



International Agreement Report

Model 3D Cores for PWR Using Vessel Components in TRACEv5.0P3

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ABSTRACT

New models for Pressurized Water Reactor (PWR) with fully 3D cores were developed using TRACE thermal-hydraulic code. To develop these new models, TRACE code was chosen because it is been developed and will be probably licensed by the Nuclear Regulatory Commission (NRC). Thus, it is easy to take advantage of current and future features of TRACE. Three 3D different models were developed, they make use of the 3D vessel component in TRACE, either cartesian or cylindrical type. These models are especially suitable to simulate cross-flow, instabilities and in general asymmetric phenomena. All three models have been successfully tested.

FOREWORD

This report represents one of the assessment or application calculations submitted to fulfill the bilateral agreement for cooperation in thermal-hydraulic activities between the Consejo de Seguridad Nuclear (CSN) and the U.S. Nuclear Regulatory Commission (NRC) in the form of a Spanish contribution to the NRC's Code Assessment and Management Program (CAMP), the main purpose of which is to validate the TRAC/RELAP Advanced Computational Engine (TRACE) code.

CSN and the Asociación Española de la Industria Eléctrica (UNESA, Electric Industry Association of Spain), together with some relevant universities, have established a coordinated framework (CAMP-Spain) with two main objectives: to fulfill the formal CAMP requirements and to improve the quality of the technical support groups that provide services to the Spanish utilities, CSN, research centers, and engineering companies.

The AP-28 Project Coordination Committee has reviewed this report: the contribution of a Spanish University to the above-mentioned CAMP-Spain program, for submission to CSN.

ISIRYM - UPV

June 2015

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EXECUTIVE SUMMARY

Three new fully 3D models for TRACE code are presented in this document. They model the reactor core using 3D vessel components. Therefore, they could be used to simulate asymmetrical phenomena in the core regardless of the phenomenon implication, either thermal-hydraulic or neutronic.

First, the Shape model is presented. It uses only one cartesian vessel with null flow area fraction on corner cells. Thus, the resulting shape resembles the radial mapping. The bypass is modeled using outermost cells and its flow area fraction is modified accordingly. The second model is named Split model. This model, similar to Shape model, makes use of several cartesian vessels. These vessels are joined sideways to resemble the radial mapping. Finally, the third model uses one cartesian vessel similar to that of the Shape model but without bypass. Besides, a cylindrical vessel is coupled to the cartesian vessel. The cylindrical vessel has two radial cells. The innermost represents the bypass and the outermost cell represents the downcomer. The cylindrical vessel is also discretized into three different theta sectors. One cold and hot leg is attached to each theta sector.

Due to the 3D cross flow represented in these models, the bypass flow strongly fluctuates along the axial axis (z-direction). An iterative method is developed for automatic adjustment of the bypass flow. Finally, a model-to-model comparison is made in section 4. Several thermal-hydraulic variables are compared with a traditional 1D model. The 1D model is also based on TRACE.

As a recommendation, when 3D feature is desired to model the core in TRACE, the Cylindrical model is advisable. This is the result of a trade of considering computational effort, realistic behavior and number of components used.

ABBREVIATIONS

PWR	Pressurized Water Reactor
NRC	Nuclear Regulatory Commission
SNAP	Symbolic Nuclear Analysis Package

NOMENCLATURE

Next, a list of all variables used is provided. Besides, a description and the source for each model are also shown. The source could be an equation, table, nuclear plant data, expert analyzer or simulation result. The variable is not used for a certain model if its source is shaded.

Variable	Description	Shape	Split	Cylind
ϕ^t	Assembly fraction for each theta sector			Eq 23
A_{in}	System inlet area	Eq 1	Eq 1	Eq 21
A_{out}	System outlet area	Eq 2	Eq 2	Eq 22
$cpowr$	Power fraction for each heat structure in assembly cells	Eq 4	Eq 4	Eq 4
$cpowr_{by}$	Power fraction for each heat structure in bypass cells	Eq 5	Eq 5	
$cpowr_{by}^t$	Power fraction for each heat structure in bypass cells for each theta sector			Eq 27
fa	Assembly flow area	Plant	Plant	Plant
fa_{by}	Bypass flow area	Plant	Plant	Plant
fa_{dc}	Downcomer flow area			Plant
fa_{break}^t	Break flow area for each theta sector			Eq 24
fa_{fill}^t	Fill flow area for each theta sector			Eq 24
FAF_a	Flow area fraction in a -direction for cylindrical vessel			Tab 11
FAF_r	Flow area fraction in r -direction for cylindrical vessel			Tab 11
FAF_t	Flow area fraction in t -direction for cylindrical vessel			Tab 11
FAF_x	Flow area fraction in x -direction for cartesian vessel	Tab 4	Tab 4	Tab 8
faf_x	Flow area fraction in x -direction for assembly cells	Expert	Expert	Expert
$faf_{x,by}$	Flow area fraction in x -direction for bypass cells	Eq 12	Eq 12	
FAF_y	Flow area fraction in y -direction for cartesian vessel	Tab 5	Tab 5	Tab 9
faf_y	Flow area fraction in y -direction for assembly cells	Expert	Expert	Expert
$faf_{y,by}$	Flow area fraction in y -direction for bypass cells	Eq 13	Eq 13	
FAF_z	Flow area fraction in z -direction for cartesian vessel	Tab 6	Tab 6	Tab 10
faf_z	Flow area fraction in z -direction for assembly cells	Eq 15	Eq 15	Eq 15
$faf_{z,by}$	Flow area fraction in z -direction for bypass cells	Eq 14	Eq 14	
$Flow_{by}$	Bypass mass flow	Sim	Sim	Sim
$Flow_{by}^*$	Theoretical bypass mass flow	Plant	Plant	Plant
$Flow_{error}$	Bypass mass flow maximum acceptable error	Expert	Expert	Expert
$Flow_{fill}^t$	Inlet mass flow for each theta sector			Eq 25
$Flow_{tot}$	Total inlet mass flow	Plant	Plant	Plant
$FVOL$	Volume fraction for cylindrical vessel			Tab 11
$fvol$	Volume fraction	Eq 16	Eq 16	Eq 16
$fvol^k$	Volume fraction for each axial level for assembly cells	Eq 17	Eq 17	Eq 17
$fvol_{by}^k$	Volume fraction for each axial level for bypass cells	Eq 18	Eq 18	
H_{by}	Power fraction that heats directly the bypass	Expert	Expert	Expert
$HD_a^{r=1}$	Hyd. diameter in a -direction for cylindrical vessel (bypass)			Eq 34
$HD_a^{r=2}$	Hyd. diameter in a -direction for cylindrical vessel			Eq 35

	(downcomer)			
$HD_r^{r=1}$	Hyd. diameter in r -direction for cylindrical vessel (bypass)			Eq 36
$HD_r^{r=2}$	Hyd. diameter in r -direction for cylindrical vessel (downcomer)			Eq 37
$HD_t^{t=1}$	Hyd. diameter in t -direction for cylindrical vessel (bypass)			Eq 38
$HD_t^{t=2}$	Hyd. diameter in t -direction for cylindrical vessel (downcomer)			Eq 39
HD_x	Hyd. diameter in x -direction for cartesian vessel	Tab 4	Tab 4	Tab 8
hd_x	Hyd. diameter in x -direction	Expert	Expert	Expert
HD_y	Hyd. diameter in y -direction for cartesian vessel	Tab 5	Tab 5	Tab 9
hd_y	Hyd. diameter in y -direction	Expert	Expert	Expert
HD_z	Hyd. diameter in z -direction for cartesian vessel	Tab 6	Tab 6	Tab 10
hd_z	Hyd. diameter in z -direction for assembly cells	Plant	Plant	Plant
$hd_{z,by}$	Hyd. diameter in z -direction for bypass cells	Plant	Plant	Plant
K_{by}^R	Bypass friction factor r -direction	Expert	Expert	Expert
K_{by}^Z	Bypass friction factor z -direction	Expert	Expert	Expert
$KFAC_a$	Friction factor in a -direction for cylindrical vessel			Tab 11
$KFAC_r$	Friction factor in r -direction for cylindrical vessel			Tab 11
$KFAC_t$	Friction factor in t -direction for cylindrical vessel			Tab 11
$KFAC_x$	Friction factor in x -direction for cartesian vessel	Tab 4	Tab 4	Tab 8
$kfac_x$	Friction factor in x -direction	Expert	Expert	Expert
$KFAC_y$	Friction factor in y -direction for cartesian vessel	Tab 5	Tab 5	Tab 9
$kfac_y$	Friction factor in y -direction	Expert	Expert	Expert
$KFAC_z$	Friction factor in z -direction for cartesian vessel	Tab 6	Tab 6	Tab 10
$kfac_z$	Friction factor in z -direction in assembly cells	Expert	Expert	Expert
$kfac_{z,by}$	Friction factor in z -direction in bypass cells	Expert	Expert	Expert
$kfac_{z,dc}$	Friction factor in z -direction in downcomer cells	Expert	Expert	Expert
n_{cells}	Number of cells	Eq 6	Eq 6	Eq 28
n_{chan}	Number of fuel assemblies	Plant	Plant	Plant
n_{chan}^t	Number of fuel assemblies for each theta sector			Expert
n_{comp}	Number of components in the system	Eq 7	Eq 19	Eq 40
n_{sjunc}	Number of single junction components			Tab 14
n_{junc}	Number of junctions in the system	Eq 8	Eq 20	Eq 41
n_t	Number of theta sectors in cylindrical vessel, typically same as recirculation loops			Expert
n_x	Number of cells in x -direction for cartesian vessel	Plant	Plant	Plant
n_y	Number of cells in y -direction for cartesian vessel	Plant	Plant	Plant
n_z	Number of cells in z -direction for cartesian vessel (axial levels)	Expert	Expert	Expert
$P(x,y,z)$	3D power distribution	Plant	Plant	Plant
rdx	Number of fuel rods per heat structure in assembly cell	Plant	Plant	Plant
rdx_{by}	Number of fuel rods per heat structure in bypass cell	Eq 3	Eq 3	
rdx_{by}^t	Number of fuel rods per heat structure in bypass cell for each theta sector			Eq 26
X_{by}	Length in x -direction for bypass cell	Eq 10	Eq 10	
X_{cell}	Length in x -direction for assembly cell	Plant	Plant	Plant
X_r	Radial discretization for cylindrical vessel			Eq 30
Y_{by}	Length in y -direction for bypass cell	Eq 11	Eq 11	

Y_{cell}	Length in y -direction for assembly cell	Plant	Plant	Plant
Y_t	Theta discretization for the cylindrical vessel			Eq 31
Z	Axial discretization for the cartesian vessel	Expert	Expert	Expert
Z_a	Axial discretization for the cylindrical vessel			Eq 29
Z_{break}	Level for break connection, Cylindrical model only			Expert
Z_{fill}	Level for fill connection, Cylindrical model only			Expert

1. INTRODUCTION

Most of the thermal-hydraulic nuclear plant models, using nuclear codes such as TRACE or RELAP5, are discretized in one dimension. This is because large amount of cells are needed to model the whole plant, and thus the matrices to be solved are big. However, in order to take advantage of the increasing computational power, it seems that the next logical step is to use 3D spatial discretization. So far, TRACE is one of the few thermal-hydraulic codes that uses 3D components [1]. The vessel component is fully discretized in 3D and the thermal-hydraulic equations solved accordingly.

