**Proceedings of the 17th International Symposium on the Packaging and Transportation of Radioactive Materials**
**PATRAM 2013**
**August 18-23, 2013, San Francisco, CA, USA**

# THE NEW FRESH FUEL PACKAGE FOR MOX PWR FUEL

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## ABSTRACT

The American nuclear power industry is currently based on the use of uranium oxide fuel that is used in the reactors on a once-through fuel cycle basis. The Mixed Oxide (MOX) Fuel planned to be produced at the Mixed Oxide Fuel Fabrication Facility (MFFF), being built near Aiken, South Carolina, is to be irradiated at commercial nuclear power plants. It will require a packaging that can transport the fuel assemblies safely, and also be compatible with the fuel handling systems currently in place at these plants. This paper covers the development of the PWR package, in combination with the fuel assembly that will meet all the transportation regulatory requirements while meeting the handling requirements for both the fuel fabrication and fuel utilization facilities.

The development of the package is based on the lessons-learned from testing of various fresh fuel packagings and the interaction of the fuel assembly with the package. The qualification of the package will be by full-scale testing of the package using prototypic fuel assemblies. The development of the package is a two-step process utilizing engineering test units (ETUs) to demonstrate capabilities, and provide a basis for the final qualification by the use of certification test units (CTUs), which undergo both free drop and thermal tests. The integrity of the fuel for both the ETU tests and the CTU tests will be demonstrated by leakage rate testing of the fuel cladding.

## INTRODUCTION

The National Nuclear Security Administration (NNSA) contracted with a consortium, now called Shaw AREVA MOX Services, LLC, to design, construct, and operate a Mixed Oxide Fuel Fabrication Facility (MFFF) as part of the United States program to dispose of surplus weapons-grade plutonium. The MFFF will utilize surplus weapons-grade plutonium, remove impurities, and mix it with depleted uranium oxide to form MOX fuel pellets for reactor fuel assemblies. These MOX fuel assemblies are to be transported in packages over public highways to commercial nuclear power plants where they are to be irradiated. The MFFF will be a NRC-licensed facility, and the packages are to be NRC-licensed in accordance with the Code of Federal Regulations, Title 10, Part 71 (10 CFR 71) requirements for the transport of the fuel assemblies.

AREVA Federal Services LLC (AFS), associated with the Business Unit Logistics of AREVA, was contracted by Shaw AREVA MOX Services, LLC, to develop a new Type B(U)F-96 package for the transport of fresh MOX Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) fuel assemblies from the MFFF to commercial nuclear power reactors, known as mission reactors. Separate packagings were designed for the PWR and BWR fuel types. This paper discusses the design considerations, packaging development, packaging configuration, and licensing of the AFS PWR MOX Fuel Package (PMFP).

The PMFP is a key component of the overall MOX project since it provides the following functions: 1) storage of fuel assemblies at the MFFF, 2) allow commercial transportation of the fuel assemblies, and 3) provides compatible handling features for use at existing commercial nuclear power plants. As with any fresh fuel package, a major consideration is to minimize the packaging weight to maximize the number of fuel assemblies that can be transported, and hence, reduce the number of shipments. Another consideration in the design was to make the packaging as similar as possible to the existing packaging currently being used for uranium oxide fuel assemblies since both MOX and uranium oxide fuel assemblies would be used at the mission reactors at the same time. Due to limited space available during refueling, the package needs to be capable of unloading with equipment that could be used for either MOX or existing uranium oxide fuel assemblies.

The challenge is to design such a package that would meet the desired handling requirements while meeting the regulatory requirements to protect the public. For the transport of any radioactive material, there are three main areas of concern for safety: containment, criticality control, and shielding. Shielding is not a primary concern for the MOX fuel being produced at the MFFF since the feedstock for this material is highly purified weapons-grade plutonium that has the majority of the gamma-emitting daughter products removed. The containment requirement for plutonium-bearing material is significantly different than that for uranium oxide material. Basically, plutonium-bearing material requires a leaktight containment boundary before and after the hypothetical accident events, while the uranium material has an unlimited release allowable per NRC regulations. The other major design driver for the package design was to maintain criticality control.

