# Development of the New Pin-by-Pin Core Calculation Method with Embedded Heterogeneous Assembly Calculation

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## Abstract

In this paper, the next generation method (NGM), which is being developed in Mitsubishi Heavy Industries, Ltd., is proposed. Our NGM is based on "On-flight" calculations with 2D cell-heterogeneous transport calculation for generating cell average constants and 3D cell-homogenous pin-by-pin core calculations. A new MOC module, GALAXY, with energy and space dependent boundary condition is being developed as a 2D cell-heterogeneous flux solver. To verify our NGM, whole system calculation was performed against 2D-C5G7 MOX benchmark problem. The result was compared with whole core cell-heterogeneous calculation results. Those results are in good agreement. We confirmed that this method is very effective and useful for parallel computing because heterogeneous calculation of each assembly can be independently performed.

***KEYWORDS: NGM, GALAXY, Method of characteristics, Sn, Boundary condition, SPH, On-flight method, C5G7MOX benchmark problem***

## 1. Introduction

Mitsubishi Heavy Industries, Ltd. (MHI) has been developing a code based on the next generation method (NGM). The NGM is defined as a nuclear core calculation method which can directly perform 3D pin-by-pin calculation. Our NGM code intends to a pin-by-pin 3D transport calculation with heterogeneous cell modeling.

Although the transport code employing heterogeneous cell modeling has already utilized in the current design system, it is limited to 2D assembly calculation for generating few-group assembly average constants to be used in 3D advanced nodal diffusion code. In such 2D assembly calculation codes, the method of characteristics (MOC) and the current coupling collision probability (CCCP) method are popular. The straightforward way to achieve out goal is to expand such 2D code to the 3D model. However, it is doubtful to perform MOC or CCCP calculations with the whole 3D calculation because of the

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limitation of computational resources, e.g. memory storage and computation speed. Therefore, some codes employ the "synthesis method", i.e., 2D whole core calculation coupled with the 1D axial calculation. CHAPLET-3D [1, 2] and DeCART[3] employ such a coupling method to perform heterogeneous 3D whole core calculation.

In the current design calculation, 3D nodal diffusion code is used as mentioned above. Improvement of the 3D nodal diffusion code is another way to achieve the NGM code except for cell heterogeneity representation. It will result in a pin-by-pin calculation based on transport theory with cell homogenization. SCOPE2 [4] developed by NFI is this type of code.

MHI is trying to develop alternative approach rather than those of the codes mentioned above. Our NGM is based on "On-flight" calculations with 2D cell-heterogeneous transport calculation for generating cell average constants and 3D cell-homogenous pin-by-pin core calculations.

## 2. Proposed Next Generation Method

MHI's NGM realizes the whole core pin-by-pin calculation by coupling with the current well-established methods using the appropriate interface. The current 2D assembly transport calculation is still used in NGM. However, the 3D nodal diffusion code is to be replaced by a 3D transport code with pin-by-pin heterogeneity. In our NGM, the 2D assembly calculation is performed by taking into account the boundary conditions obtained from the 3D pin-by-pin core calculation. By adopting the present approach, the 2D assembly calculation can consider "environment" of the lattice in the 3D core calculation. Those modules work "on-flight." In other words, 2D assembly calculation is embedded in 3D core calculation. The procedure will require iteration, but the number of iteration will not be large because the 3D core calculation has some corrections in itself employed in the current 3D nodal code. Of course, moderator density correction, depletion calculation, Doppler calculation and so on will be finally considered again in the 2D assembly calculation.

To develop our NGM, a MOC module, a SPH homogenization [5, 6] module, a Sn-nodal module and a boundary-condition transfer module are necessary. Currently, Sn-nodal module is under development. TWOTRAN-II [7] code is used for the verification and validation in the present study. The albedo is used as the boundary condition because of it applicability to the NGM.