In this study, 3D vessel components, either cartesian, cylindrical or a combination, were used to model a nuclear reactor core. This is where the most important phenomena in a nuclear power plant occur. Therefore, the use of a 3D core can improve the result accuracy and highlight phenomena that were not simulated properly in a 1D core. For example, cross-flow, instabilities and in general asymmetric phenomena either in the thermal-hydraulic or neutronic phase.

It must be said that few studies using 3D vessels to model the reactor core were found [3], [4] and [5]. Thus, this publication pretends to summarize and increase the available core modeling knowledge. Three different models were developed to simulate a 3D reactor core. The different features of these models are explained deeply in chapter 2. Next, the three models are presented:

- **Shape model.** It uses only one cartesian vessel in which the corner cells have null volume to shape it as shown in the reactor radial mapping.
- **Split model.** It uses several cartesian vessels with different sizes and attached sideways to shape them as shown in the reactor radial mapping.
- **Cylindrical model.** It uses one cartesian vessel for the core (also with some null volume cells) and a cylindrical vessel that models the bypass (inner radial cell) and the downcomer (outer radial cell). The cylindrical vessel is also discretized in the theta direction.

All different models have been tested against a TRACE 1D model, resulting in a good agreement. Among the different models, all 3D models stand out by their capability to capture asymmetric phenomena triggered by the thermal-hydraulic and/or the neutronic code. These models provide realistic simulation results when these phenomena occur in the reactor core, and thus, they are suitable for core instability studies. Among the 3D models, the Cylindrical model is the recommended option because its similarity to a real nuclear reactor (reflector and downcomer), and because it has been tested for different scenarios.

Table 1 shows the simulation time, in hours, as a function of the model and the simulation state. As can be seen, for fast calculation the traditional TRACE 1D model beats the other models. However, the 3D calculation component is lost, therefore, if one wants to include 3D calculation, the best choice is the Cylindrical model. Cylindrical model takes a little bit longer than the Shape model, but it is more realistic. Furthermore, it must be said that the Split model, despite its good agreement with other models, always takes much longer calculation times. For the transient simulation, a control rod insertion was simulated with quite short time steps and a total simulation time of 100 seconds.

Model	Components	SSA	CSS	CTR	Total time
Traditional 1D	363	0.03	0.05	1.63	1.71
Shape	731	0.63	1.78	7.68	10.09
Split	2713	3.11	15.14	127.97	146.22
Cylindrical	2589	1.07	1.79	11.87	14.73

Table 1 Simulation Time (Hours) as a Function of the Chosen Model.

A final comment must be made before explaining how to reproduce the 3D models. Due to the fact that the core is modeled using 3D components, which are connected node to node, the bypass mass flow has a strong variation along the way through the vessel (axial axis). This occurs because the bypass cells and fuel assembly cells have different volume, and thus the fluid flows freely among them. Therefore, the bypass friction factor has to be adjusted at each node, axially and radially. Furthermore, for the Cylindrical model, because it could have several theta sectors, it has to be adjusted among the different theta sectors. This is a tedious task, even for expert users. However, an iterative process to adjust the bypass friction factor for each level and each sector is presented in Chapter 3. It was proved to work successfully in all models. All three 3D models are explained in Chapter 2. Finally, in Chapter 4 the 3D models are compared against a traditional TRACE 1D model for the same nuclear reactor.

2. MODEL DESCRIPTION

2.1 Shape model

The whole core is modeled by means of only one cartesian vessel. This element provides the cross-flow between each fuel assembly node and between fuel assemblies and reflector area. This is an improvement over 1D models. The flow area fraction within this vessel is modified so the external shape is consistent with the reactor radial mapping, see Figure 1.

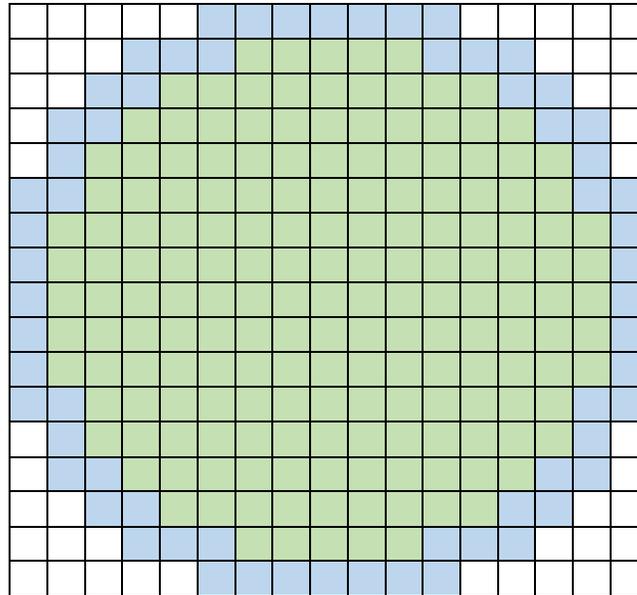


Figure 1 Cartesian Vessel Radial Cut, White Cells have Zero Flow Area Fraction, Gray Cells Represent Fuel Assembly Cells and Blue Cells Represent Bypass Cells.

Hereafter a list of main features and components used to build the Shape model is provided.

- There is only one cartesian vessel that represents the whole core, both the assemblies and the bypass. In the same axial level, each cell corresponds to one fuel assembly, thus, there is not any fuel assembly collapsed.
- The bypass is modeled using the outermost vessel nodes. The bypass node flow area fraction is modified so the sum of all bypass nodes areas is equal to the real bypass area.
- One heat structure is associated with each cell representing fuel assemblies and cells representing the bypass.
- One power component heats all heat structures.
- It is not possible to connect the fill or break component directly with a plenum, thus one-cell big pipes are used between them. Moreover, several one-cell pipes are used to connect both plenums with each cell -fuel assemblies or bypass- at both ends of the cartesian vessel.

See Figure 2 for a simplified Shape model (5x5 vessel), sketch using SNAP tool [2].

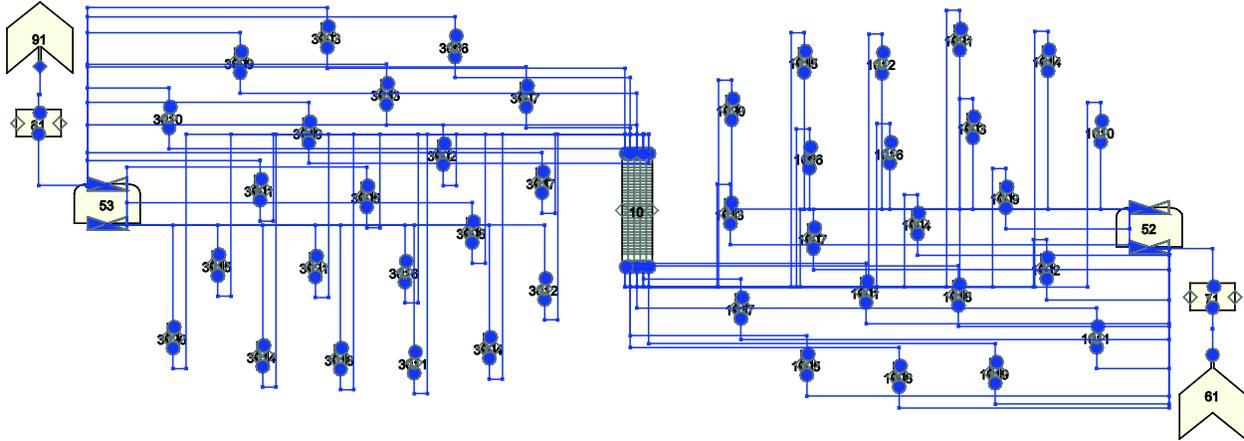


Figure 2 Shape Model Sketch, Simplified 5x5 Vessel.

The flow area into the system, A_{in} , is defined as the sum of the inlet flow area over all fuel assemblies, n_{chan} , Eq. (1). The same logic is used for the system outlet area, A_{out} , Eq. (2).

$$A_{in} = \sum_{f=1}^{n_{chan}} f a_f^{z=1} \quad (1)$$

$$A_{out} = \sum_{f=1}^{n_{chan}} f a_f^{z=nz} \quad (2)$$

Where $f a_f^z$ is the fuel assembly flow area at a certain axial node, z . The index variable f goes over all fuel assembly modeled.

These areas are assigned to the fill/break, inlet/outlet one-cell big pipe, and inlet/outlet plenum components. The inlet and outlet one-cell big pipes are set vertically and have zero friction factor values.

One cylindrical heat structure is associated to each fuel assembly. They have zero flux as inner surface boundary condition (heat structure center), and their outer surface is coupled to the associated cartesian vessel cell. The number of fuel rods for each fuel assembly is given by the fuel assembly manufacturer. This is introduced in TRACE using the surface multiplier variable (rdx). The bypass cells are heated by means of a heat structure per cell. Heat structures coupled to bypass cells are not modeled as fuel rods, variable $nofuelrod$ equal 1. The surface multiplier for each heat structure in a bypass cell, rdx_{by} , is given by Eq. (3); and its power fraction is set equal to the bypass power fraction, Eq. (5).

$$rdx_{by} = \frac{1}{n_{reflec}} \sum_{f=1}^{n_{chan}} rdx_f \quad (3)$$

Where

n_{reflec} is the number of cells representing the bypass, and
 rdx_f is the number of fuel rods per fuel assembly f .

All heat structures are powered by a single power. The total reactor power, prompt heat and the 3D nodal power distribution ($P(x,y,z)$) are supplied by the power plant, With these data, the axial power distribution (normalized to one) for each heat structure in core cells can be calculated. The power fraction for each heat structure, $cpowr$ (fuel assemblies) and $cpowr_{by}$ (for bypass) is calculated with the following formulas:

$$cpowr = P(x, y, z) \frac{1 - H_{by}}{n_{cells}} \quad (4)$$

$$cpowr_{by} = \frac{H_{by}}{n_{cells}} \quad (5)$$

Where

H_{by} is the power fraction that heats directly the bypass, and
 n_{cells} is the number of cells representing fuel assemblies plus the number of cells representing the bypass, Eq. (6).

$$n_{cells} = n_{chan} + n_{reflec} \quad (6)$$

The total number of components, n_{comp} , for Shape model is detailed in Table 2. It can be expressed as in Eq. (7).

Component	Quantity
Fill	1
Break	1
Plenum	2
Big pipe	2
Power	1
Cartesian vessel	1
Heat structure	n_{cells}
Pipe inlet vessel	n_{cells}
Pipe outlet vessel	n_{cells}

Table 2 Number of Components in the Shape Model.

$$n_{comp} = 7 + n_{vessels} + 3 \cdot n_{cells} \quad (7)$$

The same can be done with the total number of junctions, n_{junc} , for Shape model, see Table 3 and Eq. (8).

Junction from	Junction to	Quantity
Fill	Inlet big pipe	1
Inlet big pipe	Lower plenum	1
Lower plenum	Lower small pipe	n_{cells}
Lower small pipe	Cartesian vessel	n_{cells}
Cartesian vessel	Upper small pipe	n_{cells}
Upper small pipe	Upper plenum	n_{cells}
Upper plenum	Outlet big pipe	1
Outlet big pipe	Break	1

Table 3 Number of Junctions in the Shape Model.

$$n_{junc} = 4 + 4 \cdot n_{cells} \quad (8)$$

According to the vessel component in TRACE, all cells have the same dimension. Let the variables X_{cell} and Y_{cell} be the fuel assembly dimensions, given by the manufacturer, and thus the vessel unitary cell dimensions (blue straight-line cell in Figure 3). Nonetheless, the volume of a cell representing a fuel assembly does not need to be the same as the volume of a cell representing the bypass. This can be solved modifying the flow area fraction. If the total bypass flow area is fa_{by} , the flow area for one bypass cell is fa_{by}/n_{reflec} . Let the variables X_{by} and Y_{by} be the sides that define the flow area for one bypass cell, (green dashed line cell in Figure 3). Note that there is no shrink in the z-direction.

