Development of GeoNEX: A Bidirectional CAD Geometry Interface for Reactor Physics and Multiphysics Applications

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1. Introduction

Monte Carlo particle transport codes are widely used for reactor physics, criticality, shielding, and radiation transport analyses. Their geometries are generally described using constructive solid geometry (CSG), where analytical surfaces and Boolean operations define material regions. Although efficient for particle tracking, CSG does not directly provide the boundary representation (B-Rep) commonly used in computer-aided design (CAD), computational fluid dynamics (CFD), and structural analysis. STEP is a neutral CAD data exchange format that enables B-Rep geometry transfer between different CAD and CAE software.

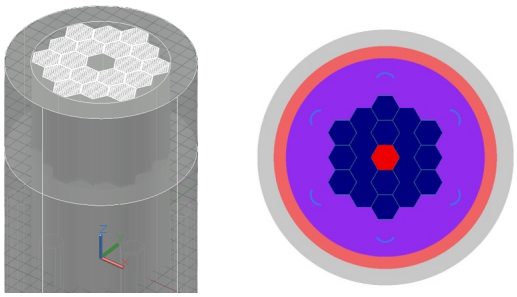


Fig. 1. SMR core model: AutoCAD(left) and SCALE6.3(right) conversion using GeoNEX

This difference becomes particularly important during iterative reactor core design. When reactor geometry is modified, separate models may need to be reconstructed for reactor physics and thermal-hydraulics analyses, increasing preprocessing effort and potentially introducing inconsistencies between physics domains. Therefore, a consistent geometry interface between CSG and B-Rep-based environments is needed for efficient reactor design and Multiphysics analysis.

Several CAD–Monte Carlo geometry conversion tools, including McCAD, SuperMC, and GEOUNED, have been developed primarily by research groups outside Korea [1,4]. Although some of these tools are open-source, others or their associated workflows may rely on commercial CAD platforms and licensed software, which can limit accessibility and practical adoption [2,3,4]. In addition, domestically developed tools dedicated to reactor-specific CAD–Reactor physics using geometry conversion remain limited. Therefore, there is a need for an accessible geometry interface that can support reactor-specific hierarchical and repeated structures, such as lattices, universes, units, and arrays, while enabling consistent geometry exchange between Monte Carlo and CAD environments.

In this study, GeoNEX (Geometry-Neutral Engineering eXchange Framework), a Python-based bidirectional CAD geometry interface for reactor physics and Multiphysics analysis, was developed to convert MCNP and SCALE CSG geometries into CAD/STEP B-Rep models while preserving geometric hierarchy and material information. In the reverse direction, newly designed or modified CAD/STEP geometries can be reconstructed as CSG models for subsequent neutronics analysis, while the STEP format enables the converted geometry to be reused in general-purpose CAD and CAE software for thermal-hydraulic, structural, and other engineering analyses.

2. Development of GeoNEX

2.1 Overall Architecture and Workflow

GeoNEX was developed as a Python-based interface for bidirectional geometry conversion and Multiphysics data transfer. First, CSG geometries used in neutronics codes, such as MCNP and SCALE, are converted into B-Rep-based CAD/STEP models that can be used for computational fluid dynamics and structural analyses. Second, newly designed or modified CAD/STEP models are converted back into CSG geometries for subsequent neutronics calculations.

In the forward workflow, MCNP or SCALE input files are processed to generate individual CAD solids or an integrated assembly STEP model. In the reverse workflow, the geometric information extracted from STEP solids is reconstructed as analytical surfaces and Boolean cell definitions for neutronics input generation. During both processes, GeoNEX interface maintains correspondence among neutronics cells, CAD solids, and material regions.

