the structural integrity of the CV is in the same degree as that of the RV and SGV, the elongated length of the CV in the 1-SGV modular configuration may cause an increase of the manufacturing cost, and increase in the pressure loss through the CV. The increase in the pressure loss will affect the RCS overall pressure loss, and may hinder core cooling under natural circulation operations.

The excessive height of PCSG module (in other words, the number of PCSG block layers) remains unchanged, and may cause severe non-uniformities in the flow rates through each layer of PCSG blocks, both in the primary and secondary side. Combined with the asymmetrical design of the RV and SGV, the PCSG blocks is highly likely to be subject to non-uniform flow rate distributions in both the vertical and horizontal directions. Therefore, this configuration is not recommended for SMART Plus.

### ***2-SGV Modular Configuration***

Figures 4 and 5 depict conceptual drawings of the RV and SGVs of the 2-SGV modular SMART Plus. In the RV, a core is installed at the bottom, and above the core an IV-CRDM is placed beneath the RCH. As in the integral and 1-SGV modular configurations of SMART Plus, PCSGs are adopted. However, in these 2-SGV modular configurations, two independent PCSG modules are used since the number of SGVs is now two. The SGVs are connected to the RV via CVs, providing primary coolant flow paths for both the hot side through the centre and cold side through the circumferential space.

By dividing the PCSG blocks to two separate modules, the excessive height of PCSG module (in other words, the number of PCSG block layers) is now reduced to half. As a result, both the primary and secondary side flow rate uniformities in vertical direction are expected to be improved. Also, the number of RCPs per a pressure vessel remains four (4) while their size is reduced since the total number of RCPs is now eight (8), the RCPs can now be installed beneath the CV lower plenum, allowing reduction in the CV flow path length. Although the number of the CV flow path is now increased to two, the shorter flow path of the CV is now regarded to be sufficient in reducing the cost and pressure loss and achieving higher core cooling capability under natural circulation operation.

Combined with the above-mentioned advantages and the design considerations regarding the RCS and reactor engineering, the 2-SGV modular SMART Plus can provide sufficiently uniform flow rates to the core and the PCSG blocks (especially in vertical direction) while suppressing major design problems from excessive RV or RV-SGV assembly height, or excessive RCS flow velocity.

The reduced height of the RV-SGV assembly results in reduction of reactor building construction cost, and shortened CV allows reduction in manufacturing cost. The horizontal area occupation of the RV-SGV assembly of 2-SGV modular arrangements is slightly increased compared to that of 1-SGV modular arrangements, but the increase is minimized due to shortened CV length. Therefore, this configuration is highly recommended for SMART Plus.

### ***3-SGV Modular Configuration***

Figures 6 and 7 are conceptual drawings of the RV and SGVs of the 3-SGV modular SMART Plus. In the RV, a core is installed at the bottom, and above the core an IV-CRDM is placed beneath the RCH. As in the previous configurations of SMART Plus, PCSGs are adopted. However, in these 3-SGV modular configurations, three independent PCSG modules are used since the number of SGVs is now three. The SGVs are connected to the RV via CVs, providing primary coolant flow paths for both the hot side through the centre and cold side through the circumferential space.

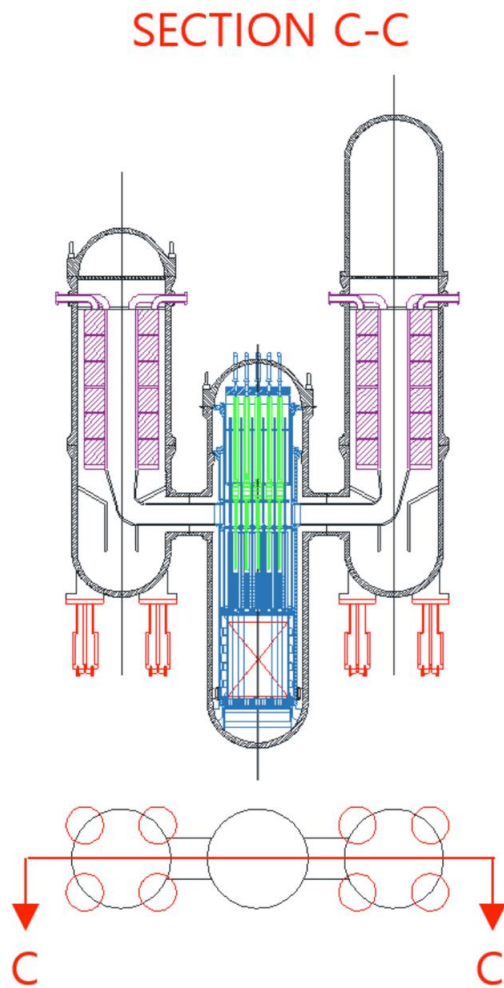


Figure 4. Conceptual drawing of a 2-SGV modular SMART Plus (PZR in one of the SGVs)