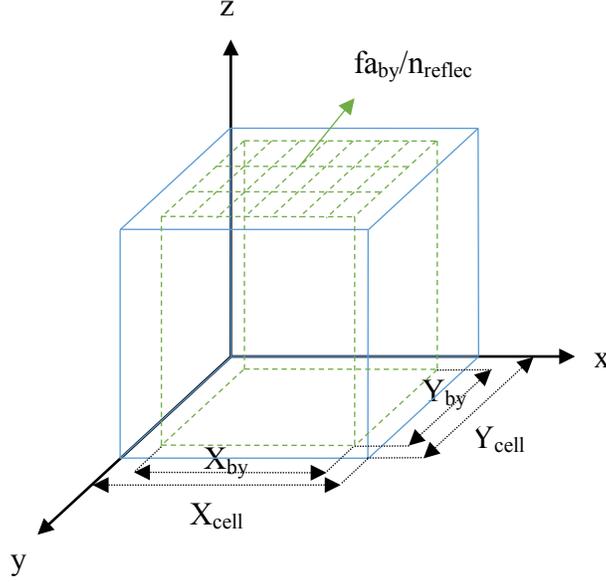


Figure 3 Cell Representing the Bypass Dimensions in a Cartesian Vessel.

The flow area fraction is defined as the ratio between the real flow area in cell (green area) and the geometry cell area (blue area). In order to obtain the flow area fraction a relationship between bypass cell dimensions (green) and fuel assembly cell dimensions (blue) must be established. We assume the following relation, Eq. 9.

$$\frac{X_{by}}{Y_{by}} = \frac{X_{cell}}{Y_{cell}} \rightarrow X_{by} = Y_{by} \frac{X_{cell}}{Y_{cell}} \quad (9)$$

As explained before, the flow area for one bypass cell is $f_{a_{by}}/n_{reflec}$ and X_{by} and Y_{by} are the sides that define the flow area for one bypass cell. Thus, the quantity $X_{by}Y_{by}$ is also the flow area for one bypass cell. If both quantities are compared, as in Eq. 10, a new relation is obtained.

$$X_{by} \cdot Y_{by} = \frac{f_{a_{by}}}{n_{reflec}} \rightarrow X_{by} = \frac{f_{a_{by}}}{n_{reflec}} \frac{1}{Y_{by}} \quad (10)$$

Combining Eq. (9) and Eq. (10).

$$Y_{by} = \sqrt{\frac{Y_{cell}}{X_{cell}} \frac{f_{a_{by}}}{n_{reflec}}} \quad (11)$$

Finally, the bypass flow area fraction, $f_{af_{by}}$, in all three dimensions can be obtained as follows, Eq. (12) to Eq. (14). Because there is no shrink in the z-direction, both the real length and cell length in z-direction are equal and they cancel each other. In Eq. (14), relationship defined in Eq. (10) is used.

$$faf_{x,by} = \frac{Y_{by}Z}{Y_{cell}Z} = \frac{Y_{by}}{Y_{cell}} \quad (12)$$

$$faf_{y,by} = \frac{X_{by}Z}{X_{cell}Z} = \frac{X_{by}}{X_{cell}} \quad (13)$$

$$faf_{z,by} = \frac{X_{by}Y_{by}}{X_{cell}Y_{cell}} = \frac{fa_{by}/n_{reflec}}{X_{cell}Y_{cell}} \quad (14)$$

The flow area fraction for a fuel assembly cell can be calculated as shown in Eq. (15). Note that the quantity $X_{cell}Y_{cell}$ (assembly total area) is bigger than the fuel assembly flow area, fa , because the structures inside the assembly block a fraction of the total area. Thus the flow area fraction for a fuel assembly cell must be smaller than one.

$$faf_z = \frac{fa}{X_{cell}Y_{cell}} \quad (15)$$

Once the flow area fraction is obtained, the main properties for the x-direction face cells in the cartesian vessel can be calculated according to Table 4. Note that because the wet perimeter is unknown, the hydraulic diameter is assumed to be equal to the flow area. Same conclusions can be applied to the y-direction.

Three different situations can be found: reflector-reflector, reflector-fuel assembly and fuel assembly-fuel assembly. The expert analyst must introduce the fuel assembly friction factors, whereas the friction factors for the bypass cells (in x and y-direction) can be adjusted iteratively, see Chapter 3. The same can be seen in Table 6 for the z-direction face properties.

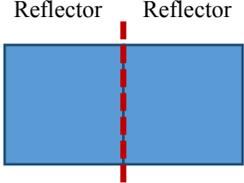
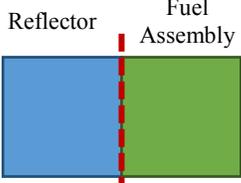
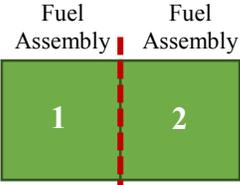
Cells	Property	Value
	Flow Area Fraction (FAF _x)	$faf_{x,by}$
	Hydraulic Diameter (HD _x)	$Y_{by} \cdot Z$
	Friction Factor (KFAC _x)	0
	Flow Area Fraction (FAF _x)	$faf_{x,by}$
	Hydraulic Diameter (HD _x)	$Y_{by} \cdot Z$
	Friction Factor (KFAC _x)	$kfac_{x,by}$
	Flow Area Fraction (FAF _x)	1
	Hydraulic Diameter (HD _x)	$Y_{cell} \cdot Z$
	Friction Factor (KFAC _x)	$0.5 \cdot (kfac_{x1} + kfac_{x2})$

Table 4 Face Cell Properties in x-Direction in the Shape Model.

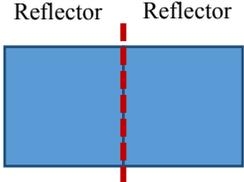
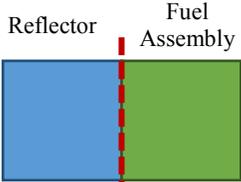
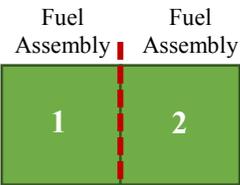
Cells	Property	Value
	Flow Area Fraction (FAF _y)	$faf_{y,by}$
	Hydraulic Diameter (HD _y)	$X_{by} \cdot Z$
	Friction Factor (KFAC _y)	0
	Flow Area Fraction (FAF _y)	$faf_{y,by}$
	Hydraulic Diameter (HD _y)	$X_{by} \cdot Z$
	Friction Factor (KFAC _y)	$kfac_{y,by}$
	Flow Area Fraction (FAF _y)	1
	Hydraulic Diameter (HD _y)	$X_{cell} \cdot Z$
	Friction Factor (KFAC _y)	$0.5 \cdot (kfac_{y1} + kfac_{y2})$

Table 5 Face Cell Properties in y-Direction in the Shape Model.

Cell	Property	Value
Reflector 	Flow Area Fraction (FAFz)	$faf_{z,by}$
	Hydraulic Diameter (HDz)	$hd_{z,by}$
	Friction Factor (KFACz)	$kfac_{z,by}$
Fuel Assembly 	Flow Area Fraction (FAFz)	faf_z
	Hydraulic Diameter (HDz)	hd_z
	Friction Factor (KFACz)	$kfac_z$

Table 6 Face Cell Properties in z-Direction in the Shape Model.

There is only one property defined in the cell center (not in the cell faces), it is the volume fraction. However, since there is no shrink in the z-direction, see Figure 3, the volume fraction is the same as the flow area fraction in z-direction, see Eq. (15) and Eq. (16).

$$fvol = \frac{fa \cdot Z}{X_{cell}Y_{cell} \cdot Z} = \frac{fa}{X_{cell}Y_{cell}} = faf_z \quad (16)$$

Moreover, the flow area fraction is obtained at cell face, but the volume fraction must be calculated at the cell center, thus a linear interpolation is applied. See Eq. (17) for fuel assembly volume fraction and Eq. (18) for bypass volume fraction. Index k represents the axial cell index.

$$fvol^k = \frac{1}{2}(faf_z^k + faf_z^{k+1}) \quad (17)$$

$$fvol_{by}^k = \frac{1}{2}(faf_{z,by}^k + faf_{z,by}^{k+1}) \quad (18)$$

As seen in Figure 2, in order to connect the vessel inlet/outlet to the lower/upper plenums, one-cell pipes for each vessel cell is used (with the exception of the null flow area fraction cells, white cells in Figure 1). It is important to know that it is not possible to define properties in the first vessel axial face in TRACE. Thus, the properties for the first/last cell face are set to zero. Instead, its properties are set in the one-cell pipe before/after the vessel. All the one-cell pipes are set vertically, their length is set to 1 m and their friction factors and hydraulic diameters are set equal to the first/last fuel assembly cell associated, as explained in Table 6. All the inlet connections are set at the bottom cell side (-Z in bottom level). Whereas all the outlet connections are set at the upper cell side (+Z in upper level).

2.2 Split model

Hereafter a list of main features and components used to build the Split model is provided.

- Several cartesian vessel are used. They represent the whole core, both the assemblies and the bypass. In the same axial level, each cell corresponds to one fuel assembly, thus, there is not any fuel assembly collapsed.
- The different cartesian vessels are joined sideways using single junctions node-to-node in all axial levels, thus the external shape is consistent with the reactor radial mapping.
- The bypass is modeled using the outermost vessel nodes resulting from all cartesian vessels joined. The bypass node flow area fraction is modified so the sum of all bypass nodes is equal to the real bypass area.
- One heat structure is associated with each cell representing fuel assemblies and cells representing the bypass.
- One power component heats all heat structures.
- It is not possible to connect the fill or break component directly with a plenum, thus one-cell big pipes are used between them. Moreover, several one-cell pipes are used to connect both plenums with each cell –fuel assemblies or bypass- at both ends in the cartesian vessel.

See Figure 4 for a simplified Split model (5x5 vessel without lateral junctions), sketch using SNAP tool [2].

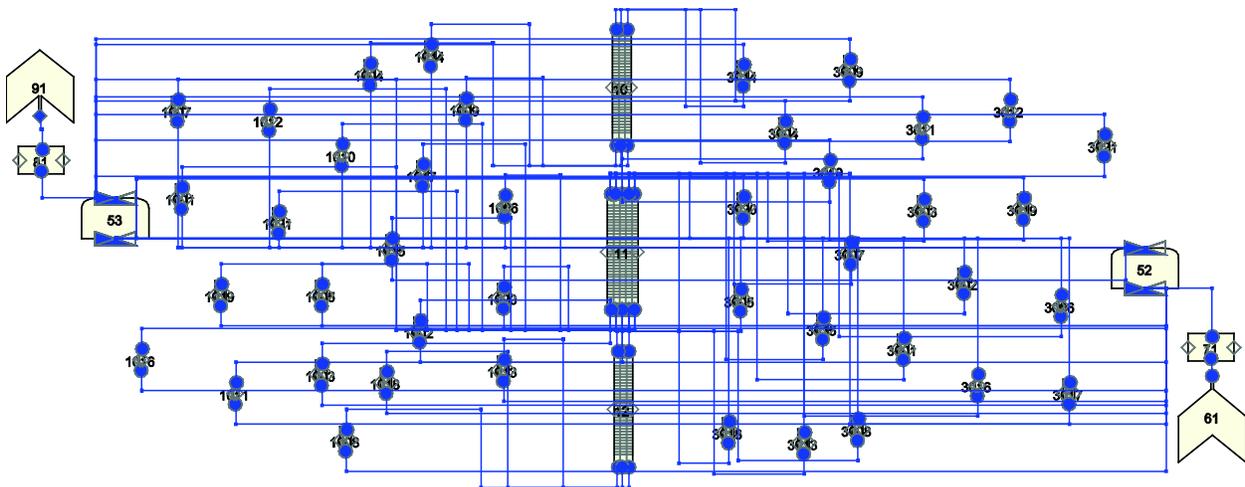


Figure 4 Split Model Sketch, Simplified 5x5 Vessel.