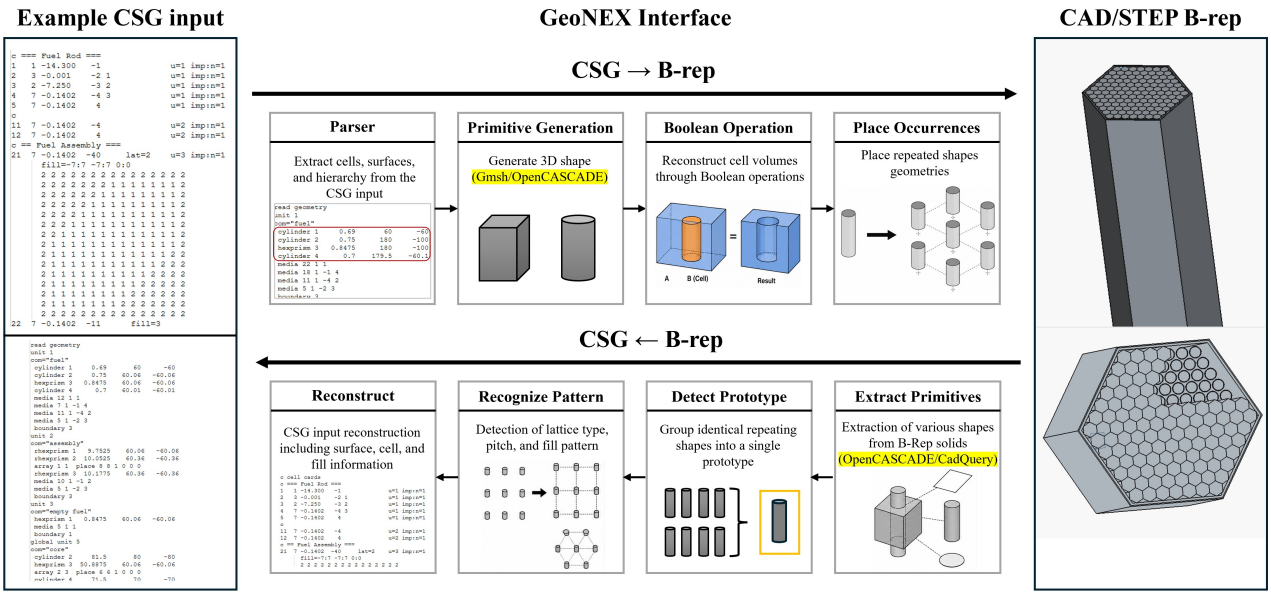


Fig. 2. CSG-B-Rep geometry conversion workflow

2.2 CSG-B-Rep Geometry Conversion

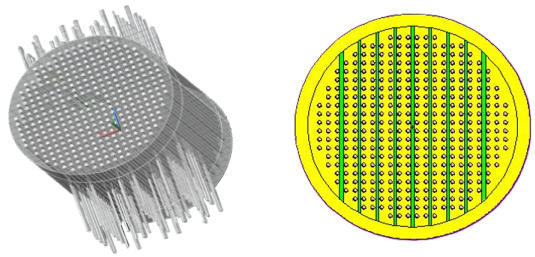


Fig. 3. CANDU reactor core models: AutoCAD(left) and MCNP6.3(right) conversion using GeoNEX

Figure 3 illustrates the hierarchy-aware bidirectional geometry-conversion of GeoNEX. Its main feature is a prototype–occurrence representation, in which reusable geometric prototypes and positioned occurrences are used to represent repeated reactor components. This approach preserves repeated structures during CSG-to-B-Rep geometry conversion and enables code-specific hierarchical models to be reconstructed from CAD geometry in the reverse direction.

CSG-to-B-Rep conversion first parses the geometry definitions of MCNP and SCALE. For MCNP, these definitions include analytical surfaces, Boolean cell expressions, universes, lattices, fills, importance, and transformations. For SCALE, surfaces, media regions, units, holes, and arrays are processed. Using the OpenCASCADE functionality provided through the Gmsh model.occ interface, analytical CSG primitives are constructed as B-Rep solids and Boolean intersection, union, and subtraction operations are performed to generate the corresponding material regions. Using the copy, translation, and rotation operations of the same OpenCASCADE interface, a repeated universe or unit is generated once as a geometric prototype, while subsequent occurrences are positioned according to lattice, array, FILL, TRCL, or hole-placement information. Generated solids and occurrences are organized and exported as a STEP assembly with product names. The resulting STEP file preserves the B-Rep geometry and material-based product names, while cell or media identifiers, material information, density, and the original neutronics hierarchy are stored separately in an associated Excel metadata file.

