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CAD based parametric breeding blanket creation for rapid design iteration

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Parametric breeder blanket model creation for rapid design iteration

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Abstract

Breeder blankets are currently being designed to breeder sufficient tritium to assure self-sufficient in prospective Deuterium Tritium (DT) fusion power plants. In addition to this breeder blankets play a vital role in shielding key components of the reactor and provide the main source of heat which will ultimately be used to generate electricity. Their design in critical to the success of fusion reactors and integral to the design process. Neutronics simulations of breeder blankets are regularly performed to ascertain the performance of a particular design. An iterative process of design improvements and parametric studies are required to optimise the design and meet performance targets. Within the EU DEMO program the breeder blanket design cycle is repeated for each new baseline. One of the first steps is to create 3D models suitable for use in neutronics analysis. This article presents a novel blanket design tool which can automate the process of producing heterogeneous 3D CAD geometries of the Helium Cooled Pebble Bed, Water Cooled Lithium Lead, Helium Cooled Lithium Lead and the Dual Cooled Lithium Lead. The tool is able to rapidly provide parametric geometry for use in neutronics and potentially engineering simulations. This paper explains the methodology and of the design tool and demonstrates use of the design tool by generating all four EU blanket designs using the EU DEMO baselines. The approach described has the potential to speed up the design cycle considerably and ease the integration of multiphysics studies.

Keywords: Fusion, parametric, CAD, neutronics, 3D, model, breeder, blanket, engineering

1. Introduction

Breeder blankets are being designed to fulfill several high level plant requirements including: breeding sufficient tritium to sustain the reactor, shielding components from the intense neutron flux and producing heat which is ultimately used to generate electricity.

Designing and engineering components for use within fusion reactors is challenging due to the high neutron fluxes and significant heat loads that they experience. Maintaining an operational and safe component within the inner vessel of a fusion reactor is already a difficulty however adding functional requirements such as breeding, shielding and heat generation makes for a particularly challenging task.

Methods of optimising designs such as parameter studies and designing by analysis approach are possible avenues for designing fusion reactor components that could provide solutions to this challenge. Such methods rely on analysis of iterative models to close in on optimal solutions.

Performing analysis on an isolated discipline will only find the optimal solution for performance metrics that are obtainable with the discipline. For instance neutronics optimisations may find the tritium breeding ratio (TBR) but not the temperature of the component. Multiphysics analysis is often required to optimise the component design. To maintain data fidelity it would be preferable to have a single model base when sharing data between analysis techniques.

Traditionally models are generated for neutronics using constructive solid geometry (CSG) which can be time consuming but the models can be used in parametric neutronics studies. Engineering analysis tends to require CAD models and CSG models are typically not compatible. Models for use in engineering analysis are often created via graphical user interfaces and once again this can be time consuming. The process of creating new engineering models and neutronics models with each release of a new EU DEMO baseline for each of the four EU blanket designs can be a time consuming exercise.

To address this some shortfalls with the current approach it would be desirable to have accurate 3D geometry produced quickly and parametrically so that the design space can be rapidly explored. Adopting a common geometry format would allow geometry to be used in multiple domains. Allowing fine details (such as cooling pipes) to be included or not during the model generation can facilitate specific requirements by analysis techniques. Use of open source geometry producing software such as FreeCAD [9], Salome [10] or PythonOCC [12] can be preprogrammed to quickly generate parametric geometry CAD geometry and exported into a variety of formats. CAD files in step format are compatible with engineering simulations and can be easily converted into surface faceted geometry (e.g. h5m or stl files) for use in neutronics codes such as DagMC [7] and Serpent II [3]. Ideally any solution to making component models would be flexible enough to work with new DEMO baseline models and produce different blanket designs.

2. Method

An automated method of reading in blanket envelopes and returning detailed geometry to the users specification was created. As a demonstration of the automated geometry maker parametric models of all four EU blanket designs for single-module segments were generated. These include the Helium Cooled Pebble Bed Blanket (HCPB) [6], Helium Cooled Lithium Lead Blanket (HCLL) [4], Water Cooled Lithium Lead Blanket (WCLL) [1] and Dual Coolant Lithium Lead Blanket (DCLL) [2].

The first stage was to read in the blanket envelopes, these can take a variety of shapes depending (see figure 1) upon the positioning within the reactor and other factors. The EU DEMO baseline model [11] has 26 different blanket modules which have different shapes, orientations and positions.