## SUMMARY OF DESIGN REQUIREMENTS

A brief summary of the key design requirements is as follows:

- Contents: The package is designed to ship two PWR fuel assemblies. The fuel is composed of MOX pellets that consisted of blended down weapons–grade plutonium and depleted uranium. The cavity size is designed to accommodate a basic 17 × 17 type of PWR fuel assembly. Additional length is added to handle potentially new fuel of similar cross section.
- Containment: The containment to be leaktight both during normal conditions of transport and after the hypothetical accident conditions of 10 CFR 71.
- Criticality Control: Criticality control is maintained by controlling the geometry of the fuel assemblies, and by a combination of borated aluminum and rigid hydrogenated material.
- Maximum Gross Weight: 10,000 pounds (4,536 kg) due to facility limits.
- Handling: Unsupported fuel assemblies must be lifted in the vertical orientation by an overhead crane. The MFFF has limited crane hook height, thus prohibiting the loading of fuel assemblies from the end of the package. The package must be loaded onto an up-ending machine to allow vertical fuel loading at the MFFF and unloading at the mission reactors. The package must also be capable of forklift or crane handling in the horizontal orientation.
- To be licensed as a Type B(U)F-96 package for the MOX fuel assemblies.

- Transportation efficiency to be maximized, including loading and unloading activities.
- The package to be designed for loading and storing of the fuel assemblies at the MFFF.
- The package is designed for unloading at mission reactors with minimal transition from current uranium oxide packages.

## DESIGN CONSIDERATIONS

The previous approach of utilizing a simplified leaktight packaging of a right cylinder with a leak testable circular end seal was not desirable or efficient for existing mission reactors. When required, the containment safety function is provided by the package rather than the fuel assembly. The approach utilized for this design relies on the fuel cladding integrity to satisfy the containment function since the cladding is constructed under a nuclear quality assurance program and is tested similar to what would be performed for a package that provides a separate containment boundary. The fuel rod is pressurized with helium prior to welding the end fitting, and is then leakage rate tested as part of the manufacturing process.

One challenge is to define the failure mechanisms of the fuel cladding and design a protective overpack to ensure that the cladding does not experience any of those mechanisms. Examination of previous testing of packages and fuel assemblies demonstrated that the fuel rod could fail when the rods underwent severe bending and/or shear action. The rods could withstand significant bending provided a rod did not undergo reverse bending. In addition, a fuel rod was also susceptible to shearing due to the thin wall of the cladding. The thin wall could also lead to failure under large crushing loads. The evaluation of the fuel failure mechanism for the PMFP was similar to that developed by Sandia National Laboratories with appropriate corrections for the un-irradiated published material properties [1].

A fuel assembly is a complex structure made up of a large number of fuel rods, tie rods, water tubes, nozzles on each end, and grids along its length, making it difficult to evaluate utilizing analyses alone. However, test results have demonstrated that if the design could prevent the buckling and bending of the fuel rods, and the rods had only minor movement relative to the other fuel assembly components, the fuel cladding integrity could be maintained. Traditionally, fuel packages used for shipping fresh fuel assemblies were very stiff and had relative little energy absorption capability. These configurations resulted in very high impact loads being transmitted to the fuel assemblies. The high impact loads not only affected the fuel assembly directly but it also allowed significant interaction of the fuel rods with other fuel assembly components.

The fuel assembly could be protected from outside influences and overall bending by designing a protective cavity around the fuel assembly. However, the interactions of the fuel assembly components could only be addressed by reducing the applied loads since any contact with the fuel assembly other than the outer grids and end tie fittings was not permitted. This approach has been proven to be successful in the design of other Type B fresh fuel packages [2].

Criticality control is addressed by including geometry, absorption, and moderation features within the package. The rigid structural fuel cavity is designed to provide the geometric control. Borated aluminum and thermoplastic sheets are arranged around the fuel cavities for neuron absorption and moderation, respectively.