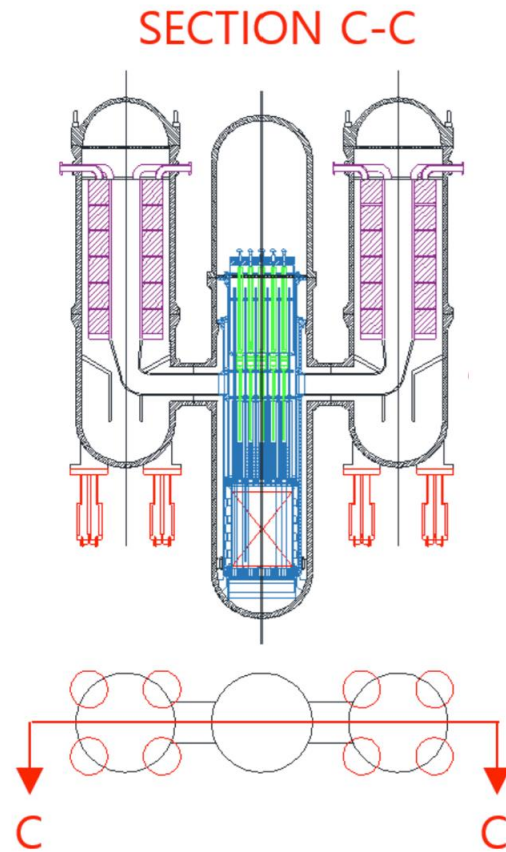


Figure 5. Conceptual drawing of a 2-SGV modular SMART Plus (PZR in the RV)

By dividing the PCSG blocks to three separate modules, the height of PCSG module (in other words, the number of PCSG block layers) is now further reduced. As a result, both the primary and secondary side flow rate uniformities in vertical direction are expected to be improved.

However, compared to the 2-SGV modular design, the reduction in the total height of the RV-SGV assembly is limited, while the horizontal area occupation of the RV-SGV assembly is greatly increased, and the number of the SGVs and CVs is increased by one. Therefore, overall construction cost for the reactor building is expected to be significantly increased. Furthermore, the increased number of SGVs and CVs will cause increase in manufacturing cost, and the natural circulation of the reactor will last for a shorter time compared to the previous designs, due to increased volumes of SGV lower plenum, which does not contribute to natural circulation driving force nor prevention of core uncover. The SGV lower plenum volumes is not preferred by the safety system designers.

Also, since the three SGVs are arranged symmetrically by 120 degrees apart around the RV, the symmetry (60 degrees) is not compatible to the core, which is symmetric up to 45 degrees. Thus, during the design of reactor internal structures, the simulation domain for the CFD analyses shall be