The blanket designs share some common features such as filleted corners on the toroidal HCPB,HCLL and WCLL designs (see figure 3) or poloidal DCLL (see figure 4) edges. The first step was to correctly identify the two edges that require filleting from the twelve available edges in each blanket envelope. This help with this task the rear face of each module was found by finding the face within the envelop furtherest from the plasma source. Then the face not touching or connecting to the rear face was identified as the front face of each blanket envelop. Simply detecting the closest face to the plasma often results in some of the edge faces being selected and this indirect method of finding the rear face first, then the front face was found to be more robust. Once the first face was found the two edges which have little or no variation over the Z axis where identified as toroidal edges and the remaining two edges on the four edge front face were found to be the poloidal edges. Once the correct edges had been found they could be filleted to the desired radius.

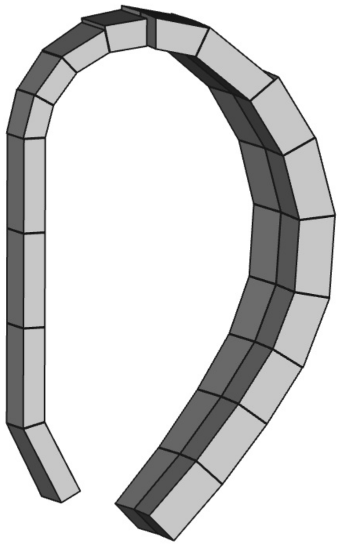

Figure 1: Blanket modules from the EU DEMO baseline [11]

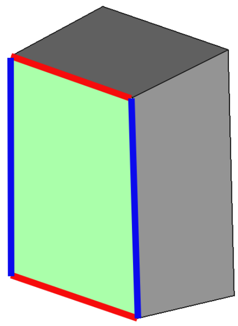

Figure 2: Example blanket envelope showing the front face (green), poloidal edges (blue) and toroidal edges (red)

Another common feature that all four blanket designs share is a thin layer of armour which covers the first wall and the filleted corners. For this operation the software detects the front face of the newly filleted envelope and the two faces that make up the filleted corners. Finding

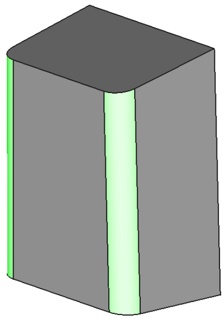

Figure 3: Example blanket envelope filleted poloidal edges (green), in this case the fillet radius has been increased to clearly show the the operation

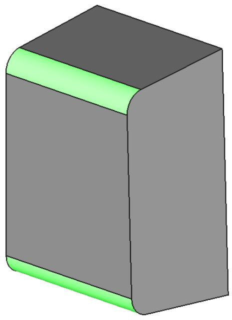

Figure 4: Example blanket envelope filleted toroidal edges (green), in this case the fillet radius has been increased to clearly show the the operation

the filleted faces is done by first finding the rear face and the faces in contact with the rear face. This provides a list of faces that are not the filleted faces or the front face and the filleted faces and first wall face can then be found by deduction. The midpoint of each face is then found and the faces are extruded from the midpoint in the negative normal direction by the user specified amount (armour thickness parameter). A boolean cut operation is then applied to the filleted envelope to reduce it in size. The sides of the envelope are also taken back to the same level as the armour for continuity. See figures 6 and 5.

The next stage is to form the first wall from the remaining envelope. This wraps around the front surface, filleted surfaces and either the side walls or top and bottom walls. In the case of a toroidally (see figure 7) filleted blanket then the first wall will wrap around the top and bottom faces and in the case of a poloidally (see figure 8) filleted blanket then the first wall wraps

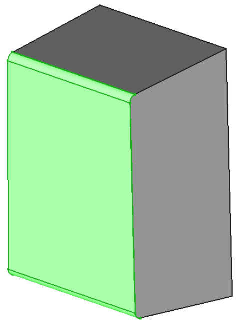

Figure 5: Example blanket envelope filleted toroidal edges and with first wall armour (green).

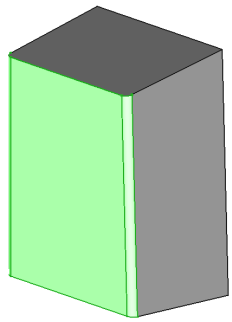

Figure 6: Example blanket envelope filleted poloidal edges and with first wall armour (green).

around the side walls. The creation of the first wall relies on a thicken operation and identification of all the faces that require thickening. To find the correct faces, all the faces within the remaining envelope are added to a list, then faces with more than four edges are removed and the rear wall is also removed from the list. The remaining faces all belong to the first wall and are thickened to the user specified amount (first wall thickness parameter).

