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LIGHTWEIGHT DESING OF BWR CONTROL ROD VELOCITY LIMITERS BY ADDITIVE MANUFACTURING

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1. INTRODUCTION

The control rods used in BWRs (Boiling Water Reactors) contain neutron absorbers and are crucial devices that not only control the reactor output but also have the function of shutting down the reactor in emergencies. These control rods are equipped with velocity limiters at their lower ends, which function to limit the drop speed of a control rods in the event of a drop accident (Figure 1).

By loading more neutron absorbers into the control rods, it is possible to improve the reactor's control capability and extend the lifespan of the control rods. However, there is a mass limit set for the control rods. There is a speed limiter made of cast stainless steel at the bottom of the control rod, and if it can be hollowed out to reduce weight, more neutron absorbers can be loaded into the control rods. In doing so, it is necessary to maintain the outer shape to limit the drop speed of the control rods.

As a means to achieve weight reduction, design changes were made through topology optimization and dimensional optimization. Additive Manufacturing (AM) technology was focused on as a manufacturing technique capable of realizing these designs.

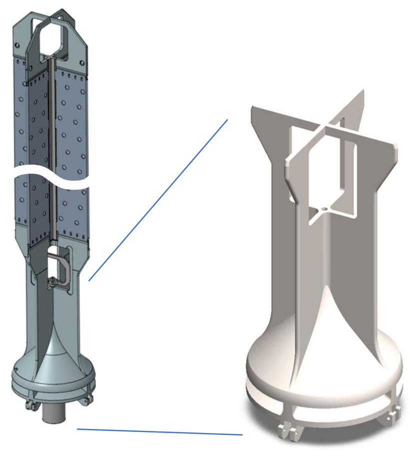


Figure 1: Control Rod and Velocity Limiter

2. DEVELOPMENT PROCESS

To reduce the weight of the speed limiter, topology optimization is performed first. Next, dimensional optimization is carried out considering AM fabrication. Additionally, the selection of fabrication methods using AM technology is conducted.

2.1 TOPOLOGY OPTIMIZATION AND DIMENSIONAL OPTIMAIZATION METHODS

In the topology optimization process, the design area to be hollowed out is defined first, along with the load and constraint conditions. Figure 2(a) shows the original half-cut shape, and Figure 2(b) shows the design area. To maintain fluid characteristics such as drop speed and scram speed, the constraint was set to maintain the outer shape of the velocity limiter. Next, optimization calculations using the finite element method (FEM) are performed to determine the optimal material layout and extract the main framework. The main framework is extracted through manual CAD modelling. Figure 2(c) shows topology optimization results and figure 2(d) shows framework extraction results. In the subsequent dimensional optimization process, dimensional optimization using the FEM is performed again based on the extracted framework, adjusting the dimensions of the parts to withstand specific load conditions. Figure 2(e) shows dimension optimization results. This series of processes achieves both weight reduction and high performance of the product.

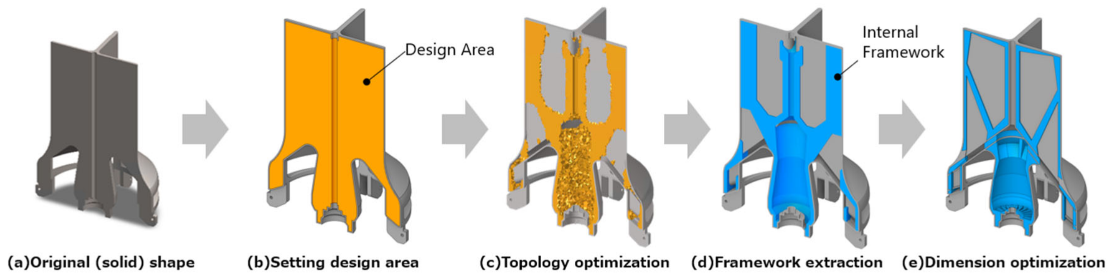


Figure 2: Flow of lightweight design

Table 1: Analysis Conditions for FEM Solver

	Topology optimization	Size optimization
Solver	OptiShape 2019	Ansys Mechanical 2022R2
Model Type	Full Model	⇐
Objective function	Compliance minimization	⇐
Constraints	50% mass reduction	⇐
Other options	density distribution is quarter-symmetric	Large Deformation