Essentially, the Split model could be explained with the same equations as the Shape model. However, there are multiple cartesian vessels, see Figure 5 as an example, each color is a different vessel. These vessels are connected sideways by means of single junctions, see Figure 4. These are equivalent to pipe components but with no volume, thus only using a face as a connection. One single junction is set for each vessel cell that is next to a different cartesian vessel. Moreover, this is repeated for each axial level. The result is that the number of components and junctions increases drastically, as can be seen in Table 1.

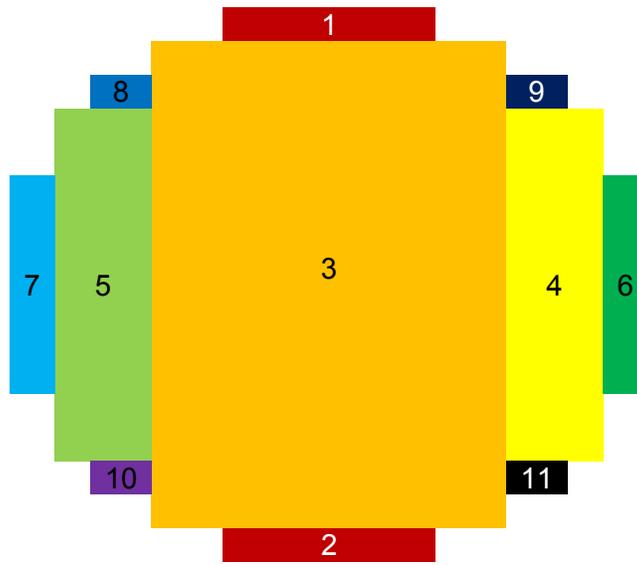


Figure 5 Cartesian Vessel Distribution in the Split Model (Size and Shape).

The axial connections are defined as explained previously for the Shape model. Besides, all single junctions (sideways junctions) are connected to two different cartesian vessels, either in the x -direction ($\pm X$) or the y -direction ($\pm Y$). Single junctions are set horizontally and its length is set to 0.1 m, other properties for x -direction single junctions can be seen in Table 7. Same conclusions can be extrapolated for the y -direction single junctions. Again, three different situations can be found: reflector-reflector, reflector-fuel assembly and fuel assembly-fuel assembly.

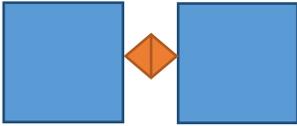
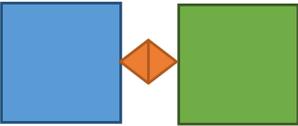
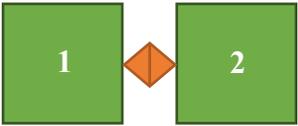
Cells	Property	Value
<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;">Reflector </div> <div style="text-align: center;">Reflector</div> </div>	Flow Area	$x_{cell} \cdot Z \cdot fa_{x,by}$
	Hydraulic Diameter	$x_{cell} \cdot Z \cdot fa_{x,by}$
	Friction Factor	0
<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;">Reflector </div> <div style="text-align: center;">Fuel Assembly</div> </div>	Flow Area	$x_{cell} \cdot Z \cdot fa_{x,by}$
	Hydraulic Diameter	$x_{cell} \cdot Z \cdot fa_{x,by}$
	Friction Factor	$kfac_{x,by}$
<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;">Fuel Assembly </div> <div style="text-align: center;">Fuel Assembly</div> </div>	Flow Area	$x_{cell} \cdot Z$
	Hydraulic Diameter	$x_{cell} \cdot Z$
	Friction Factor	$0.5 \cdot (kfac_{x1} + kfac_{x2})$

Table 7 Single Junction Properties in x-Direction in the Split Model.

The number of total components, Eq. (19), and total junctions, Eq. (20), are similar to that of the Shape model, Table 2 and Table 3. However, the number of vessels, $n_{vessels}$, has been increased and the single junctions, n_{sjunc} , must be added to the count.

$$n_{comp} = 7 + n_{vessels} + 3 \cdot n_{cells} + n_{sjunc} \cdot n_z \quad (19)$$

$$n_{junc} = 4 + 4 \cdot n_{cells} + 2 \cdot n_{sjunc} \cdot n_z \quad (20)$$

Where n_z is the number of axial levels or cells in the z-direction for a given vessel.

2.3 Cylindrical model

Hereafter a list of main features and components used to build the Cylindrical model is provided.

- There is only one cartesian vessel that represents only the fuel assemblies (not the bypass). In the same axial level, each cell corresponds to one fuel assembly, thus, there is not any fuel assembly collapsing.
- One cylindrical vessel with two radial nodes is modeled. The innermost node represents the core bypass and the outermost simulates the downcomer.
- The cylindrical vessel has n_z+2 axial levels, n_z equally distributed as the cartesian vessel plus two additional axial levels representing the upper and lower plenum.
- The cylindrical vessel could be discretized in the theta direction to model different theta sectors.
- To establish the theta connection, a mapping between fuel element and its theta sector is needed.
- One break component is connected to each downcomer theta sector (outer radial node in the cylindrical vessel). The connections are established at a certain axial level, z_{break} . Each break is connected to a different theta sector. Similarly, several fill connections are established at a lower level, z_{fill} .
- One heat structure is coupled with each cell representing a fuel assembly within the cartesian vessel. Besides, one heat structure is associated with each bypass theta sector in the cylindrical vessel.
- The heat transfer between bypass and downcomer (reactor barrel) is modeled through a heat structure -with no fuel rods- coupled to the inner/outer radial cell of the cylindrical vessel.
- One power component heats all heat structures coupled with fuel assemblies and bypass cells. The heat structure simulating the reactor barrel is not heated by the power component. It has convection boundary conditions at both sides.
- It is not possible to connect the fill or break component directly to the cylindrical vessel, thus one-cell big pipes are used between them.
- In order to connect both vessels, single junctions are used in the axial connections. See Table 12 for axial connection information.
- Moreover, both vessels are also connected sideways at all levels, one-cell pipes are used. See Table 13 for radial connection information. Single junctions cannot be used as sideways junctions for the Cylindrical model, see Figure 8.
- There is not any plenum component in the Cylindrical models.

See Figure 6 (left) for an example of a cylindrical vessel discretized into three theta sectors. Figure 6 (right) is an example of the mapping between fuel assemblies and theta sectors.

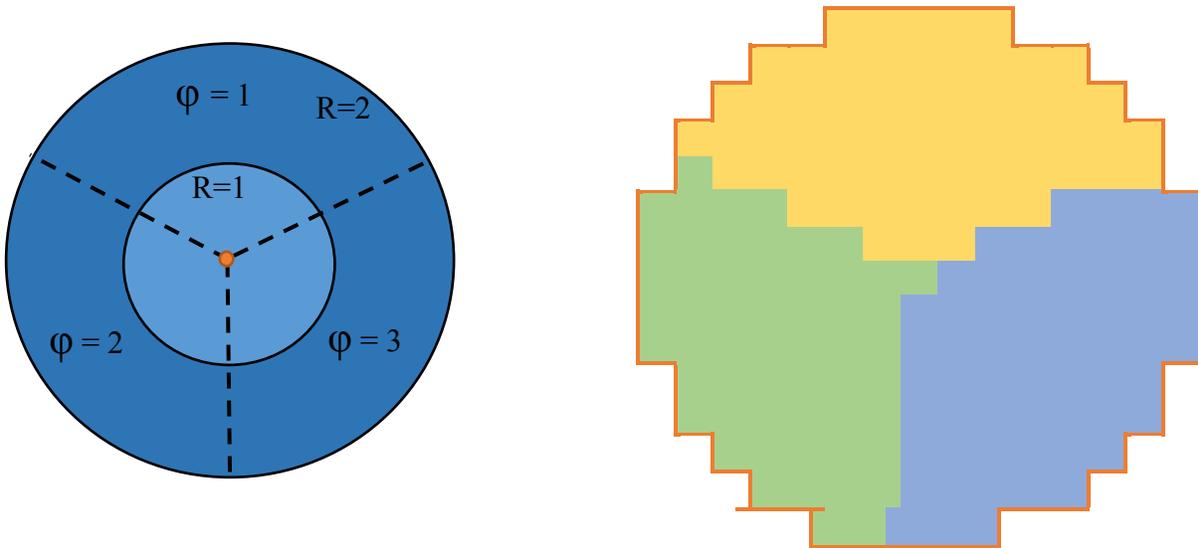


Figure 6 Left: Cylindrical Vessel (Radial Cut) with Three Theta Sectors. Right: Cartesian Vessel with the Fuel Assembly-Theta Sector Association.

See Figure 7 for a simplified Cylindrical model (5x5 vessel without lateral junctions), sketch using SNAP tool [2].

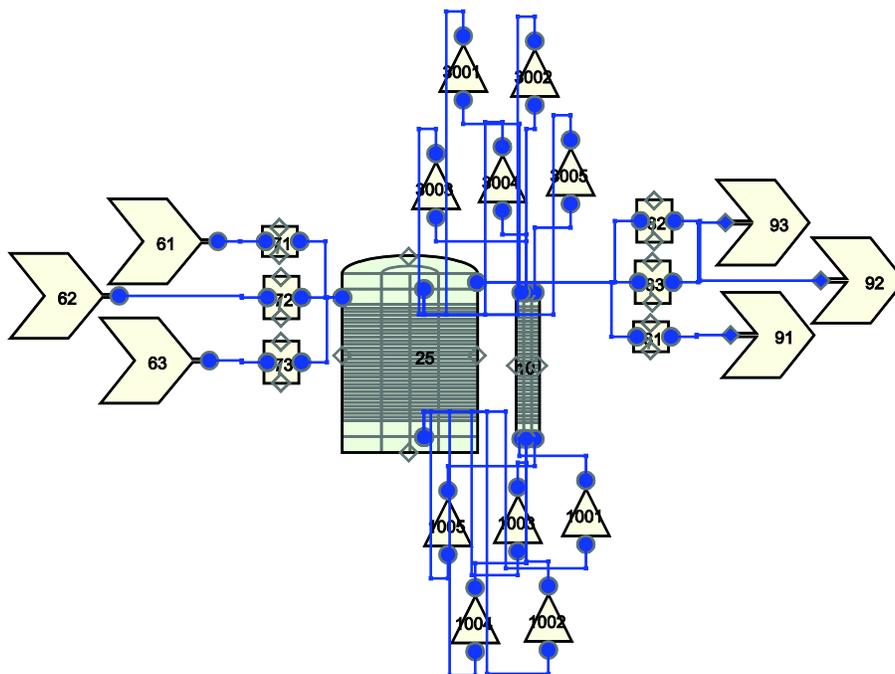


Figure 7 Cylindrical Model Sketch, Simplified 5x5 Vessel.