End caps can now be identified and formed. This is achieved by looping through all the faces in the remaining envelope and finding the faces with six edges. There are currently eight faces in the remaining envelope and all but two have four edges. Once the correct end cap faces are found they are enlarged and extruding the faces along their negative normal vector bu the use specified amount (end cap thickness). It is necessary to enlarge the faces to avoid missing slithers of material when extruding as some of the blanket module shapes are skewed and change shape in the poloidal direction. Any common volume between the newly extruded faces

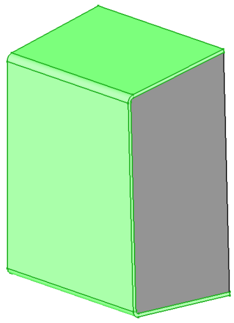

Figure 7: Example blanket envelope filleted toroidal edges and with first wall (green).

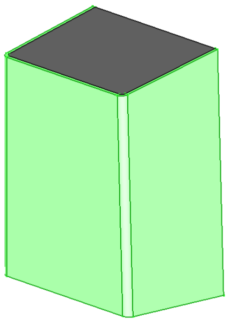

Figure 8: Example blanket envelope filleted poloidal edges and with first wall (green).

and the remaining envelope is then identified as the end caps and the remaining envelope is reduced again by cutting the end caps of the body. See figures 9 and 10 for the resulting shapes

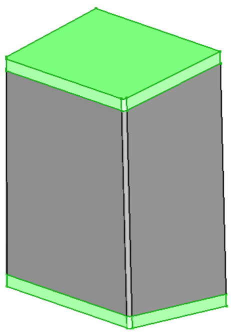

Figure 9: Example blanket envelope filleted toroidal edges and with end caps (green).

The next step is to form the rear plates. This is done by simply finding the face furthest from the plasma,

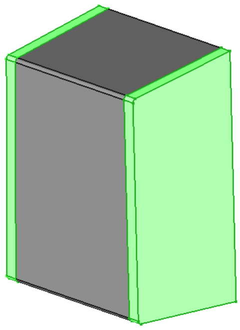

Figure 10: Example blanket envelope filleted poloidal edges and with end caps (green).

enlarging the face and then extruding it on a negative face normal vector. Once again the common volume shared between the remaining envelope and the newly extruded solid are found and this becomes a rear plate. The reaming envelope is reduced in size by the appropriate amount using a boolean cut operation. This operation of creating a rear wall is repeated several times and each blanket design has different rear plates layouts. The number of plates and thickness of each plate can be specified by the user (thickness of each rear plate parameter). See figures 11, 12, 14 and 13 for the resulting shapes.

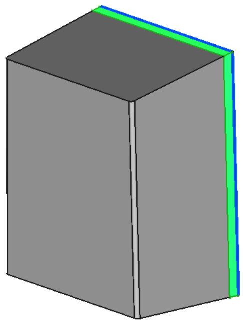

Figure 11: Example HCPB blanket envelope filleted poloidal edges with back wall components shown in (blue and green)

The segmentation of the breeder zone varies for each of the four breeder blankets but is mainly combination of poloidal, toroidal and radial based segmentations. Naturally this can be expressed programmatically and can be applied to create all the blanket designs. Starting with poloidal segmentation the simplest example would be equally spaced segments as shown in figure 15. To create such a segmentation the midpoint of the first wall is found and a surface is created perpendicular to the first wall at the midpoint. This surface is then extruded

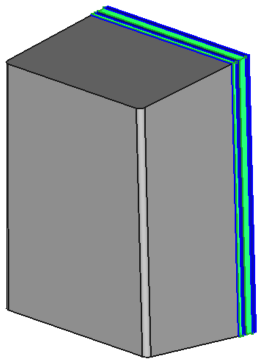

Figure 12: Example HCLL blanket envelope filleted poloidal edges with back wall components shown in (blue and green)

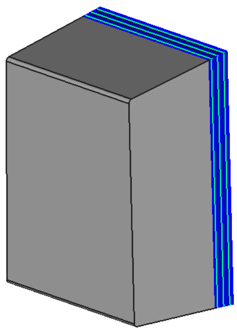

Figure 13: Example DCLL blanket envelope filleted toroidal with back wall components shown in (blue and green)