2.2 MANUFACTURING METHODS USING AM FABRICATION TECHNOLOGY

AM technology is a manufacturing method that adds and layers materials, enabling the production of complex shapes such as hollow structures and the integration of multiple parts, which were impossible with traditional methods. AM technology includes several methods such as Powder Bed Fusion (PBF), Directed Energy Deposition (DED), and Binder Jetting (BJT). We have chosen to use Powder Bed Fusion with Laser Beam (PBF-LB), which allows for the fabrication of particularly complex structures. This method uses a laser to melt and solidify metal powder, enabling manufacturing. PBF-LB is expected to be applied in fields that require high precision and detailed reproducibility.

Additionally, challenges in AM fabrication using PBF include the manufacturability of overhangs without supports and the removal of powder from hollow sections. Both are difficult to achieve as there is no underlying structure to support the fabrication, making it challenging to create the design as intended.

3. LIGHTWEIGHT DESIGN USING TOPOLOGY OPTIMIZATION AND DIMENSIONAL OPTIMAIZATION

3.1 LIGHTWEIGHT DESIGN PROCESS

In the process of lightweight design, topology optimization using the density method was adopted. Figure 3 shows the processes involved in topology optimization using the density method. Topology optimization using the density method is a technique for optimizing the material distribution within the design domain. In this method, the density of each element is treated as a design variable, varying within the range of 0 to 1. A density of 1 indicates the presence of material, while a density of 0 indicates the absence of material. The objective of the optimization is to maximize or minimize the performance of the structure under given constraints. Specifically, the density distribution is adjusted to minimize stress or deformation. The density method is efficient in computation and allows for the optimization of complex shapes due to its use of a continuous density function.

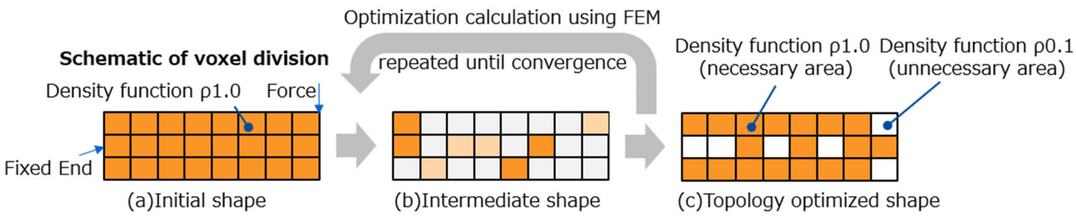


Figure 3: Internal processing of topology optimization

3.2 STRENGTH EVALUATION

The following loads are applied to the control rods, including the speed limiter:

- No-buffer scram
- Earthquake scram

It was confirmed that the speed limiter has no strength issues under the above loads. The analysis conditions at that time are shown in Table 2.

Table 2: Analysis Conditions

Item	Condition
Material	Type 316L
Young's Modulus	176 GPa @ 302℃
Poisson's Ratio	0.3
Density	7.98×10^3 kg/m³
Load	Load values of domestic plants in Japan
Allowable Stress	Standards for Nuclear Power Generation Equipment Applied allowable stress for core support structures in design and construction standards

3.2.1 NO-BUFFER SCRAM

The control rod drive mechanism that moves the control rod is equipped with a function to limit the control rod insertion speed during a scram. However, if this function is lost, as shown in Figure 4(a), an inertial force acts mainly in the vertical direction on the control rod. In this case, the speed limiter experiences a tensile load at the lower fixed end, as shown in Figure 4(b), as a reaction force to the no-buffer scram load. It is required that the control rod does not sustain damage even if this event occurs.