As it can be seen, there is not any independent component representing the plenums (they are included in the cylindrical vessel) in the Cylindrical model. The inlet and outlet flow area for the cylindrical vessel have different definitions compared to previous models, see Eq. (21) and Eq. (22).

$$A_{in} = Z(z_{fill}) \cdot 2\pi \sqrt{\frac{fa_{dc} + fa_{by}}{\pi}} \quad (21)$$

$$A_{out} = Z(z_{break}) \cdot 2\pi \sqrt{\frac{fa_{dc} + fa_{by}}{\pi}} \quad (22)$$

Where

fa_{dc} is the downcomer flow area,
 fa_{by} is the bypass flow area,
 z_{fill} is the axial level where the fill component is connected,
 z_{break} is the axial level where the break component is connected, and
 $Z(k)$ is the cell height for a given axial level (k).

Since there are several fills and breaks, the flow area for each fill or break component, fa_{fill}^t and fa_{break}^t , is the inlet/outlet flow area times the sector fraction or theta fraction, see Figure 6 (right) and Eq. (24). If n_{chan} is the total number of fuel assemblies and n_{chan}^t is the number of fuel assemblies in each theta sector, the theta fraction, φ_t , is defined as in Eq. (23). Similarly, the flow through each fill, $Flow_{fill}^t$, can be obtained with Eq. (25).

$$\varphi_t = \frac{n_{chan}^t}{n_{chan}} \quad (23)$$

$$\begin{aligned} fa_{fill}^t &= A_{in} \cdot \varphi_t \\ fa_{break}^t &= A_{out} \cdot \varphi_t \end{aligned} \quad (24)$$

$$Flow_{fill}^t = Flow_{tot} \cdot \varphi_t \quad (25)$$

This flow area is applied to the fill/break flow area and its attached one-cell pipe. In contrast to Shape model, the one-cell big pipes are set horizontally and their friction factors are zero. The one-cell big pipes are connected to the cylindrical vessel at inlet and outlet levels (z_{fill} and z_{break}), one to each theta sector and to the outer radial cell (+R).

The heat structures and power component are defined similarly to those of the previous models. Heat structures have zero flux as the center boundary condition. Their outer surface is coupled with the associated hydraulic cell. Including the heat structures associated to each bypass theta sector (innermost radial cell at cylindrical vessel). The characteristics of the fuel rods for each fuel assembly are given by the manufacturer. As in the Shape model, the surface multiplier in each heat structure in a bypass cell must be defined. For the Cylindrical model, it is given by Eq. (26).

$$rdx_{by}^t = \varphi_t \sum_{f=1}^{n_{chan}^t} rdx_f \quad (26)$$

The heat structure modeling the barrel between the downcomer and the core bypass has no power associated. Its thickness is set equal to the barrel thickness and the chosen material is stainless steel 304. All other heat structures are powered by a single power component. The power distribution is defined as in the previous model. However, to calculate the power fraction that reaches the bypass heat structures Eq. (27) is used. This time, n_{cells} variable is defined as Eq. (28).

$$cpowr_{by}^t = \frac{H_{by}}{n_{cells}} \varphi_t n_t \quad (27)$$

$$n_{cells} = n_{chan} + n_t \quad (28)$$

Where H_{by} is the power fraction that heats directly the bypass, and φ_t , is defined in Eq. (23). The number of theta sectors is represented by n_t .

The properties for the cartesian vessel cell face in the x-direction and y-direction can be seen in Table 8 and Table 9. The same properties for the cell face in the z-direction can be seen in Table 10. In comparison to the previous models, now only one situation is possible: fuel assembly–fuel assembly.

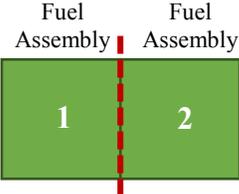
Cells	Property	Value
	Flow Area Fraction (FAFx)	1
	Hydraulic Diameter (HDx)	$Y_{cell} \cdot Z$
	Friction Factor (KFACx)	$0.5 \cdot (kfac_{x1} + kfac_{x2})$

Table 8 Face Cell Properties in x-Direction, Cartesian Vessel in the Cylindrical Model.

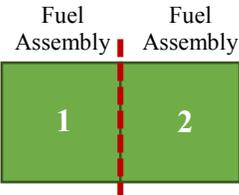
Cells	Property	Value
	Flow Area Fraction (FAFy)	1
	Hydraulic Diameter (HDy)	$X_{cell} \cdot Z$
	Friction Factor (KFACy)	$0.5 \cdot (kfac_{y1} + kfac_{y2})$

Table 9 Face Cell Properties in y-Direction, Cartesian Vessel in the Cylindrical Model.

Cell	Property	Value
Fuel Assembly	Flow Area Fraction (FAFz)	faf _z
	Hydraulic Diameter (HDz)	hd _z
	Friction Factor (KFACz)	kfac _z

Table 10 Face Cell Properties in z-Direction, Cartesian Vessel in the Cylindrical Model.

Regarding the cylindrical vessel, as mentioned, it has two additional axial levels to simulate the lower/upper plenum. The height of these additional levels is the same as the first/last axial levels height in the cartesian vessel. Spatial discretization for the cylindrical vessel, *a*-direction (axial), *r*-direction (radial) and *t*-direction (theta), can be seen in Eq. (29) to Eq. (31).

$$Z_a = [Z(1), Z(1), Z(2), \dots, Z(nz), Z(nz)] \quad (29)$$

$$X_r = \left[\sqrt{\frac{fa_{by}}{\pi}}, \sqrt{\frac{fa_{by} + fa_{dc}}{\pi}} \right] \quad (30)$$

$$Y_t = 360 \frac{n_{chan}^{az}}{n_{chan}^t} \quad (31)$$

Where

fa^{by} is the bypass flow area,
 fa^{dc} is the downcomer flow area,
 $Z(i)$ is the vessel cell height for axial level i , and
 n_{chan}^t is the number of fuel assemblies in the t^{th} theta sector.

Other properties, such as flow area fraction and friction factor, can be seen in Table 11.

Property	Value	
	Bypass (r=1)	Downcomer (r=2)
Flow Area Fraction Radial (FAFr)	see comment below	0
Flow Area Fraction Theta(FAFt)	1	1
Flow Area Fraction Axial (FAFa)	1	see comment below
Volume Fraction (FVOLA)	1	1
Friction Factor Radial (KFACr)	0	0
Friction Factor Theta (KFACT)	0	0
Friction Factor Axial (KFACa)	$kfac_{z,by}$	$kfac_{z,dc}$

Table 11 Cylindrical Vessel Properties.

The flow area fraction in radial direction for the first and last axial levels, Eq. (32), is set to 1. These cells simulate the lower and upper plenum, and thus the fluid must flow from the bypass to the downcomer and vice versa.

$$FAF_r^z = 1 \text{ if } z \text{ is } 1 \text{ or } nz, 0 \text{ otherwise} \quad (32)$$

The flow area fraction in axial direction for the downcomer (outer radial cell in the cylindrical vessel) between the z_{fill} and z_{break} is set to zero. However, the expert analyst could set this value to a specified flow area fraction, $faf_{fill2break}$. Thus, the inlet fluid could flow directly upwards through the downcomer and directly to the outlet without cooling the core, Eq. (33). This behavior is more realistic. Nonetheless, studies have shown that $faf_{fill2break}$ near 10^{-3} leads to convergence and stability problems.

$$FAF_a^z = faf_{fill2break} \text{ if } z_{fill} < z < z_{break}, 1 \text{ otherwise} \quad (33)$$

The hydraulic diameter for both radial cells can be expressed as in Eq. (34) to Eq. (39).

$$HD_a^{r=1} = hd_{by} \quad (34)$$

$$HD_a^{r=2} = hd_{dc} \quad (35)$$

$$HD_r^{r=1} = Z \cdot 2\pi \cdot \varphi_t \sqrt{\frac{fa_{by}}{\pi}} \quad (36)$$

$$HD_r^{r=2} = Z \cdot 2\pi \cdot \varphi_t \sqrt{\frac{fa_{by} + fa_{dc}}{\pi}} \quad (37)$$

$$HD_t^{r=1} = Z \sqrt{\frac{fa_{by}}{\pi}} \quad (38)$$

$$HD_t^{r=2} = Z \sqrt{\frac{fa_{by} + fa_{dc}}{\pi}} \quad (39)$$

In order to connect both vessels, single junctions are used in the axial connections. All single junctions are set vertically. Their friction factors and hydraulic diameters are set equal to the first/last fuel assembly cell associated, as explained for Shape model in Table 6 (fuel assembly situation). The axial connections between both vessels must be set according to Table 12, otherwise the fluid does not flow correctly. To establish the theta connection a mapping between fuel elements and its theta sector is needed, see Figure 6 (right). The mapping for the upper and lower connections could be different. Please bear in mind that the axial level in the cylindrical vessel is referred to a maximum level of n_z+2 (because of the two additional levels, upper and lower plenums).

	Cylindrical vessel		Cartesian vessel	
	Axial level	Direction	Axial level	Direction
Lower plenum	1	+Z	1	-Z
Upper plenum	$n_z + 2$	-Z	n_z	+Z

Table 12 Axial Connections for both Vessels in the Cylindrical Model.

For sideways connections one-cell pipes are used. Single junctions cannot be used as sideways junctions for the Cylindrical model because TRACE does not allow more than one single junction to be connected to the same target cell and the same direction. See Figure 8.

```
*****
**  warning  **
*****
```

```
Connections in the same plane in one vessel are not in the same
plane of the other vessel
```

```
*****
**  warning  **
*****
```

```
vessel 10, junction 3070201 is inconsistent with vessel 10,
junction 1110201
```

Figure 8 Error if Single Junctions are used as Sideways Connections.

Sideways pipes are set horizontally and its length is set to 0.1 m. Connections are set for every axial level and every single cell between the outermost cartesian vessel cells and the inner radial cell in the cylindrical vessel (i.e. between all orange faces in Figure 6 -right- and the center orange point in Figure 6 -left-). Again, the theta connections are determined by the fuel element-theta sector mapping. The lateral connections are summarized in Table 13.

Cylindrical vessel			Cartesian vessel	
Axial level	Radial cell	Direction	Axial level	Direction
2, 3, ... n_z+1	1	-R	1, 2, ... , n_z	$\pm X$ or $\pm Y$

Table 13 Sideways Connections for both Vessels in the Cylindrical Model.

The other properties for the sideways connections are the same as explained in Table 7 (reflector – fuel assembly situation) for the Split model.

The total number of components for the Cylindrical model is detailed in Table 14, and expressed in Eq. (38).

Component	Quantity
Fill	n_t
Break	n_t
Big pipe	$2 \cdot n_t$
Power	1
Cartesian vessel	1
Cylindrical vessel	1
Heat structure bypass	n_t
Heat structure barrel	n_t
Heat structure fuel	n_{chans}
Lower Single Junction	n_{chans}
Upper Single Junction	n_{chans}
One-cell pipes	$2 \cdot n_z \cdot (n_x - 2 + n_y - 2)$

Table 14 Number of Components in the Cylindrical Model.

$$n_{comp} = 1 + n_{vessels} + 6 \cdot n_{sectors} + 3 \cdot n_{chan} + 2 \cdot n_z \cdot (n_x - 2 + n_y - 2) \quad (40)$$

The same can be done with the total number of junctions for Cylindrical model Table 15 and Eq. (41).