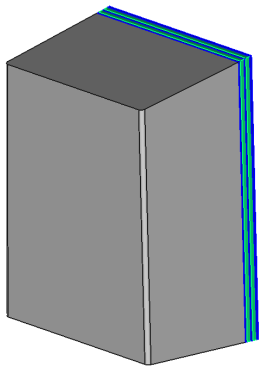

Figure 14: Example WCLL blanket envelope filleted toroidal with back wall components shown in (blue and green)

along the surface normal and negative normal at the required step length. The previously created extrusion are subtracted from each new extrusion to form separate poloidal layers. The first layer in each direction is set to half the layer length to keen the model as symmetrical as possible.

EU blanket designs have more complex arrangements

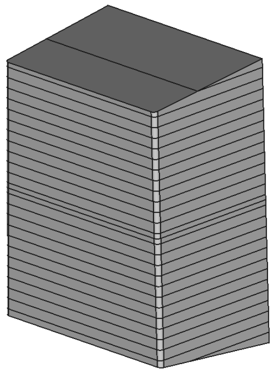

Figure 15: Example blanket envelope filleted toroidal with regular poloidal segmentation

of materials and additional segmentation rules are required. For example the HCLL advanced plus design [4] can be represented by a series of poloidal segmentations with alternating layers of cooling plates and lithium lead layers. This can be reproduced using alternate poloidal segmentation with alternating extrusion lengths (see figure 16)

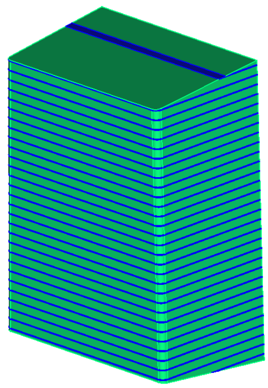

Figure 16: Example HCLL advanced plus design with alternating layers of lithium lead and cooling plates

The HCPB pebble bed can also be approximated with poloidal segmentation however two additional rules are required. In the case of the HCPB there are alternating layers of lithium ceramic and neutron multiplier with cooling plates between. The poloidal segmentation functions have been flexibly designed to allow any number of repeatable layers so that 1, 2, 3 or more layers are not a difficultly as demonstrated in figures 15, 16 and 17. Additionally the wedge shaped regions at the upper and lower extremities of the module are filled with neutron multiplier. To achieve such a layout additional options are included on the extrude function and as the extrude is carried out the number of resulting faces on the new layer is checked. If the number of faces is different to the very first layer created then this indicates that the new layer is being created within the final wedge shaped region and the creation of the layer ceases. At this point the software backtracks through the layers created to finds the last neutron multiplier layer. The previously created neutron multiplier layer is then enlarged and extruded to the end of the module envelope. Layers created after the final neutron multiplier layer are discarded.

Radial cuts can also be accomplished with the blanket geometry making tool and these are required for both the WCLL and the DCLL blanket designs. First a radial segmentation in it's most simple form would be uniform distribution of slices from the first wall moving along the negative of the face normal vector. In much the same ways as for poloidal segmentation it is possible to extrude an enlarged face through the module envelope and slice the geometry into radial segments. This is demonstrated by figure 18

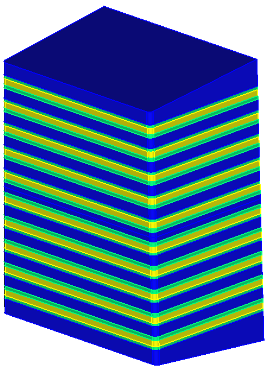

Figure 17: Example HCPB design with alternating layers of lithium ceramic, neutron multiplier and cooling plates

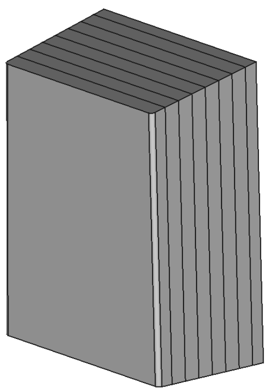

Figure 18: Example blanket envelope filleted toroidal with radial segmentation.