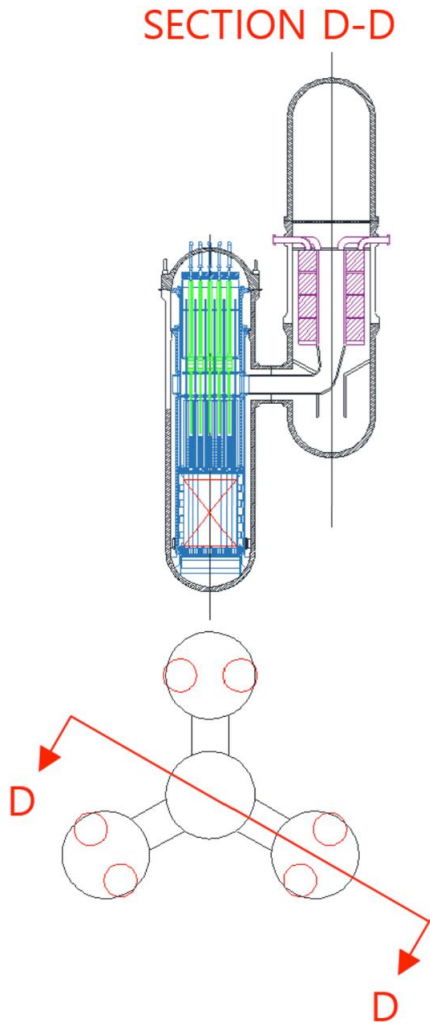


Figure 6. Conceptual drawing of a 3-SGV modular SMART Plus (PZR in one of the SGVs)

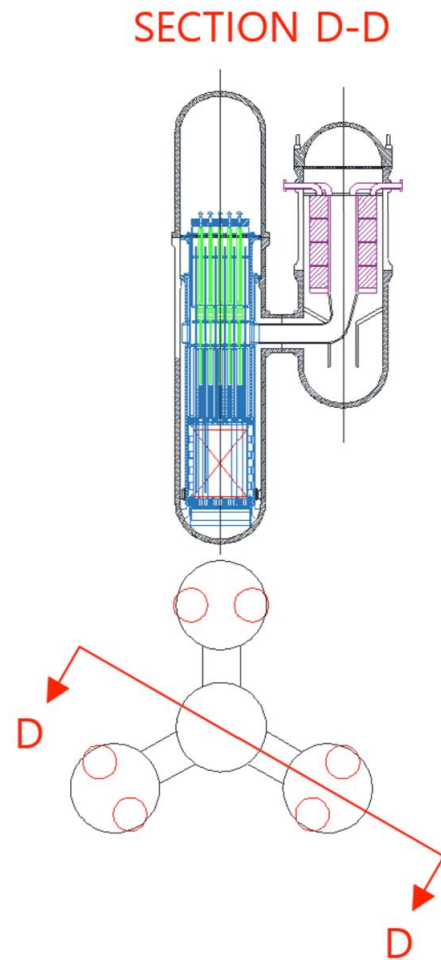


Figure 7. Conceptual drawing of a 3-SGV modular SMART Plus (PZR in the RV)

360 degrees (full simulation), which consumes the simulation capacity (or time) up to eight (8) times compared to previous designs. This increases the costs and time for design procedure.

As a result, the 3-SGV modular type increases the overall cost compared to the 2-SGV modular design, but the benefits are very limited.

#### ***4-SGV Modular Configuration***

Figures 8 and 9 exhibit a conceptual drawing of the RV and SGVs of the 4-SGV modular SMART Plus. In the RV, a core is installed at the bottom, and above the core an IV-CRDM is placed beneath the RCH. As in the previous configurations of SMART Plus, PCSGs are adopted. However, in these 4-SGV modular configurations, four independent PCSG modules are used since the number of SGVs is now four. The SGVs are connected to the RV via CVs, providing primary coolant flow paths for both the hot side through the centre and cold side through the circumferential space.

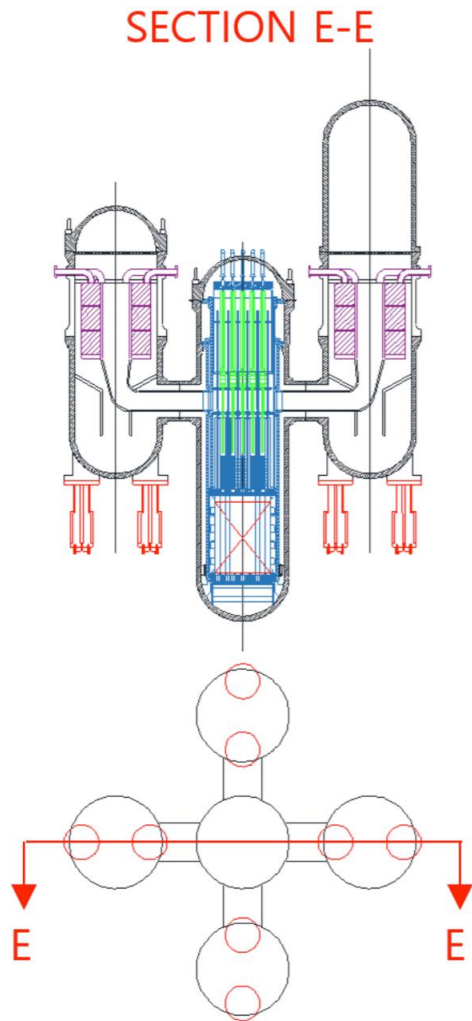


Figure 8. Conceptual drawing of a 4-SGV modular SMART Plus (PZR in one of the SGVs)