Junction from	Junction to	Quantity
Fill	Inlet big pipe	n_t
Inlet big pipe	Cylindrical vessel	n_t
Cylindrical vessel	Outlet big pipe	n_t
Outlet big pipe	Break	n_t
Cylindrical vessel	Lower single junction	n_{chan}
Lower single junction	Cartesian vessel	n_{chan}
Cartesian vessel	Upper single junction	n_{chan}
Upper single junction	Cylindrical vessel	n_{chan}
Cartesian vessel	Sideways one-cell pipe	$2 \cdot n_z \cdot (n_x - 2 + n_y - 2)$
Sideways one-cell pipe	Cylindrical vessel	$2 \cdot n_z \cdot (n_x - 2 + n_y - 2)$

Table 15 Number of Junctions in the Cylindrical Model.

$$n_{junc} = 4[n_{sectors} + n_{chan} + n_z \cdot (n_x - 2 + n_y - 2)] \quad (41)$$

Where n_x and n_y are the number of cells in the cartesian vessel in x and y-directions respectively.

3. BYPASS FLOW ADJUSTMENT

An iterative process to adjust the bypass flow is developed [3]. The process modifies the bypass friction factor until the specified theoretical flow value is reached. In Figure 9 a flow chart for the friction factor iterative process is presented.

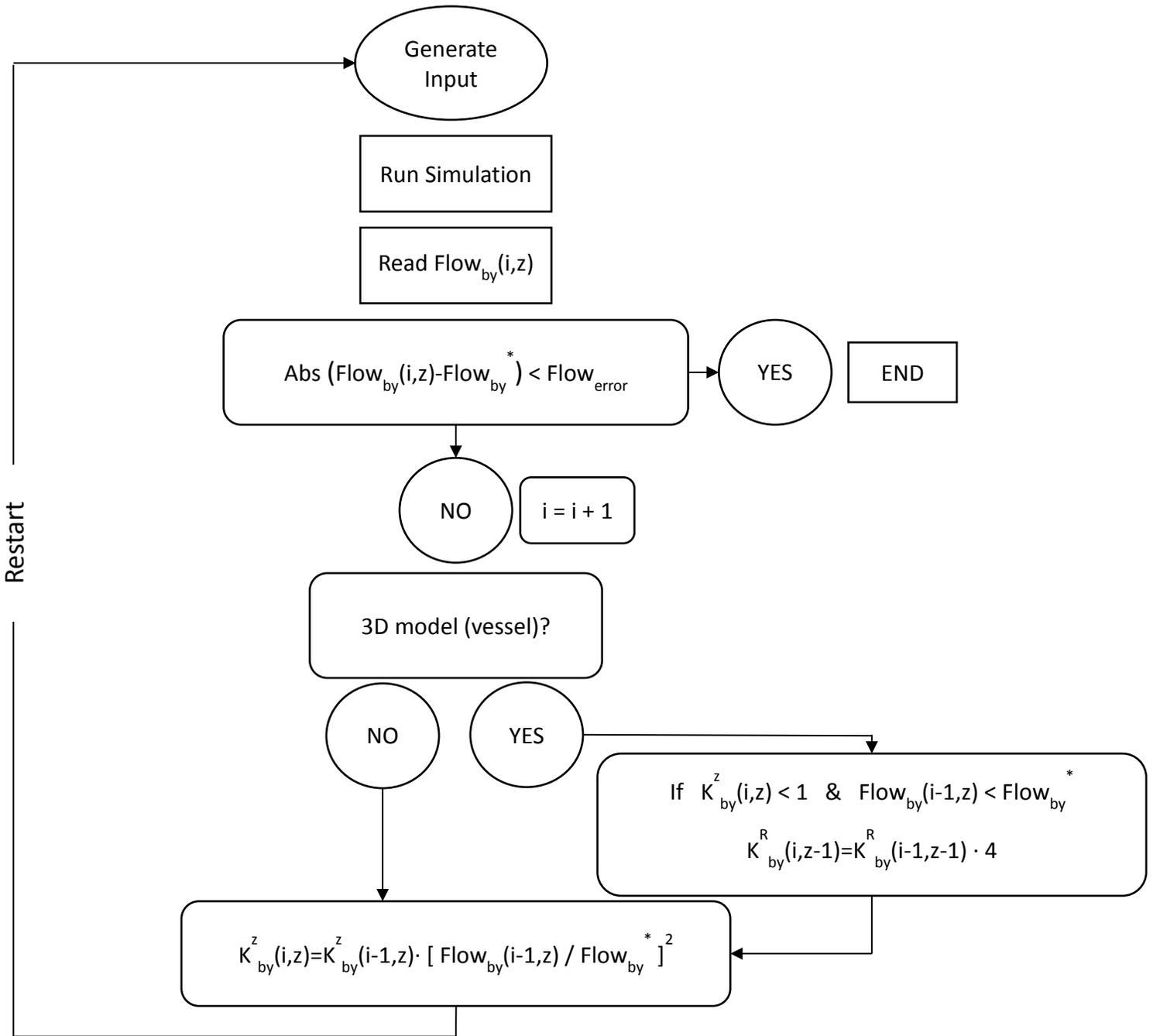


Figure 9 Bypass Friction Factor Adjustment Iteration Process.

Where:

i: iteration count

z: axial node

$Flow_{by}^*$: theoretical bypass flow

$Flow_{by}(i,z)$: simulation bypass flow

$Flow_{error}$: maximum acceptable error

$K_{by}^z(i,z)$: bypass friction factor (axial)

$K_{by}^R(i,z)$: bypass friction factor (radial)

The iteration process starts generating the input deck and running the simulation. The resulting bypass flow, $Flow_{by}$, is read and compared with the theoretical bypass flow, $Flow_{by}^*$. If the difference is small enough (smaller than $Flow_{error}$), the iteration process ends. Otherwise it applies a correction for the axial bypass friction factor, K_{by}^z , for each axial level (1D and 3D models). Only for 3D models, it is also possible to apply a radial bypass friction factor, K_{by}^R , correction for each axial level.

The correction for the axial bypass friction factor is proportional to the square ratio of the last obtained bypass flow and the theoretical flow (for each axial level). However, imagine that a certain bypass friction factor is small (say less than 1) and the resulting bypass flow is less than the theoretical bypass flow. In this case, the desired increase in bypass flow cannot be archived decreasing the friction factor anymore. Thus, the radial bypass friction factor at the immediate inferior level is increased by a factor of four. As a result, less flow will escape the bypass radially in the immediate inferior level and it will flow axially upwards.

The iteration process is carried out until the absolute error is satisfied. The error, $Flow_{error}$, is obtained comparing the bypass flow, for the last iteration step, with the theoretical bypass flow. For each new iteration step, a restart file is created. Thus, a restart is run with the considerable decrease in the simulation time. Once the friction factors are adjusted for the steady state simulation (SSA), the process is repeated for the coupled (with PARCS) steady state simulation (CSS). By default the initial guess for the CSS simulation is the converged value for the SSA. However, if the expert analyzer requests it, a new guess for the CSS simulation could be introduced. Once the CSS simulation is converged, the coupled transient simulation is run (CSS converged friction factors are used). See Figure 10.

Traditional 1D models do not have cross flow, thus the bypass flow is constant with height. Nevertheless, 3D vessel models simulate the cross flow for the whole core. The cross flow exists between reflector area and fuel assemblies, and also among fuel assemblies. Therefore, in 3D models, because of the cross flow, the bypass flow strongly fluctuates along the axial axis. This is especially relevant in the Cylindrical model. Due to its theta sectors, friction factors could vary from one theta sector to another. This process was successfully used to adjust the bypass flow for all three models explained in previous chapters. As an example, in Figure 11, the bypass flow for a Cylindrical model with three theta sectors (dashed lines) is compared with a 1D model (straight lines). The x-axis represents the axial cells (z-direction). The 1D model was built using pipes in RELAP5 code. In this case, a maximum absolute error of 5 kg/s was set.

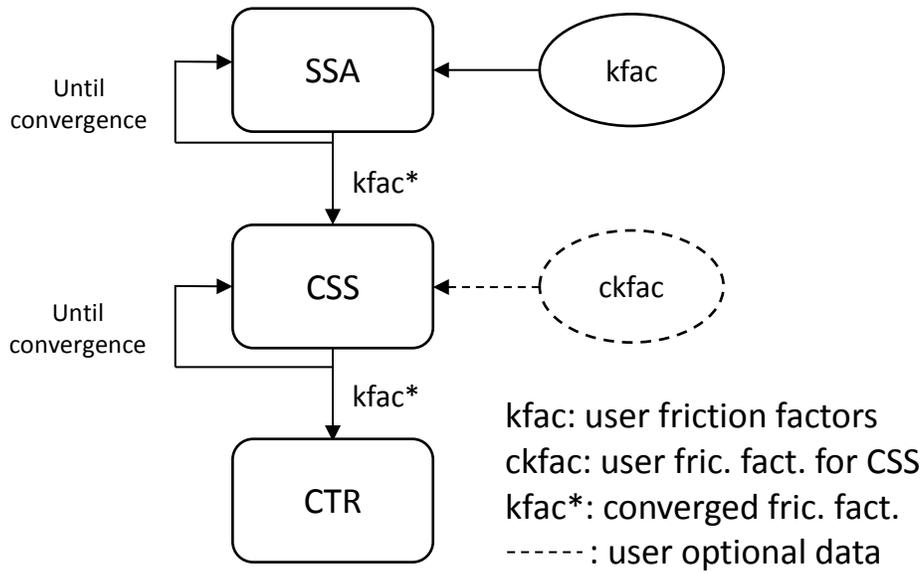


Figure 10 Friction Factor Input Value for Different Simulation States.

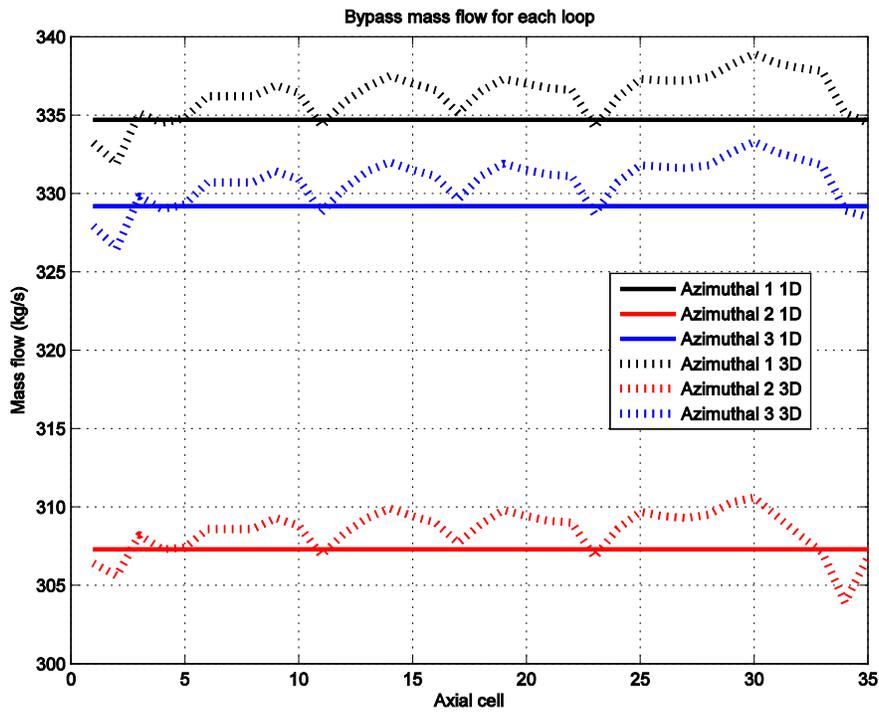


Figure 11 Cylindrical Model with Three Theta Sectors, Bypass Flow in z-Direction.