### 2.1 MOC Module

Published MOC codes do not have a capability to use energy and space dependent albedo as input. In our 2D assembly calculation, energy dependent and cell-wise albedo is needed. Therefore, the new MOC code named GALAXY is developed. GALAXY (**G**eometrically **A**rbitrary **L**attice Physics and **A**ssembly calculation code in **X-Y** coordinate system) is based on the assembly-wise or multi-assembly-wise cyclic ray-trace method[8], which can directly represent the complicated geometries such as assembly gaps and irregular rod arrangement. The complicated geometries can be handled by combinatorial geometry method which is widely used for the Monte Carlo method. In GALAXY, "R-function Solid Modeler" technique [9] is used for definition and numbering the material and flat source regions. GALAXY is written in FORTRAN90.

### 2.2 SPH Module

SPH correction method has been established under the reflective boundary condition. Our NGM also employs the SPH correction to reduce the homogenization error. Another objective to use SPH is to incorporate a flexible geometry capability into the 3D pin-by-pin code. GALAXY can treat irregular rod array even if a rod is located across the cell boundary. In such case, pin-by-pin 3D cell-homogeneous calculation is questionable. To confirm the applicability of SPH in such case, mini-core calculation is performed. The result will be shown in the next section. The most important thing to do with SPH is if SPH works in case of an assembly with leakage at boundary. SPH is defined as neutron flux ratio between homogeneous and heterogeneous cell. With leakage at the surface, the definition may not be correct. Therefore, SPH with leakage model was established in our NGM.

### 2.3 Core Calculation Module

TECHXY-3D [10] code developed by Osaka University will be implemented to our NGM code. Modification of TECHXY-3D for the interface to GALAXY through boundary feedback module is under development. In this paper, TWOTRAN-II is used to validate our NGM as core calculation module.

### 2.4 Interface module between 2D and 3D calculations

Angular neutron flux, neutron current and albedo [11, 12] are considered as candidates of the interface parameters between 2D and 3D calculations. In this paper, albedo is selected because it is easy incorporated in the current lattice and core calculation codes. The others will be confirmed in near future if albedo gives efficient results.

The ratio of in-current to out-current obtained with TWOTRAN-II is used as albedo. It is assumed that all neutrons at a cell in GALAXY are reflected with the albedo that is generated at the cell in TWOTRAN-II calculation. For instance, the dependency of angular direction is neglected in this study.

## 3. Validation Test

### 3.1 GALAXY

To validate GALAXY module, 2D-C5G7 benchmark problem [13] were analyzed. The calculation geometry is shown in Figure 1. The result was compared with MCNP [14] results using 300 million history [13]. The comparison of k-effective and pin-wise fission rate distribution is shown in Table 1 and Fig, 2. It can be seen that GALAXY results agree very well with MCNP results. These results indicate that GALAXY has enough accuracy in the treatment of high heterogeneity.

Figure 1. Geometry of 2D-C5G7MOX benchmark. This mini core consists of 17x17 UO2, 17x17 MOX assemblies and reflectors. 7 group heterogeneous cross-sections used in this benchmark is shown in Reference 14.