The WCLL can be reconstructed with a combination of poloidal segmentation and toroidal segmentation. Both the toroidal and poloidal directions have alternating thicknesses for the structural plates and the lithium lead. Every other layer of poloidal structural plate has an offset from the first wall, this to allows lead to flow between plates. The poloidal segmentation for such as model can be carried out in a similar way to the HCLL however the WCLL has an additional complication and requires a radial segmentation. A radial segmentation function can be used to form the offset and every other layer of structural plates which overlap with the radial offset can be cut with the radial layer. The resulting volume from the cut operation is added to the list of lithium lead solids. The thickness of the radial offset is user specified via the radial segmentation parameter.

The next step is to add toroidal segmentation to the WCLL model. To create the extrusion surface for the segmentation the software detects the front face, midpoint, negative normal vector and the toroidal edges of the front face (see figure 2). These are then combined to create a large surface which goes through the blanket toroidally. This surface is then extruded to form toroidal segments in a similar manger to the poloidal and radial extrusions. Once again there is a feature that insures the triangular sections are dealt with correctly. In the case of the WCLL the triangular edges should be lithium lead and there should be no toroidal structural supports within them. The resulting product of the toroidal segmentation can be see in figure 20.

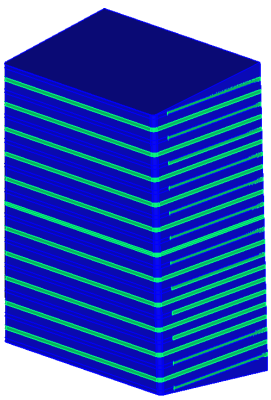

Figure 19: Example blanket envelope showing progression towards a WCLL model, this model has a combination of radial segmentation with poloidal segmentation

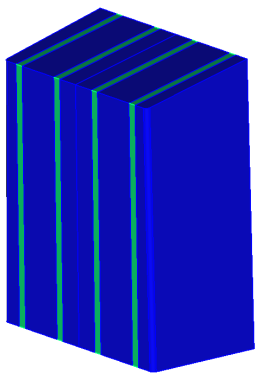

Figure 20: Example blanket envelope showing progression towards a WCLL model, this model displays toroidal segmentation with alternating layer thickness

To combine lithium lead solids formed from different segmentation methods one can simply create a nested loop to cycle through all the combinations and find volumes common to all segmentation methods. To combine structural plates formed in different methods a nested loop can once again be used, however this time a boolean cut operation is required. The resulting material volumes become more complex compared to the individual parts (see figures 21 and 22).

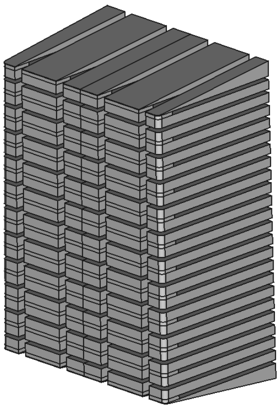

Figure 21: Example lithium lead component of the WCLL with toroidal, poloidal and radial segmentation.

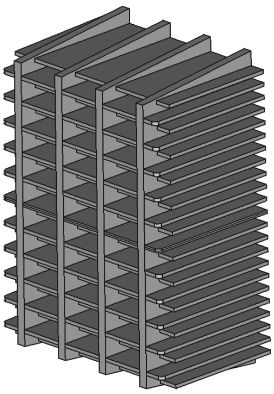

Figure 22: Example structural components of the WCLL with toroidal, poloidal and radial segmentation.

The DCLL breeder zone can be formed from a combination of radial and toroidal segmentation and some additional parts to guide the flow of lithium lead. The procedure used was to first radially segment the blankets into three or five parts (depending upon the radial depth of the blanket). In General most of the inboard blankets accommodate three radial layers and the outboard blankets accommodate five radial layers. The combination of radial and toroidal segmentation for structural plates and lithium lead can be seen in the figures 24, 23, 25, 26.

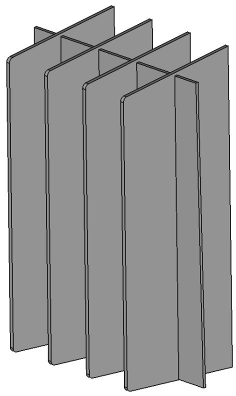

Figure 23: Example structural components of the DCLL with a single radial toroidal segmentations.

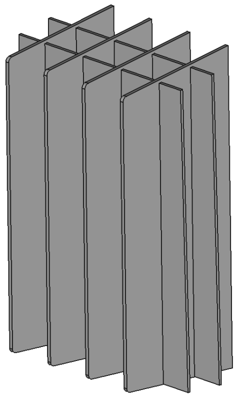

Figure 24: Example structural components of the DCLL with two single radial toroidal segmentations.