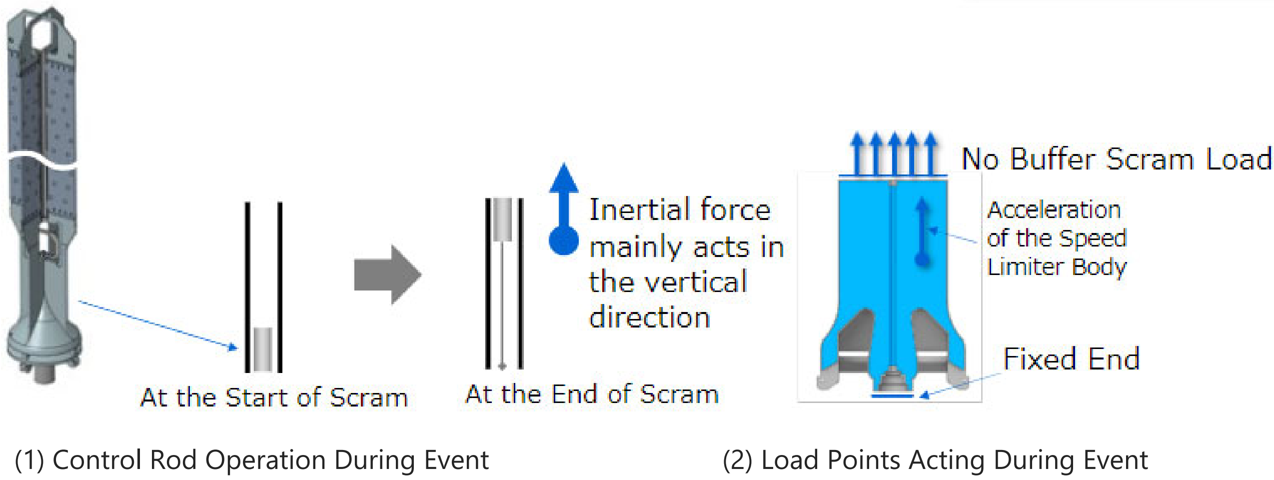
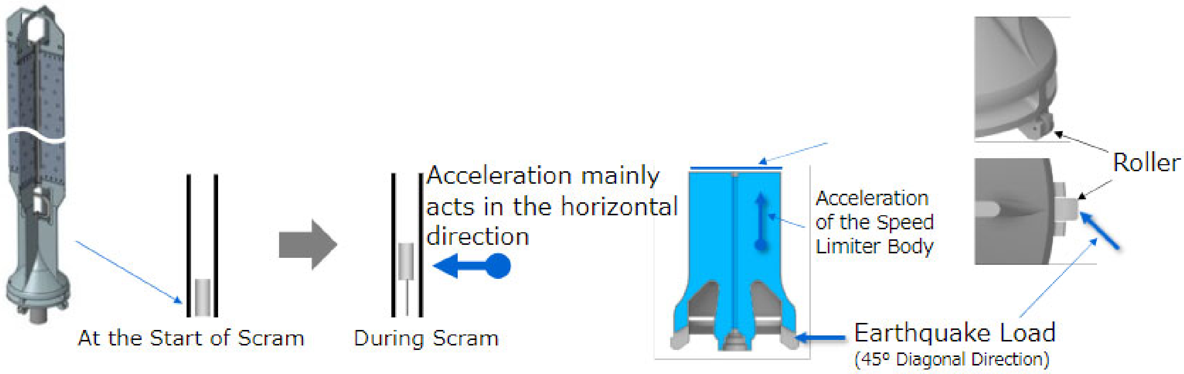


Figure 4: Loads Acting During No-buffer Scram

3.2.2 EARTHQUAKE SCRAM

In the event of an earthquake, if the acceleration exceeds a certain threshold, the plant is designed to initiate a scram, rapidly inserting the control rods fully to shut down the reactor. When an earthquake occurs, as shown in Figure 5(1), a horizontal acceleration primarily acts on the speed limiter. In this case, the speed limiter experiences the maximum load on the rollers, as shown in Figure 5(2), due to the seismic load. It is required that the control rod does not sustain damage even if this event occurs.