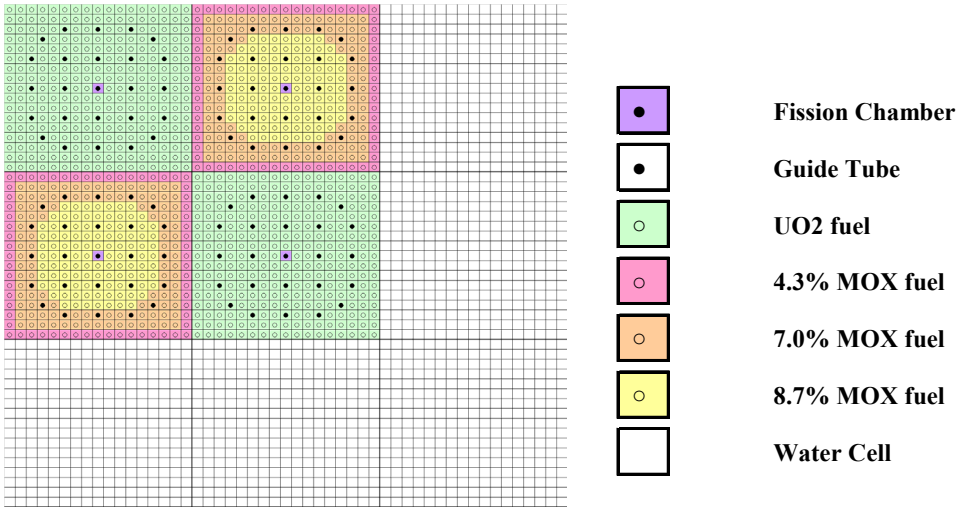
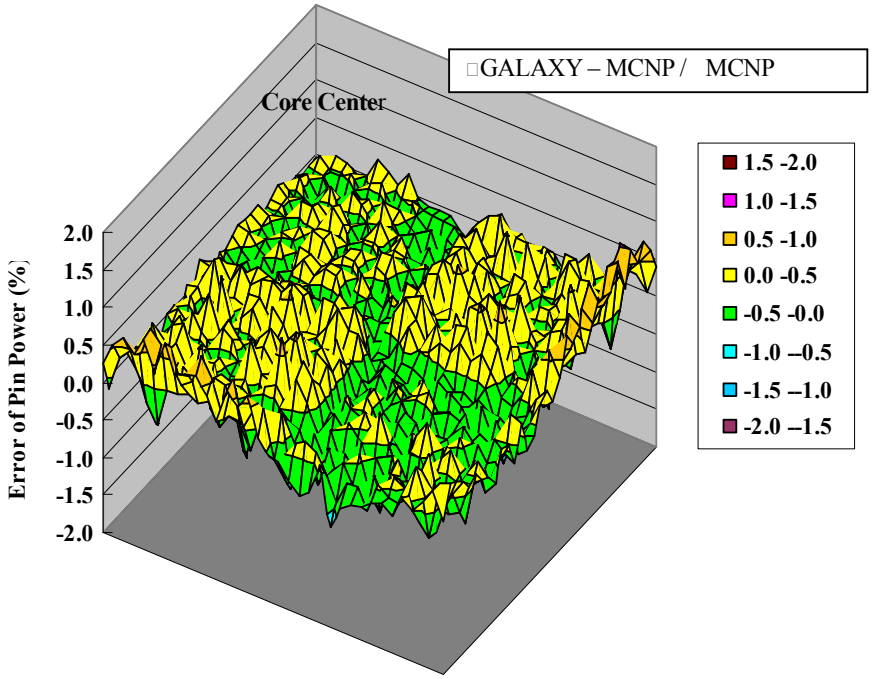



Table 1.Calculation results of 2-D C5G7 MOX benchmark problem. The reference results with MCNP were published.

| Code Name | K-eff | Error(pcm) | Max. Pin power | Error(%) | Min. Pin power | Error(%) | Max. error(%) | RMS Error(%) |
|---|---|---|---|---|---|---|---|---|
| **Reference MCNP** | 1.186550 | +/- 8 | 2.498 | +/-0.16 | 0.232 | +/-0.58 | ----- | 0.34 |
| **GALAXY** | 1.186574 | 2 | 2.495 | -0.09 | 0.232 | 0.40 | 1.04 | 0.28 |

Figure2. Difference of pin power distribution between GALAXY and MCNP in UO2 and MOX assemblies of 2D-C5G7 MOX benchmark. The MCNP results were published.




3.2 Validation of homogenization error correction with SPH method

To validate SPH correction on the complex geometry where a rod located across the adjacent cell boundary, cell homogeneous Sn calculation with SPH was compared with cell heterogeneous MOC calculation. In the MOC calculation, 2X3 rod array which consist of several types of fuel rod is used to get 2X2 homogeneous cell constants as illustrated in Fig.3. The cell-averaged production rate distribution of 2X2 homogeneous calculation was compared with the MOC results. In the comparison, 2X3 MOC cell-averaged production rate are distributed with micro-region volume to match with 2X3 cell. k-effective is also compared between MOC and Sn. It is found that SPH correction works well even if the very complex homogenization is performed.

Figure3. Heterogeneous 2x3 rod array and homogenized 2x2 cell. Heterogeneous 2x3 cell is homogenized to get 2x2 homogeneous cell constant.

