Background
The first wall and divertor of DEMO will experience heat, particle, and neutron fluxes beyond what has been seen for any existing fusion experiments, and beyond what will be seen in ITER. Each plasma facing component (PFC) must satisfy numerous, often competing, requirements. Among the many challenges that must be addressed in designing these components are, neutron activation, particle sputtering and redeposition, erosion, helium implantation, swelling, fuel implantation, stresses produced by thermal gradients and coolant fluid pressure, fatigue from thermal cycling, creep from high temperature operation, etc. One issue that must be addressed is the ability to effectively remove heat from the component in a manner that does not jeopardize any of the other requirements for the PFCs.

From an engineering standpoint, the PFC can be conceptually divided into three aspects – the plasma facing surface, the coolant, and the intermediate thermal structure. Currently, many options are being considered for the plasma facing surface, and none are without problems and shortcomings. Tungsten is a commonly assumed candidate, but other materials, particularly other refractory metals, could be considered [1]. The concept of a liquid metal wall has also been examined [2]. Several options are also being considered for the coolant. Water will be the primary coolant in ITER, and is still being considered for DEMO, particularly by the European fusion program [3, 4]. But water has many limitations when considered for a fusion power plant [5], not least of which are: the possibility of tritium contamination, the high operating temperature of the wall, and the possibility of transmutation to Nitrogen 16. Helium and liquid metals are being considered as alternatives, but further research is necessary before it will be clear that either will be an adequate coolant in a fusion power plant. Finally, the possible compositions and shapes of the intermediate thermal structure are too many to mention. It seems clear that PFCs will need to be engineered components, probably several materials in alloy and/or unique shape. The proposed research is focused on a novel approach to the design of this intermediate structure using the tool of topology optimization.

Proposal
Significant research, development, and creative scientific and engineering effort has gone into increasing the effectiveness of heat removal for PFCs, pushing the bounds of heat removal. For water cooling, this has included monoblocks with twisted tape [6] and other internal enhancements [7], hypervapotrons [8], and jet impingement elements [9]. For helium cooling, this has included finger configurations [10-13], a so-called “T-tube” configuration [14], and refractory metal foams [15-16]. One limitation that is generally seen in designs that produce improved thermal transfer is that enhancements that tend to increase the surface area over which the fluid can act also tend to increase the pressure drop across the cooled region. As innovative and significant as the different technologies have been, their development and improvement has generally come through ad hoc or trial-and-error methods. By what criteria do we discern which of these designs is optimal? Or could there be another, yet to be developed, technology or design for this intermediate region that would be an improvement over any of the existing designs?

Optimization studies have been conducted in order to improve the performance of these components [17]. However, these studies have generally used traditional shape optimization techniques. Topology optimization differs from shape optimization, in that topology optimization does not require any assumption about the topology of the structure in question. In shape optimization, certain parameters (such are the shapes, sizes, or material properties of bars in a truss configuration) are varied in order to meet some objective (such as maximizing the stiffness) subject to certain constraints (such as a maximum stress). However, the problem is limited by the initial configuration (such as the number of members, or
the locations of the members). The solution will only be as good as the initial “guess” of the topology, and a better initial topology will result in a better solution.

The basic idea behind topology optimization is that no a priori assumptions are made about the structure’s topology. Using homogenization theory in conjunction with finite elements, a design domain is created, where each element can be made up of a combination of the various material constituents [18]. The material properties of that element are the result of the “homogenized” values of the constituents assuming a microstructure made up of infinitesimal “unit cells,” or “microcells,” periodically distributed over the domain. For example, in the case of a clamped beam shown in the figure [19], the two constituents are an elastic material and a “void”. The optimal design is found by varying the dimension of the void in each finite element, for a given maximum volume of material. The figure shows the evolution through several iterations. Each element tends toward being 100% material (represented by black squares) or 100% void (represented by white squares), depending on where the material can be best placed in order to achieve the design objective (maximum stiffness). The final result looks like a truss structure, but it is not a topology that would have likely been chosen initially for shape optimization of a truss. The primary critiques of topology optimization are that it has heavy computation requirements, and that the resultant shapes are not manufacturable. The first critique is addressed by the continuously improved computational speeds and the use of parallel processing, which reduce the computational challenges with each passing year. The second critique is addressed by advances in additive manufacturing, which substantially reduces any penalty for geometric complexity [20-23].

One additional hurdle in using this technique for the development of novel heat transfer structures is modeling of the coolant. Shape optimization has been used for maximizing cooling in fusion applications [24]. Traditionally, topology optimization has been used primarily for structural problems, and the homogenization technique used for describing physical properties. However, recent studies have also begun using topology optimization for problems in forced convection [25-27]. So, this would not require developing an entirely new technique, but would be a matter of extending an existing method to the cooling regime required for PFCs. Many objectives could be considered for the optimization. One logical objective to be considered initially would be to minimize the temperature of the plasma facing surface for the given heat flux and available coolant mass flow and pressure. It would be possible to perform a multi-objective study, both minimizing the peak surface temperature, and minimizing the pressure drop in the fluid. The thermal structure whose shape is optimized could be a single material, or could be multi-material. All three coolant options (water, helium, liquid metal) should be considered independently.

The primary needs for this research are personnel related. The structural, fluid, and algorithmic models need to be set up. The homogenization technique lends itself well to implementation in a finite element model. Commercial finite element and computational fluid dynamic codes (such as ANSYS) should be employed. Commercial optimization software (such as VisualDoc) also could be used to shorten software development time. Once new design emerge from the optimization process, they should be prototyped (probably using additive manufacturing facilities) and tested in existing high heat-flux facilities.

**Anticipated Results**

The expected outcome of this research program would be the development of novel designs of intermediate structures that improve heat transfer capabilities for a DEMO type reactor. In addition, it is expected that the underlying physical mechanisms that drive improvements to the design of such structures will be better understood for future development.
References