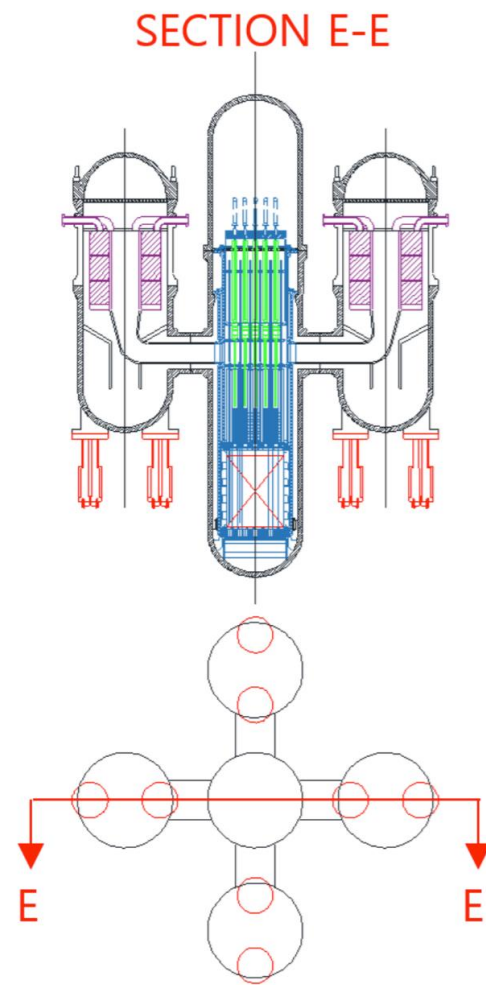


Figure 9. Conceptual drawing of a 4-SGV modular SMART Plus (PZR in the RV)

By dividing the PCSG blocks to four separate modules, the height of PCSG module (in other words, the number of PCSG block layers) is now much further reduced. As a result, both the primary and secondary side flow rate uniformities in vertical direction are expected to be improved slightly.

However, compared to the 3-SGV modular design, the reduction in the total height of the RV-SGV assembly is limited if the pressurizer is installed in one of the SGVs, and no reduction in the height is occurred if the pressurizer is installed in the RV. Also, the horizontal area occupation of the RV-SGV assembly is greatly increased, and the number of the SGVs and CVs is increased by one. Therefore, overall construction cost for the reactor building is expected to be significantly increased. Furthermore, the increased number of SGVs and CVs will cause increase in manufacturing cost, and the natural circulation of the reactor will last for a shorter time compared to the previous designs, due to increased volumes of SGV lower plenum, which does not contribute to natural circulation driving force nor prevention of core uncover. The SGV lower plenum volumes is not preferred by the safety system designers.

As a result, the 4-SGV modular type increases the overall cost significantly, but the benefits are very limited.

## CONCLUSIONS

An integral arrangement is beneficial for achieving uniform flow rate to the core and the PCSG modules horizontally, but the excessive height of the RV yields difficulties in mechanical structural design. The 1-SGV modular arrangement can slightly reduce the total height of the RV-SGV assembly, but the asymmetrical RCS flow path yields design difficulties. The 2-SGV modular arrangement reduces the height of the PCSG modules to half. The cross-vessel flow path is shorter than that of the 1-SGV modular arrangement with slower flow velocity, thus it is advantageous both in cost and RCS pressure loss. The 3-SGV and 4-SGV arrangements can further reduce the height of the RV-SGV assembly, but the degree of height reduction is relatively small against the linear increase of cost.

It can be concluded that 2-SGV modular configuration has many advantages over others, while the disadvantages by addition of the SGV is sufficiently limited as well. The design concerns discussed in the present study for each design candidate contributed to design improvements of SMART Plus.

## REFERENCES

KAERI and K.A.CARE. (2019). *Preliminary Safety Analysis Report for SMART Units 1&2*. Republic of Korea