(1) Control Rod Operation During Event (2) Load Points Acting During Event
Figure 5: Loads Acting During Earthquake Scram

3.3 LIGHTWEIGHT DESIGN AND ANALYSIS RESULTS

Figure 6 (a) shows topology optimization results and Figure 6 (b) shows framework extraction results. The main framework was extracted from the topology-optimized shape, and the shape was modified considering the manufacturability by AM and subsequent processes. Figure 6 (c) shows modified and dimensionally optimized results. Specifically, this involved angling the ceiling surface, which is an overhang, and establishing a powder removal path connecting the umbrella part and the roller housing part. Subsequently, dimensional optimization was performed using the framework dimensions as parameters, achieving approximately 50% weight reduction.

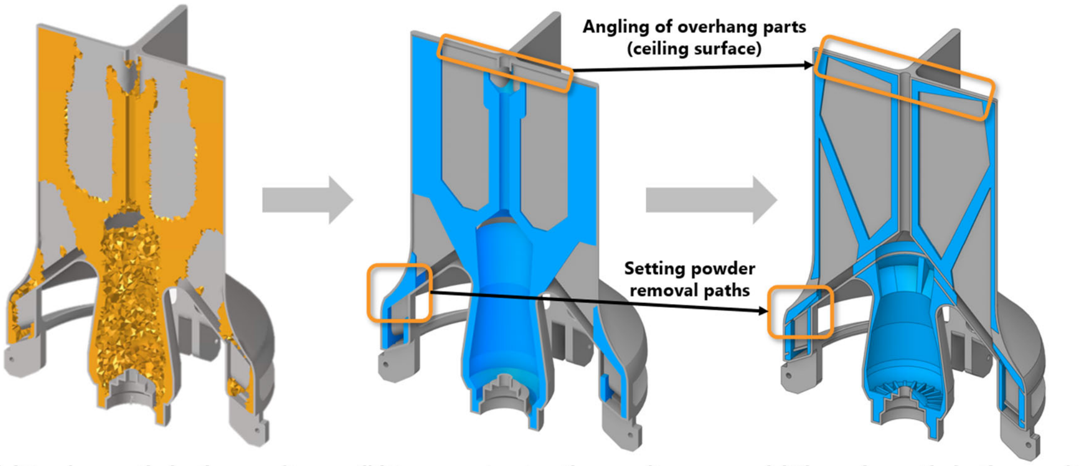


Figure 6: Results of topology optimization, framework extraction and dimension optimization

Under the no-buffer scram condition, it was confirmed that the wing section deforms in the direction of extension, and the ratio of the maximum stress to the allowable stress at the maximum stress location is 95%, which does not exceed the allowable stress. Additionally, under the earthquake scram condition, it was confirmed that the umbrella section deforms in the direction of being pushed diagonally, and the ratio of the maximum stress to the allowable stress at the maximum stress location is 97%, which does not exceed the allowable stress.