B-Rep-to-CSG conversion first imports the STEP model and separates it into individual solids and faces. Using CadQuery and face-orientation information, individual B-Rep faces are classified as analytical surfaces such as planes, cylinders, spheres, and cones. Using the GeoNEX geometric-recognition algorithm, combinations of these analytical faces are then interpreted to construct CSG regions and to recognize geometric features such as axis-aligned cuboids and regular hexagonal prisms. Using geometric and material signatures generated by GeoNEX, equivalent solids are grouped as reusable prototypes, and their spatial distributions are analyzed to identify square, rectangular, or hexagonal lattice patterns. Using the MCNP writer, the detected prototypes and arrangements are reconstructed using universe, LAT, FILL, and TRCL definitions. Using the GeoNEX SCALE writer, the extracted surfaces and solid regions are converted into surface, media, and unit definitions, while detected repeated arrangements are represented using array and fill structures. If a repeated pattern cannot be identified reliably, GeoNEX generates explicit MCNP cells or a flat SCALE global unit instead of imposing an uncertain hierarchy.

For general STEP models, GeoNEX reconstructs an MCNP or SCALE compatible CSG model from the geometry and spatial arrangement of individual solids, since STEP alone does not contain neutronics-specific hierarchy information. For STEP models generated by GeoNEX, the associated Excel metadata file provides cell or media identifiers, material information, density, and hierarchy information, enabling more direct and consistent reconstruction of the neutronics model.

3. Application and Demonstration

The converted geometry can also be used as a common geometry basis for Multiphysics applications [5]. GeoNEX generated STEP models can be imported into engineering software such as STAR-CCM+, ANSYS, and Abaqus, while material-based product names and the associated metadata maintain the correspondence between neutronics regions and CAD solids. This capability enables the same converted geometry to be reused for subsequent thermal-hydraulic or structural analyses without reconstructing the same model independently for each analysis environment.

The geometry-conversion accuracy was evaluated using a WH17x17 fuel-assembly model and a reactor-core model. The WH17x17 assembly was selected to evaluate the preservation of individual component dimensions and repeated pin structures, while the reactor-core model was used to examine the consistency of GeoNEX when applied to a larger geometry containing multiple repeated assemblies.

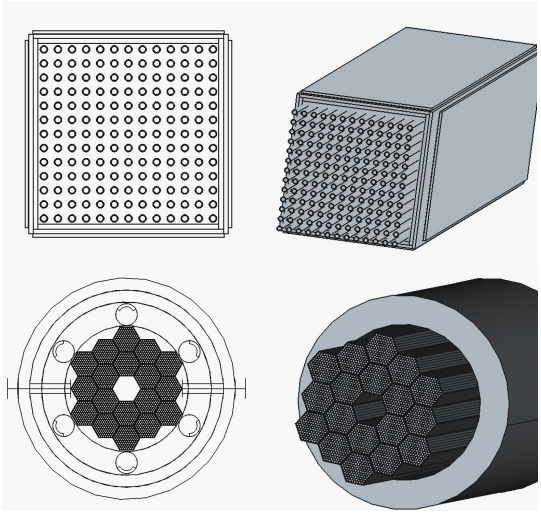


Fig. 4. FreeCAD representations of the WH17x17 and reactor-core model generated using GeoNEX: 2D cross-sectional view (left) and 3D B-Rep model (right)

Both conversion directions, CSG-to-B-Rep and B-Rep-to-CSG, were independently examined using equivalent geometry models. For the WH 17×17 assembly and reactor-core models, equivalent CSG and CAD geometries were prepared and converted between the two representations using GeoNEX. The converted models were subsequently evaluated by calculating and comparing their total volumes to assess the consistency of the geometry conversion. The results are summarized in Table I, and examples of the corresponding converted geometries are shown in Fig. 4.

The geometric accuracy was evaluated by comparing the volumes of the original CSG models with those of the corresponding GeoNEX-converted B-Rep models. This comparison was performed for both the single fuel assembly and the reactor-core model to evaluate whether geometric errors accumulate when GeoNEX is applied to larger repeated structures. The resulting volume differences are summarized in Table 1.