Unlike uranium oxide fuel packages, the decay heat from the MOX fuel provided a design challenge for the PMFP. Although not extremely high at a bounding design value of 80 watts per fuel assembly, the decay heat is sufficient to have an effect on both normal fuel handling and during the regulatory hypothetical accident conditions. Not only do the fuel assemblies need to be protected from the regulatory thermal event, but also the neutron absorber and moderator materials require protection. Additionally, the foreign material exclusion barrier for the fuel assemblies had to be selected for the increased normal shipping temperature. Modifications in the design were required to accommodate the higher potential temperatures during transport and as the starting temperatures for the regulatory thermal event. This condition included the proper selection of materials to accommodate the differences in thermal expansion.

## DESIGN

The design of the PMFP is based on the design of the MAP fresh fuel package (USA NRC Certificate of Compliance USA/9319/B(U)F-96 [2]. The MAP package was qualified by test that demonstrated that the fuel assemblies could be adequately protected during the hypothetical accident events as well as providing an efficient package for the fuel assembly transport. The PMFP is of similar configuration, and is shown in Figures 1 and 2. It is planned to be qualified in a similar, but more rigorous manner.

The MOX fuel assemblies were evaluated to establish load limits for various orientations, based on previous testing results. The fuel acceleration limits were then used for sizing the packaging impact protection and internal structures. Sizing calculations were utilized to ensure the expected applied loads were below the limits found by evaluating the fuel for different orientations and conditions. Impact protection was based on past uranium oxide packages and modified for optimization. In reviewing the performance of previous packages and the response of the fuel assembly interaction, several improvements to provide larger margins for the MOX fuel assemblies were incorporated into the design.

The same diagonal fuel assembly orientation concept used for the MAP package design was used for the PMFP (refer to Figure 3). The advantage of the fuel assemblies in this orientation allows the assemblies to withstand slightly higher impact loadings. Also, the fuel doors and end restraints can be preloaded quickly and efficiently to minimize any movement during transport. The fuel bed, in which the fuel assembly lies, provides a protective shell in combination with the doors around the fuel assemblies. The fuel bed is structurally secured to the remainder of the package base. It uses a space frame type of approach that provides significant stiffness to the package to preclude any bending of a fuel assembly in either normal handling or hypothetical accident conditions. In the PMFP, the fuel bed thickness was increased from the MAP packaging design to facilitate the fabrication and reduce weld distortion. The increased fuel bed thickness also provided a larger design margin for the fuel assembly components, such as the end nozzles moving relative to the fuel rods.

An important MAP package design feature in the PMFP is the use of a spacer under the bottom end nozzle that prevents deformation of the bottom nozzle plate, which is common in fresh fuel packages where the nozzle plate is not supported [3]. In addition to the support spacer, the package incorporates tapered end impact limiters of polyurethane foam on each end to reduce the axial impact load to the fuel assemblies. Although the end impact limiters on the MAP package successfully prevent any buckling or damage to the fuel during drop testing, the end impact limiters on the PMFP were lengthened slightly to provide additional margin against fuel assembly damage.

To accommodate the higher decay heat of the MOX fuel assemblies, a higher melting temperature for the thermoplastic moderator was selected to be over 490 °F (255 °C). The moderator and neutron absorber are secured by the transverse stiffening ribs, and are in a sealed cavity with air immediately outside of the moderator. This configuration provides added thermal protection during the hypothetical accident condition thermal event. The body foam, both in the lid and the base, was increased in density from the MAP packaging design to provide better conductivity during normal conditions for the decay heat removal, and also better thermal protection during the hypothetical thermal event. A double layer of ceramic fiber paper is also used on the exterior of the body foam to provide additional thermal protection, as previously proven in both bench testing and full-scale fire tests. The fiber paper provides additional thermal protection of the foam that permits reduced thickness of foam. The exterior shell has also been increased in thickness to prevent the puncture of the outer steel sheet. Although the MAP packaging design was successful with a partial penetration of the outer steel sheet due to the puncture drop, there was a small amount of melting of the thermoplastic moderator immediately beneath the puncture location in the fire event.