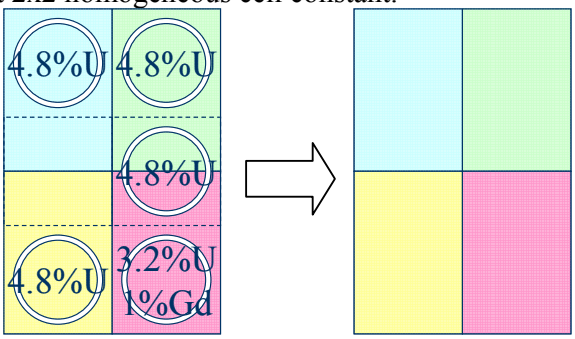


Table2. Comparison of cell homogeneous calculation between with SPH and without SPH.

| Reference MOC with hetero-XS k=1.00941 | | |
|---|---|---|
| **Sn with homo-XS** | **with SPH** | **without SPH** |
| **Reactivity difference** | **0pcm** | **942pcm** |
| **Max. difference of cell-averaged production rate** | **0.00%** | **-3.10%** |

3.3 Boundary Condition

In our NGM, the assembly calculation with albedo boundary should be consistent with that of the assembly located in 3D core calculation. For boundary condition validation in 2D model, a mini core which consists of UO2 assemblies and rodded UO2 assemblies is shown in Fig. 4. In this mini core, the k-effective of heterogeneous assembly calculation with albedo boundary condition can approximately capture the k- effective of mini core as shown in Table 3. It is found that the spectrum used in the assembly calculation can be approximately consistent with that of 3D core calculation.

The boundary condition validation in 3D model will be confirmed in near future.

Figure 4. 2D mini core geometry which consists of 17x17UO2 and rodded 17x17UO2 assembly. The heterogeneous cross-sections of C5G7 MOX benchmark are used.

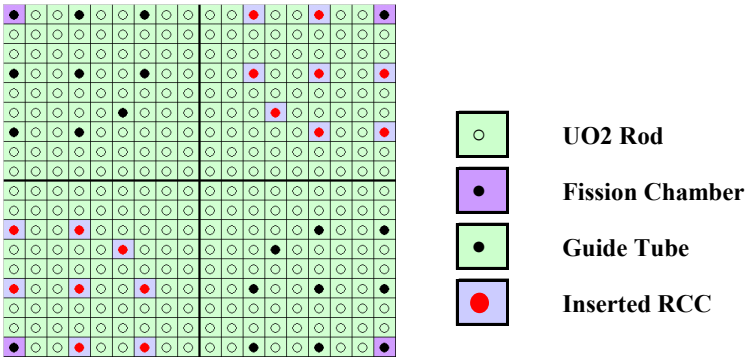



Table 3. Comparison of k-effevtive among mini core calculation, assembly calculation with reflective boundary and assembly calculation with albedo boundary

| **2D Mini Core** | 1.1598 | |
|---|---|---|
| Boundary Condition | Reflective | Albedo |
| **UO2 assembly** | 1.3338 | 1.1585 |
| **Rodded UO2 assembly** | 0.9572 | 1.1610 |

## 4. Verification Test

To verify our NGM, whole system calculation is performed against 2D-C5G7 MOX benchmark calculation. 7-group heterogeneous cross-sections of C5G7MOX benchmark are used. In this paper, TWOTRAN-II is used as core calculation module. Therefore, 2D benchmark is selected. TWOTRAN-II calculation is performed in the condition of 7-group, S8 and 3X3 mesh division in a cell, without energy-group collapsing. The reference result is obtained by the whole core cell-heterogeneous calculation with

GALAXY as already shown in Section 3.1. In the on-flight method, 2D-C5G7MOX mini core is separated into 4 sub-domains, which are singleUO2 assembly located in the core center, two MOX assemblies with adjacent reflector and UO2 assembly with reflector. In each sub-domain, the heterogeneous calculation with albedo boundary condition is performed and the SPH factor is recalculated. SPH factor of the reflectors is fixed to unity. On the other hand, the conventional pin-by-pin method uses the once through cross section and the SPH factor which are generated by single assembly model with reflective boundary condition. We call this conventional method as "once thru". In both the once thru and the on-flight methods, each assembly or sub-domain calculation is executed on independent CPU.