In addition to the volumetric comparison, the numbers of repeated components and major dimensional parameters were also compared to verify the preservation of the reactor-specific geometric structure. The agreement of these parameters indicates that GeoNEX consistently reproduces both component dimensions and repeated arrangements during CSG–B-Rep conversion.

Table I. Comparison of geometric parameters between the CSG and GeoNEX-converted CAD models.

WH17x17 Assembly			
Inventory	**CSG Volume [cm³]**	**CAD Volume [cm³]**	**Difference [cm³]**
Total Fuel rod	50,927.7841860053	50,927.7841860053	1.46×10^{-11}
Total cladding	17,561.4175204485	17,561.4175204489	3.78×10^{-10}
Total Guide tube	1,377.82560811438	1,377.82560811441	2.82×10^{-11}
Total coolant	98,059.7750854318	98,059.7750854291	2.76×10^{-9}
Reactor Core			
Inventory	**CSG Volume [cm³]**	**CAD Volume [cm³]**	**Difference [cm³]**
Total Fuel rod	410,303.787814463	410,303.78781446	9.31×10^{-10}
Total Structural	7,626,161.708511720	7,626,161.708880855	3.69×10^{-4}
Total Control drum	152,681.402964464	152,681.402964462	2.42×10^{-9}
Total Coolant	1,017,574.823939367	1,017,574.823939699	3.32×10^{-7}
Total Material	9,639,575.988775650	9,639,575.989145130	3.69×10^{-4}

As shown in Table I, the volume differences between the converted CSG and CAD models were on the order of 10^{-4} cm³ or less, corresponding to negligible relative errors. The remaining differences are attributed to numerical precision and geometric tolerances during B-Rep construction and Boolean operations, particularly in the more complex structural regions.

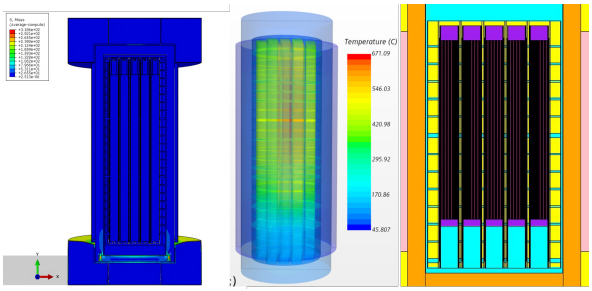


Fig. 5. Application of the GeoNEX-generated KORAD21 model in Abaqus (left), STAR-CCM+ (center), and MCNP 6.3 (right).

In addition to the geometry-conversion verification, GeoNEX was previously applied to a Multiphysics analysis workflow through a related research project. In this application, a GeoNEX-generated KORAD21 model was transferred to Abaqus and STAR-CCM+ and was also reconstructed for MCNP6.3 analysis, demonstrating the applicability of the common geometry model across different engineering analysis environments, as shown in Fig. 5.

4. Conclusions

In this study, GeoNEX was developed as a Python-based bidirectional geometry interface for converting reactor models between CSG and CAD/STEP B-Rep representations. The geometry conversion interface was demonstrated using a WH 17×17 fuel assembly and a reactor-core model, and the comparison of major geometric parameters confirmed that component dimensions and repeated structures were consistently preserved during the conversion process.

By converting reactor-physics geometries into general CAD/STEP models, GeoNEX allows reactor models to be reused in CAD-based engineering and mechanical design environments, thereby improving their applicability beyond neutronics analysis. In addition, the GeoNEX-generated geometries were successfully transferred to STAR-CCM+ and Abaqus, demonstrating their compatibility with CFD and FEA environments. These capabilities indicate that GeoNEX can provide a common geometric basis for reactor physics, CAD-based design, and Multiphysics applications, reducing repeated geometry reconstruction and improving the extensibility of reactor design workflows.

The present B-Rep-to-CSG conversion and validation are primarily limited to planar and cylindrical surfaces. Although MCNP can analytically represent general quadrics and tori, their automatic reconstruction from trimmed or non-convex B-Rep faces may require additional geometric decomposition and Boolean operations, increasing model complexity and sensitivity to geometric tolerances. Future work will extend GeoNEX to spheres, cones, general quadrics, and tori and validate the conversion using complex curved geometries. The unstructured-mesh method will also be investigated as a complementary conversion route for free-form surfaces.

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