Based on the bounding allowable impact loads that the fuel is expected to be capable of withstanding, several additional features were modified on the PMFP. Unlike the MAP design where the external spacers were fabricated from hollow formed sheet metal, the PMFP spacers are larger and filled with polyurethane foam to provide predictable impact energy absorption. By increasing the stroke and filling with polyurethane foam, the expected impact loads can be managed. A collar impact limiter was also added at each end of the lid to reduce the potential impact loads during a slap down free drop event. In testing of the MAP, it was noted that the stiffer end plates at certain angles would contact the impact surface, and could introduce higher than desired loads being transmitted to the fuel assemblies. The collar impact limiter, which can be seen in Figure 1, reduced the potential for this end plate contact. In the PMFP design, the package is also heavier, and the body foam is of higher density.

The end impact limiters are an integral part of the lid, as shown in Figure 1. The lid and end impact limiters are secured to the base by the use of interlocking angles at each end, and (44) ball lock pins. This closure has proven to be a labor saving and efficient method of loading and unloading the package for fuel handling operations. In the final design, one of the impact absorbing spacers will also be modified to accommodate a radio transmitting tamper indicating device that is being developed.

The package lid is removed from the base in the horizontal orientation. The base is then secured to an up righting frame that is used to upright the package to a vertical position for fuel loading and unloading. Prior to up righting, the end restraint bar for the fuel assemblies is removed. Once the package base is in the vertical position, the fuel doors may be opened and a fuel assembly may be loaded or unloaded. An upper fuel spacer is used to interface the top of the fuel assembly with the end restraint bar. A unique fuel spacer is required for each fuel assembly length.

The impact absorbing spacers required for reducing impact forces resulted in a wider package, thus preventing the shipment of two packages side-by-side on the transport trailer. The gross weight of the PMFP is approximately 9,600 pounds (4,355 kg), which limits a legal-weight conveyance within the United States to five packages that contain ten fuel assemblies (refer to Figure 4).

## REFINEMENT AND CERTIFICATION

The certification plan for the PMFP includes developing ETUs that are subject to drop testing, and then incorporating any design improvements into the CTUs. The complete CTU test results will then be included in a NRC application. Since one of the main features that have to be demonstrated for the package is containment, prototypic fuel assemblies with containment boundaries (i.e. fuel cladding) will be fabricated to the same standards that will be used for production fuel, and will be used for both ETU and CTU testing. This configuration means each fuel rod is pressurized with helium, welded shut, and leakage rate tested to demonstrate leak tightness per ANSI N14.5.

Currently, the packaging development of the MOX project has been placed on hold as the US Department of Energy (DOE) has been instructed to evaluate alternatives for disposal of the weapons-grade plutonium. Two ETUs and prototypic fuel assemblies using tungsten carbide pellets to simulate the MOX fuel pellets have been fabricated, Figure 5. When the project is restarted, the current plan is to perform free drop tests of each ETU twice from 30 ft (9 m), followed by 40-in (1-m) puncture drop tests. Each ETU will be tested with one prototypic fuel assembly and one ballast assembly (consisting of steel plates having the same mass and bending properties as a MOX fuel assembly). One ETU will be tested cold, and the other ETU will be tested hot. These packages will also be instrumented with active accelerometers to measure and record impacts. The fuel assemblies at the completion of the drop testing will then be helium leakage rate tested in accordance with ANSI N14.5. Each fuel rod will also be punctured at the end of the leakage rate test to verify the presence of helium within the rod.

Based on the results of the engineering tests, the package design may be modified for the certification tests. The certification test orientations will then be selected based on both the ETU tests and the MAP certification tests that were previously performed. The two CTUs will focus on two different types of tests. The first CTU will undergo test orientations that will be the most challenging to the fuel assembly. The second CTU will be tested in orientations that are judged to impart the most damage to the packaging. The most damaged CTU will then be exposed in a pool fire in accordance with 10 CFR 71. Following the fire test, the prototypic fuel assemblies will then undergo the same leakage testing and helium verification as described for the ETUs. Based on that performance testing, the Safety Analysis Report (SAR) will be prepared and submitted to the NRC for licensing.