4. PROTOTYPE OF VELOCITY LIMITER BY LASER POWDER BED FUSION

A prototype of a velocity limiter for weight reduction was fabricated using a PBF-LB machine. The machine used was Concept Laser M2 made by COLIBRIUM ADDITVE (GE Aerospace company), and the powder was gas atomized Type316L made by SANYO SPECIAL STEEL Co., Ltd. Due to the limited building area and powder supply volume, the velocity limiter was divided into a wing part and an umbrella part. In addition, several holes were placed in the building model to remove the powder inside the velocity limiter after building. The building conditions were laser output 300W and laser scanning speed 700mm/s. The building time was about 36 hours for the wing part and about 110 hours for the umbrella part. Figure 7 shows the appearance of the wing part and the umbrella part after building. The upper side of the wing part is joined with the upper side of the umbrella part to form an integrated velocity limiter. From the appearance of both parts, it was confirmed that there was no building collapse and that the prototype of velocity limiter satisfied the target shape. Figure 8 shows the observation of the inner surface of the umbrella part after solution heat treatment and half-cutting. It was confirmed that the hollow structure was formed as per the 3D model, and no powder residue was found inside the umbrella part. However, a rough area was observed on the overhanging inner surface of the umbrella part. In the future, optimization of building conditions and consideration of surface treatment conditions such as shot blasting and polishing will be necessary etc. In addition, the integrated building of the wing part and umbrella part using a large building machine will be studied in parallel.

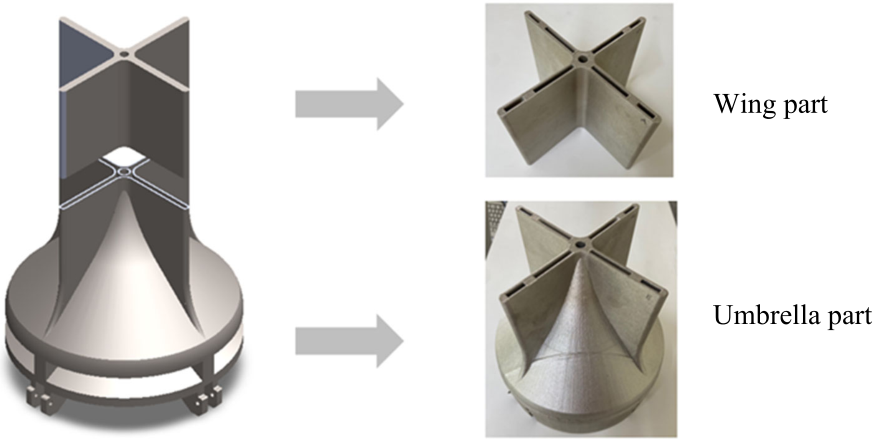


Figure 7: Velocity limiter fabricated using a laser powder bed fusion machine.

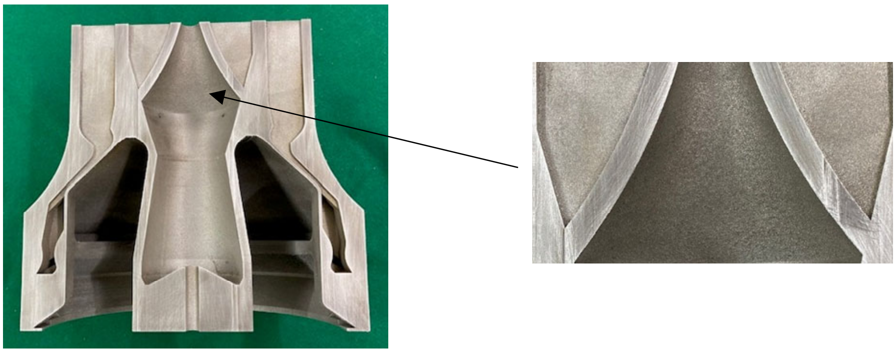


Figure 8: The inner surface of the umbrella part after half-cutting.

5. CONCLUSION AND FUTURE CHALLENGES

By maintaining the outer shape of the conventional BWR control rod velocity limiter, and considering hollowing through topology optimization and dimensional optimization as well as AM manufacturability, we have achieved an estimated 50% weight reduction without compromising the performance of the speed limiter. Additionally, we confirmed that the general shape could be fabricated using AM. Future challenges include improving the surface roughness on the underside of the overhang sections, verifying weldability, and transitioning to integrated fabrication.

6. REFERENCES

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