4. MODEL-TO-MODEL COMPARISON

In order to compare the 3D models, a traditional 1D model was created in TRACE. It has one pipe per fuel assembly (no collapsed model) and its heat structure associated. The bypass is modeled using a bigger pipe, also with a heat structure component. All pipes are connected to an upper and lower plenum. The boundary conditions in the fill and break components are the same as in the 3D models. See Figure 7 for a simplified traditional model (collapsed), sketch using SNAP tool [2].

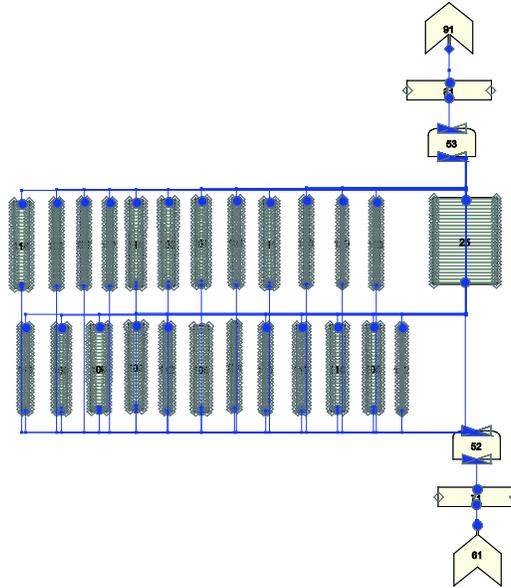


Figure 12 Traditional Collapsed Model Sketch.

In Table 16 the summary for the compared variables is presented.

Variable distribution	Figure
Moderator density	13
Mass flow	14
Moderator temperature	15
Fuel center temperature	16
Fuel surface temperature	17
Bypass mass flow (z-direction)	18
TRACE-PARCS power	19

Table 16 Comparison Plot Summary.

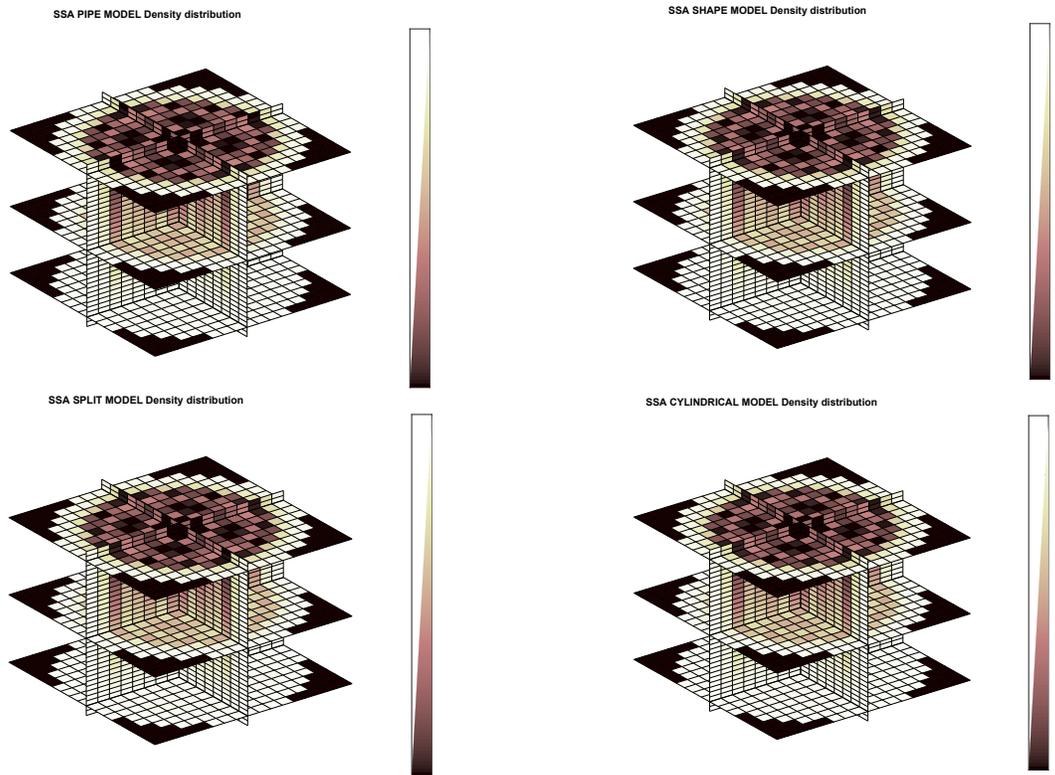


Figure 13 Moderator Density 3D Distribution.

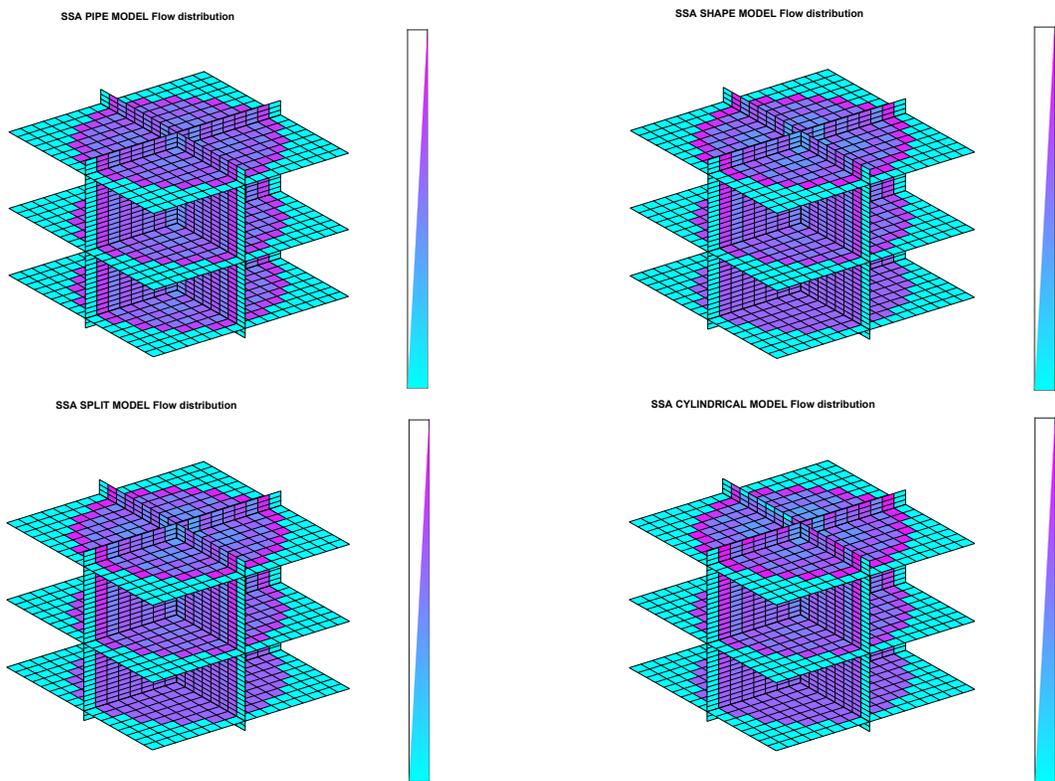


Figure 14 Mass Flow 3D Distribution.

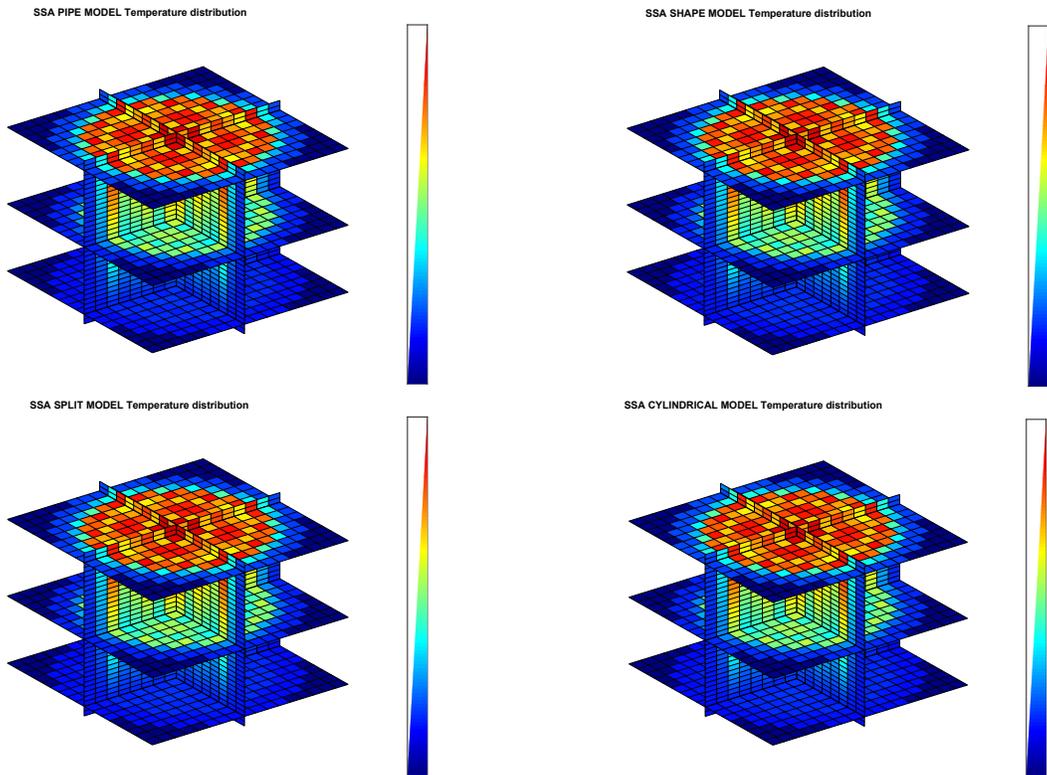


Figure 15 Moderator Temperature 3D Distribution.