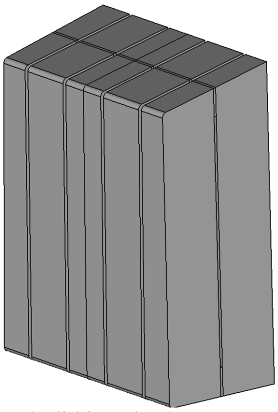

Figure 25: Example lithium lead components of the DCLL with a single radial toroidal segmentations.

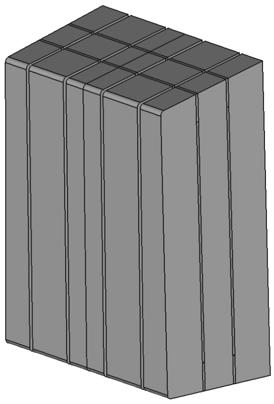

Figure 26: Example lithium lead components of the DCLL with two single radial toroidal segmentations.

The DCLL blanket design allows the lithium lead to flow around the structure. To include this feature in the model the radial plates must be shortened at both ends. This can be achieved by extruding the upper and lower faces of the remaining envelop on a negative normal vector. Any resulting overlap can then be subtracted from the radial structural plate volumes and added to the lithium lead volumes. Detection of the upper and lower plates is achieved by examining the normal vector of all faces (ignoring the front and back) and finding vectors that point predominantly in the X or Z direction. Vectors pointing in the Y direction indicate the side walls of the blanket box. With the DCLL it is not possible to detect the upper and lower poloidal faces using the methods applied to the HCPB, HCLL, WCLL as the DCLL does not have six edge faces on the upper and lower poloidal faces. The resulting upper and lower flow channels are showing in figures 27.

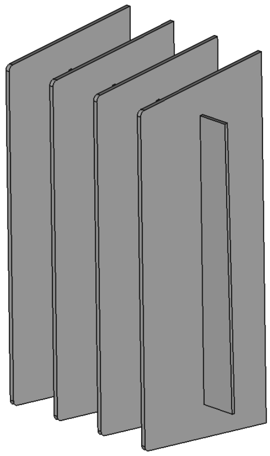

Figure 27: Example structural components of the DCLL with a single radial toroidal segmentations.

To guide the lithium lead around the structural geometry so that it flows in one direction it it is necessary to have an additional structural component at the upper end of each blanket module. This is achieved in a similar manner to the previous extrusion from the upper surface. The only additional complication is that a boolean subtraction with the first radial layer is also require to obtain the desired structural plate shape. This results in lithium lead and structural components showing in figures 28 and 29.

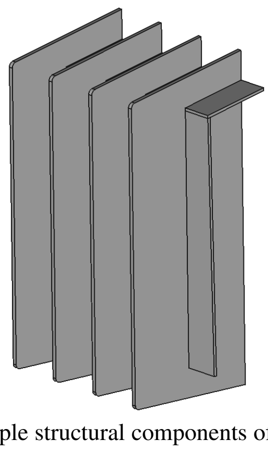

Figure 28: Example structural components of the DCLL with with a single radial toroidal segmentations and additional channel guide.

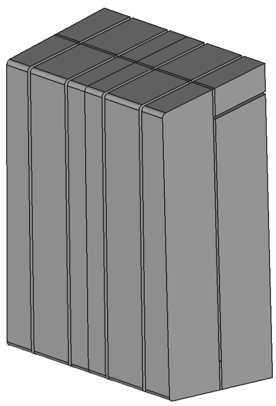

Figure 29: Example structural components of the DCLL with with a single radial toroidal segmentations and additional channel guide.

Cooling channels within the first wall can be added to the model by reusing the toroidal or poloidal segmentation functions. The first wall also requires a layer at the front and back to contain the coolant, these layers were made with an adapted version of the first wall segmentation function. The first wall was separated into three parts a front layer, middle layer and back layer. The middle layer was segmented (toroidally or poloidally) into coolant and first wall material. The channel pitch, front face offset and dimensions of cooling channels are options the user can specific or the the first wall can be homogenized.