Table 4 shows the comparison of k-effective, cell production rate distribution, total running time including initial cell constants generation and required maximum memory per CPU between the once thru method and the on-flight method. The difference of k-effective is small. The maximum difference of cell production rate with the once thru method is about 2.30%. That with the on-flight method was reduced to -1.07%. It is also found that the root mean square of the differences was reduced form 0.75% to 0.44%. In this case, two on-flight iterations are enough after initial calculation with once through cross section. In comparison with the whole core heterogeneous calculation, total running time and maximum memory of the on-flight method is reduced to about 0.4 because heterogeneous calculation of each assembly is independently performed. Form the view point of total running time and maximum memory per CPU, it can be seen that the once thru method is better than on-flight in this mini core, this time increase is caused by the assembly calculation. However, in the 3D commercial core calculation, 3D Sn core calculation time will be much larger than the assembly calculations, therefore, the time difference described in Table 4 will be negligible. We guess that the total calculation time of on-flight will be comparable to the once thru calculation time. In the on-flight method, it is guessed that no more complicated pre-tabulation cross-sections are needed. The whole core calculation which has consistency with the heterogeneous calculation can be performed with more reduced memory, in comparison with direct whole cell heterogeneous calculation.

Figure 5 and 6 show the difference of the cell production rate distribution from the reference result for the once thru method and the on-flight method, respectively. In both the once thru and on-flight method, the cell production rate distribution in the inner core region agrees with the reference results well in this case. In particular, it is found that the on-flight method reduced the difference in core peripheral cells.

We confirmed that our NGM method can work well.

Table 4. Comparison of k-effective, cell-wise production rate distribution, total CPU time and required maximum memory per CPU among the reference, the once thru and the on-flight. The reference case is the heterogeneous core calculation with GALAXY as shown in Section3.1.

| Code Name | Difference of k-eff | Cell production rate | | Total running time (Arbitrary Unit) | Max. Memory /CPU (Arbitrary Unit) |
|---|---|---|---|---|---|
| | | Max. percent error(%) | RMS Error(%) | | |
| Reference GALAXY | --- | --- | --- | 1 | 1 |
| Once thru method | +44pcm | 2.30 | 0.75 | 0.06 | 0.13 |
| On-Flight method | +49pcm | -1.07 | 0.44 | 0.42 | 0.41 |

Figure 6. Difference of cell-wise production rate between the conventional method and the reference in UO2 and MOX assemblies of 2D-C5G7 MOX benchmark