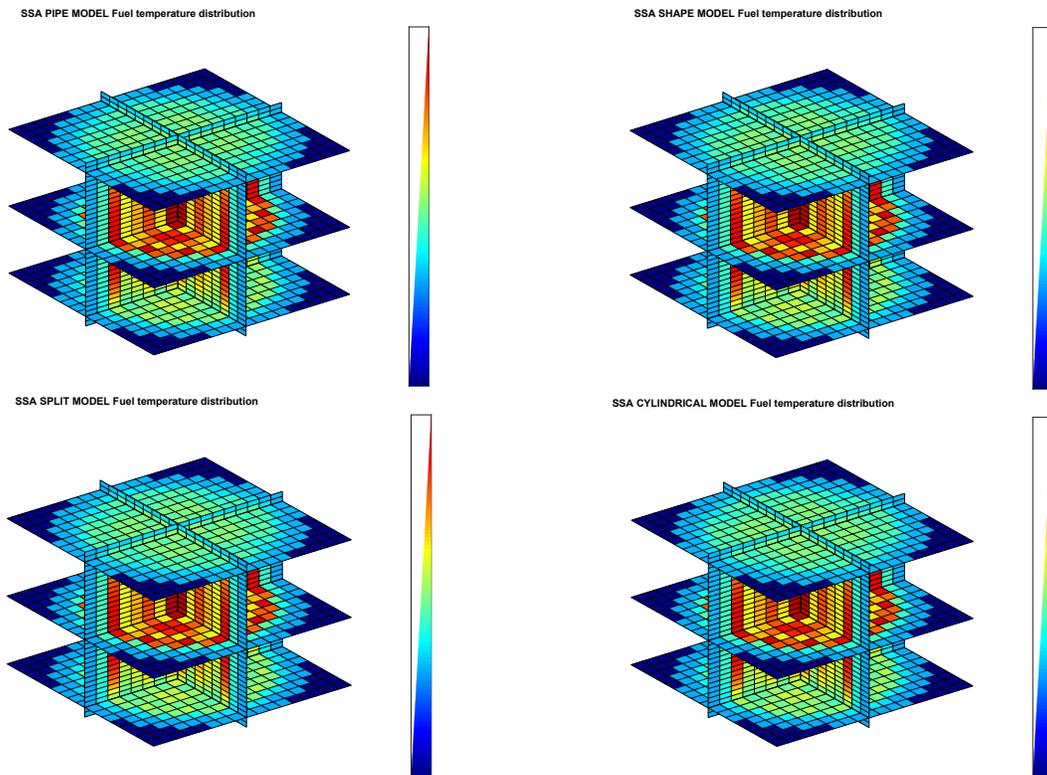


Figure 16 Fuel Center Temperature 3D Distribution.

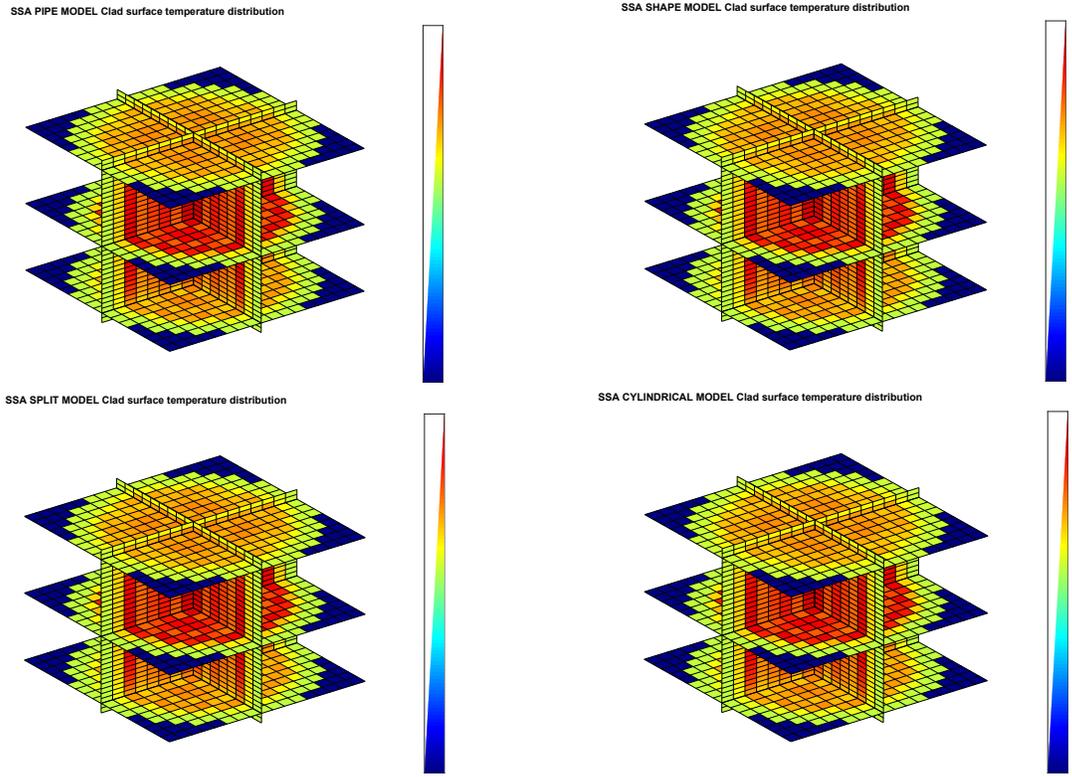


Figure 17 Fuel Surface Temperature 3D Distribution.

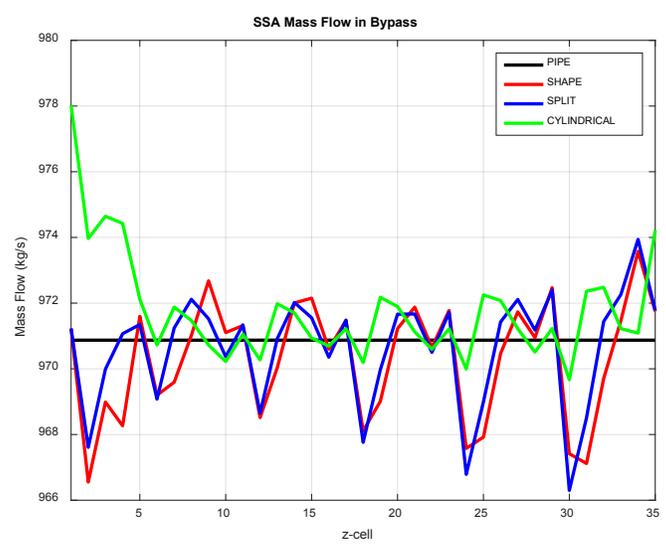


Figure 18 Bypass Mass Flow as a Function of the Axial Cell or z-Direction.

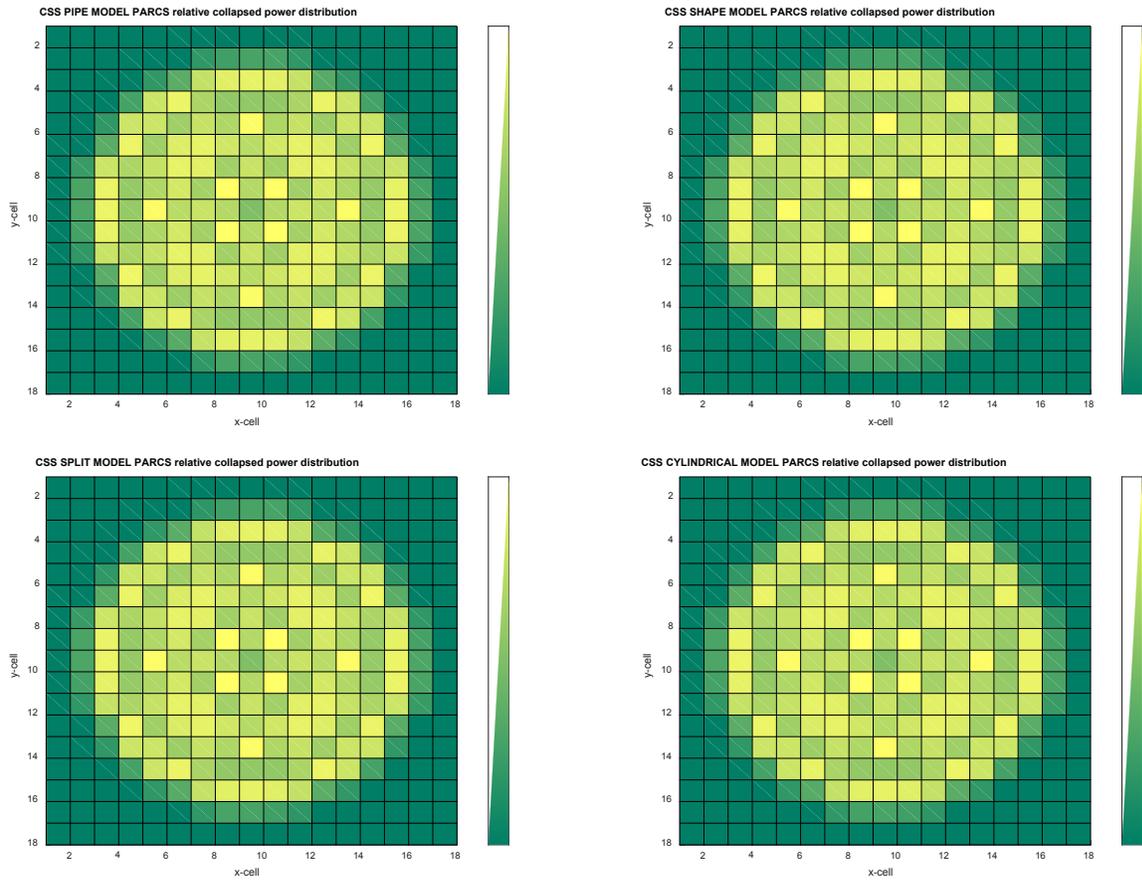


Figure 19 TRACE-PARCS Coupled Simulation Steady State Power 2D Distribution.

5. CONCLUSIONS

System codes take the advantage of 1D component simulations to speed up the calculation time. Nevertheless, due to the improving computational hardware, more and more complicated models are computational affordable.

In this study, three different 3D models to simulate the reactor core are presented. This is an interesting work, mainly due to the scarce literature available regarding this issue. The first presented model is the Shape model, with only one cartesian vessel. The second model or Split model, with several cartesian vessels joined sideways. Finally, the third model is the Cylindrical model with a cartesian vessel and a cylindrical vessel with two radial cells, the bypass and downcomer. Moreover, an iterative process is designed to adjust the bypass flow for all models. This iterative process modifies the bypass friction factors (axially and radially) until the desired bypass flow is archived. It is proved to be very helpful.

All three models are seen to be in perfect agreement against a traditional 1D model. All 3D models were built to resemble the counterpart 1D model. In this document the particularities regarding each model and problems encountered during its definition or simulation are explained in detail. The work done is expected to broaden the scarce related literature and, to serve as a basis for new 3D model developments and implementations.

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10. SUPPLEMENTARY NOTES

K.Tien, NRC Project Manager

11. ABSTRACT (200 words or less)

Three new fully 3D models for TRACE code are presented in this document. They model the reactor core using 3D vessel components. Therefore, they could be used to simulate asymmetrical phenomena in the core regardless of the phenomenon triggering the code (thermal-hydraulic or neutronic). First, the Shape model, is presented. It uses only one cartesian vessel with null flow area fraction on corner cells. Thus, the resulting shape resembles the radial mapping. The bypass is modeled using outermost cells and its flow area fraction is modified accordingly, see Figure 2. The second model is named Split model. This model, similar to Shape model, makes use of several cartesian vessels. These vessels are joined sideward to resemble the radial mapping, see Figure 4. Finally, the third model uses one cartesian vessel similar to that of the Shape model but without bypass. Besides, a cylindrical vessel is coupled to the cartesian vessel, see Figure 7. The cylindrical vessel has two radial cells. The innermost represents the bypass and the outermost cell represents the downcomer. The cylindrical vessel is also discretized into three different azimuthal sectors. One cold and hot leg is attached to each azimuthal sector, see Figure 6. Due to the 3D cross flow represented in these models, the bypass flow strongly fluctuates along the axial axis (z-direction). An iterative method is developed for an automatic adjustment of the bypass flow, Figure 9 and Figure 11. Finally a model-to-model comparison is made in section 4. Several thermal-hydraulic variables are compared with a traditional 1D model. The 1D model is also TRACE based. See from Figure 13 to Figure 19. As a recommendation, when 3D feature is desired to model the core in TRACE, the Cylindrical model is advisable. This is the result of a trade of considering computational effort, realistic behavior and the number of components used, as it is shown in Table 1.

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