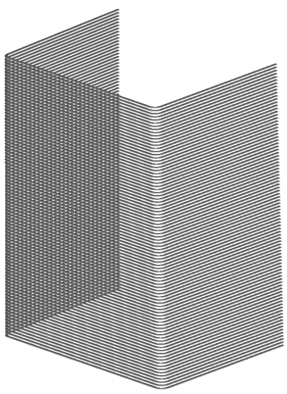

Figure 30: Example coolant channels for the first wall created with poloidal segmentation of the first wall.

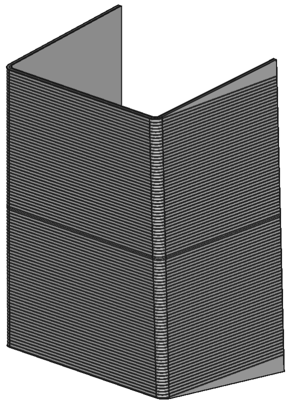

Figure 31: Example of the remaining first wall structural material after cooling channels have been removed. Created with poloidal segmentation of the first wall.

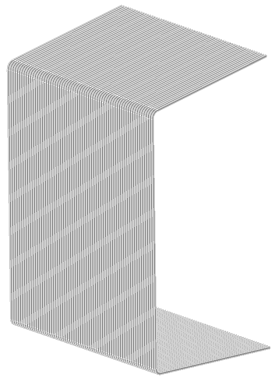

Figure 32: Example coolant channels for the first wall created with toroidal segmentation of the first wall.

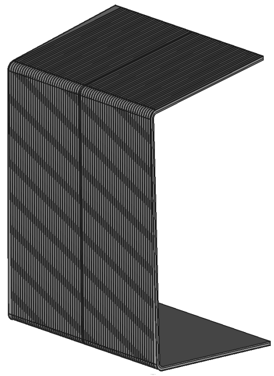

Figure 33: Example of the remaining first wall structural material after cooling channels have been removed. Created with toroidal segmentation of the first wall.

3. Results

As a result of the method previously described there is now an automated procedure for obtaining semi detailed CAD geometry for the HCPB, HCLL, WCLL and DCLL. The process relies on a library of common functions which can be mixed and matched to create particular blanket designs. The library of common functions includes operations such as find front face of blanket envelope, segment poloidally etc.

The model construction process is parametric which allows models required for parameter studies to be generated rapidly. Currently the parameters that a user can input are:

- filename of blanket envelope required for segmentation
- blanket type (HCPB, HCLL, WCLL, DCLL)
- poloidal fillet radius for first wall and first wall armour
- toroidal fillet radius for first wall and first wall armour
- first wall armour thickness
- first wall thickness
- end cap thickness
- thickness of each rear plate
- thickness of each poloidal segmentations
- thickness of each toroidal segmentations
- thickness of each radial segmentation
- first wall coolant channel poloidal height
- first wall coolant channel radial height
- first wall coolant channel pitch
- first wall coolant channel offset from the front face
- output file format (STEP or STL) and tolerance.

Not all parameters are needed for each design as some are not applicable, for instance the breeder zone in the HCPB blanket has no radial segmentation option and does not require this input. The following figures show each of the four blanket designs formed from a particular module from the baseline DEMO model [11]. Parameter values have been enlarged in some cases to increase viability of components. The process of building a blanket module from an envelope is typically less than 10 seconds on a single core. Build time depends on the input parameters as many very small layers would necessitate more boolean operations than a few large layers. The process is parallelizable and therefore a model such as the EU DEMO with 26 blanket modules typically takes a minute on a four core Intel i5 CPU.

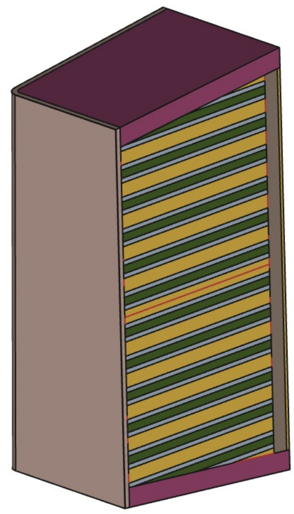

Figure 34: Example HCPB blanket module.

4. Conclusion

The design tool capable of generating parametric designs for fusion breeder blankets has been demonstrated on single module blanket envelopes for the HCLL, HCPB, WCLL and DCLL. A wide range of design parameters can be changed to generate CAD geometry for use in parameter studies. The geometry generated is available in CAD format (STEP and STL). Conversion to CSG for neutronics simulation can be achievable via existing software such as McCad [5] or MCAM [8]. Although the option of faceted geometry allows CSG geometry to be avoided in favor of more CAD based neutronic simulation techniques such as Dagmc [7] or Serpent II [3]. The provision of CAD geometry also enables manipulation to be performed with standard CAD software as opposed to CSG geometry where manipulation of the shapes is less convenient.