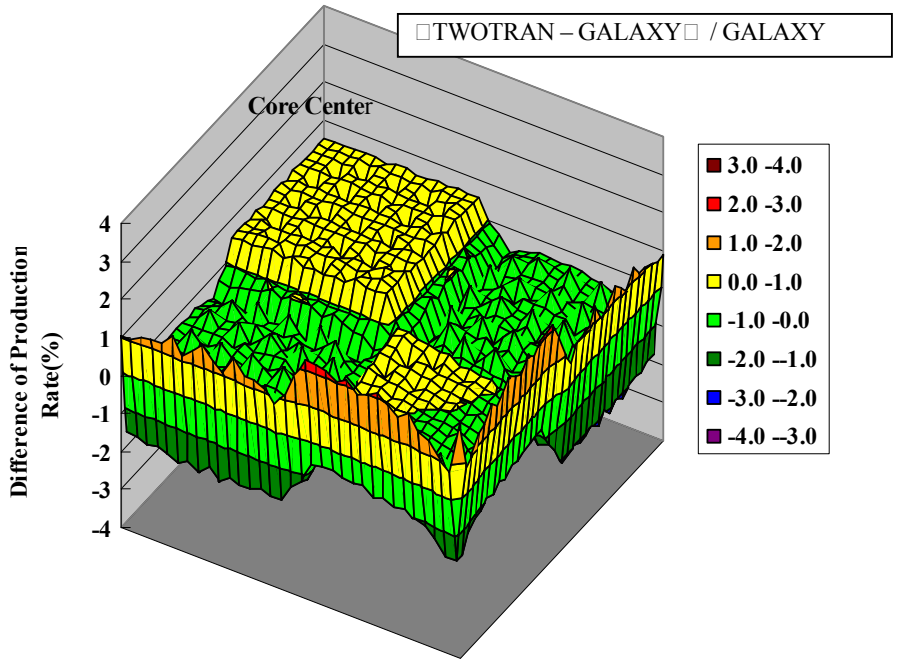
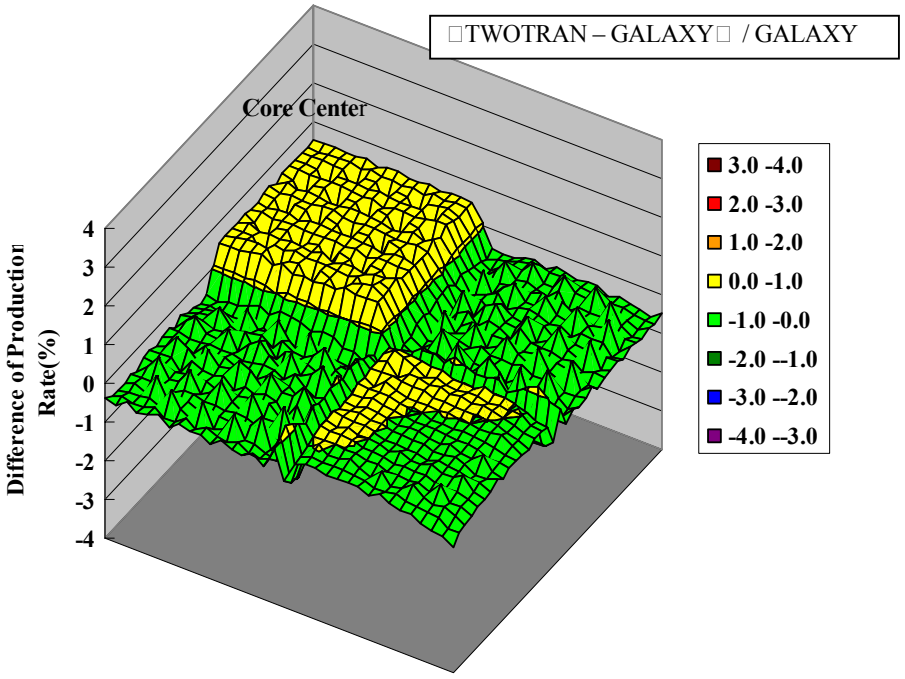



Figure 7. Difference of cell-wise production rate between the on-flight method and the reference in UO2 and MOX assemblies of 2D-C5G7 MOX benchmark



## 5. Conclusion

The alternative next generation core calculation method (NGM), which is different from the 2D whole core heterogeneous calculation with 1D axial calculation or the cell homogeneous pin-by-pin 3D calculation, is proposed. The new NGM will consist of the cross-section, the 2D heterogeneous assembly calculation with boundary condition and the 3D pin-by-pin core calculation modules. Those modules work "on-flight." In other words, the 2D assembly calculation is embedded in the 3D core calculation. The cell average constants used in the 3D calculation is generated "on-flight" by 2D assembly calculation with boundary conditions obtained by the 3D calculation.

This time being, the 2D module, the homogenization module and the feedback module of boundary condition from 3D to 2D have been developed. Although the 3D core calculation and the cross-section modules are under development, our NGM was validated and verified by using TWOTRAN-II and the macroscopic cross section of C5G7 instead of those modules.

Our NGM was applied to the 2D-C5G7 benchmark problem. The result was compared with whole core cell-heterogeneous calculation results by GALAXY as well as MCNP. Those results are in good agreement.

We confirmed that this method is very effective and useful for parallel computing and memory reduction because heterogeneous calculation of each assembly can be independently performed.

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