5. Acknowledgments

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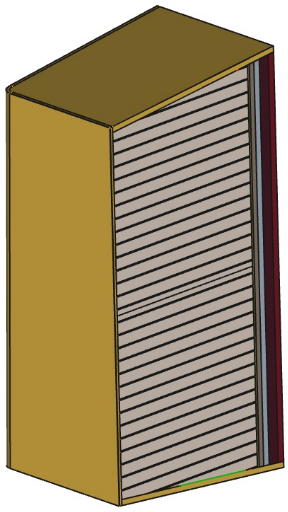

Figure 35: Example HCLL blanket module.

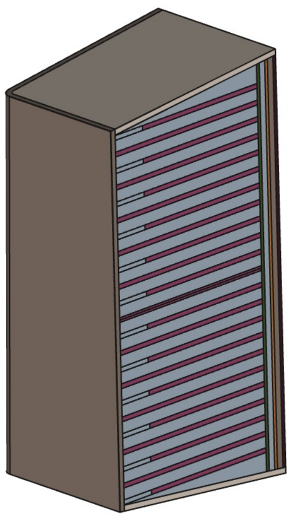

Figure 36: Example WCLL blanket module.

been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opin-

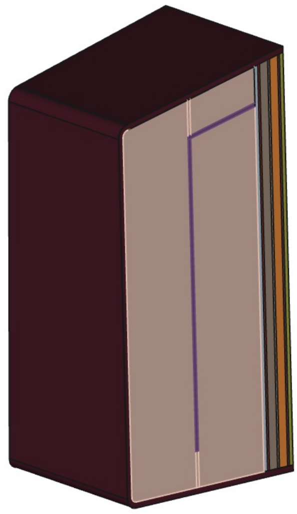

Figure 37: Example DCLL blanket module.

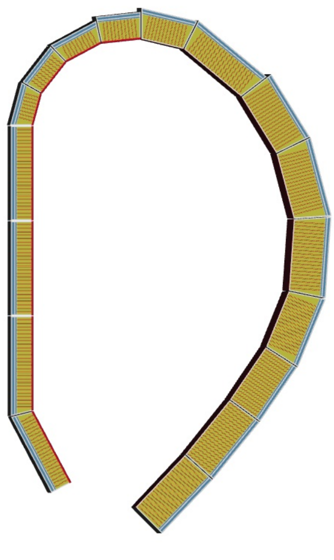

Figure 38: Example HCPB reactor model.

ions expressed herein do not necessarily reflect those of the European Commission. This work has also been part-funded by the RCUK Energy Programme [grant

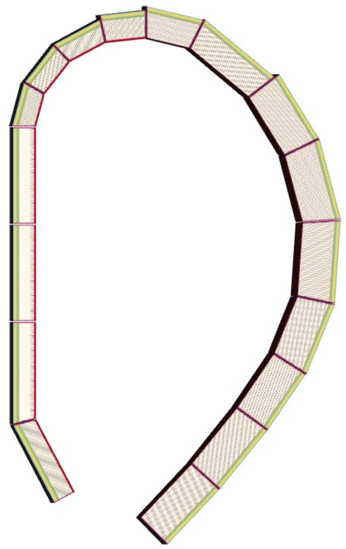

Figure 39: Example HCLL reactor model

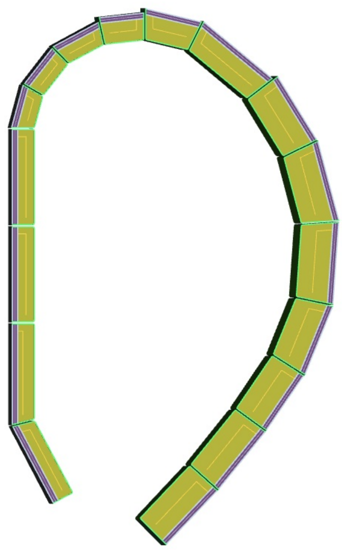

Figure 40: Example HCPB reactor model.

number EP/I501045]. The author would also like to thank the HCLL, HCPB, DCLL and WCLL breeder blanket design teams.

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