## CONCLUSION

A new MOX PWR packaging has been designed to transport two fuel assemblies. The PMFP packaging is designed as Type B(U)F-96. Based on the successful MAP package design, the PMFP is easy to load and unload while allowing up to five packages to be placed on a conveyance. It is efficient not only for transport but for storing fuel and compatibility with uranium oxide fuel handling equipment currently used at commercial nuclear power plants. The packaging protects the fuel assemblies from damage, allowing the fuel cladding to satisfy the required containment safety function for the MOX fuel. Developmental and certification testing will be conducted using prototypic fuel assemblies for both the ETUs and CTUs. Currently, two ETUs have been fabricated and testing will be completed in the next phase of the project. Testing will demonstrate the adequacy of the design. Certification testing will be used to license the package for the transport of MOX fuel assemblies.

## REFERENCES


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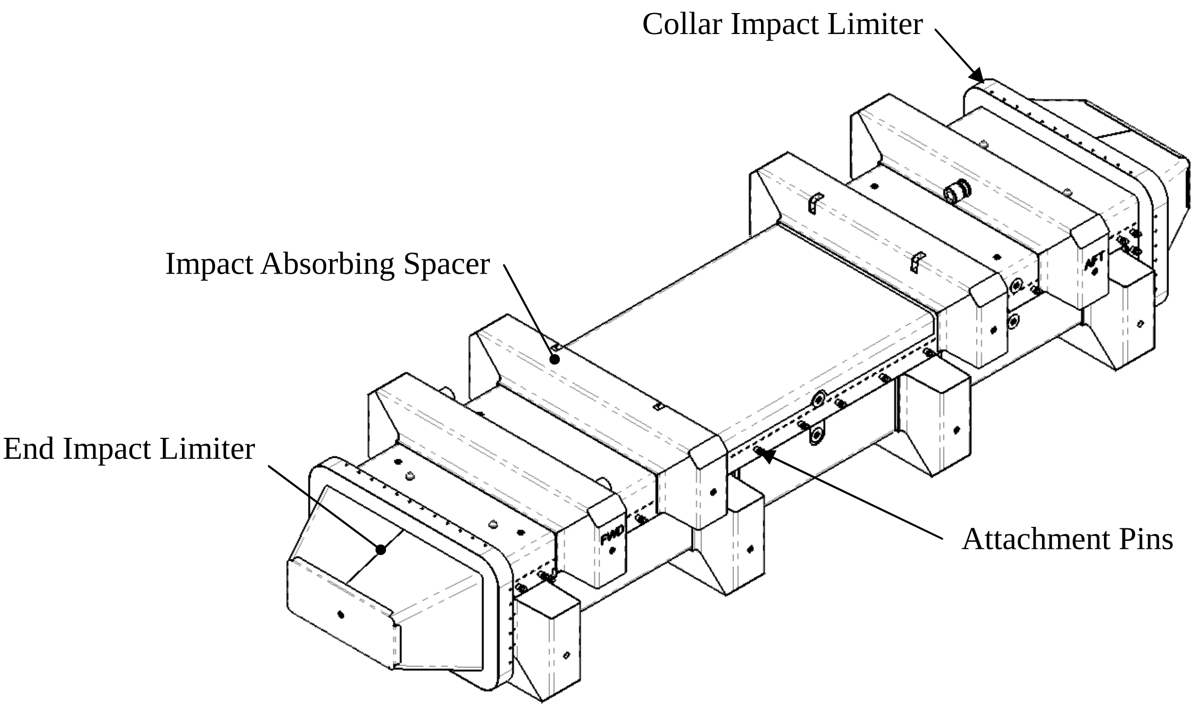


**Figure 1. PMFP Design**

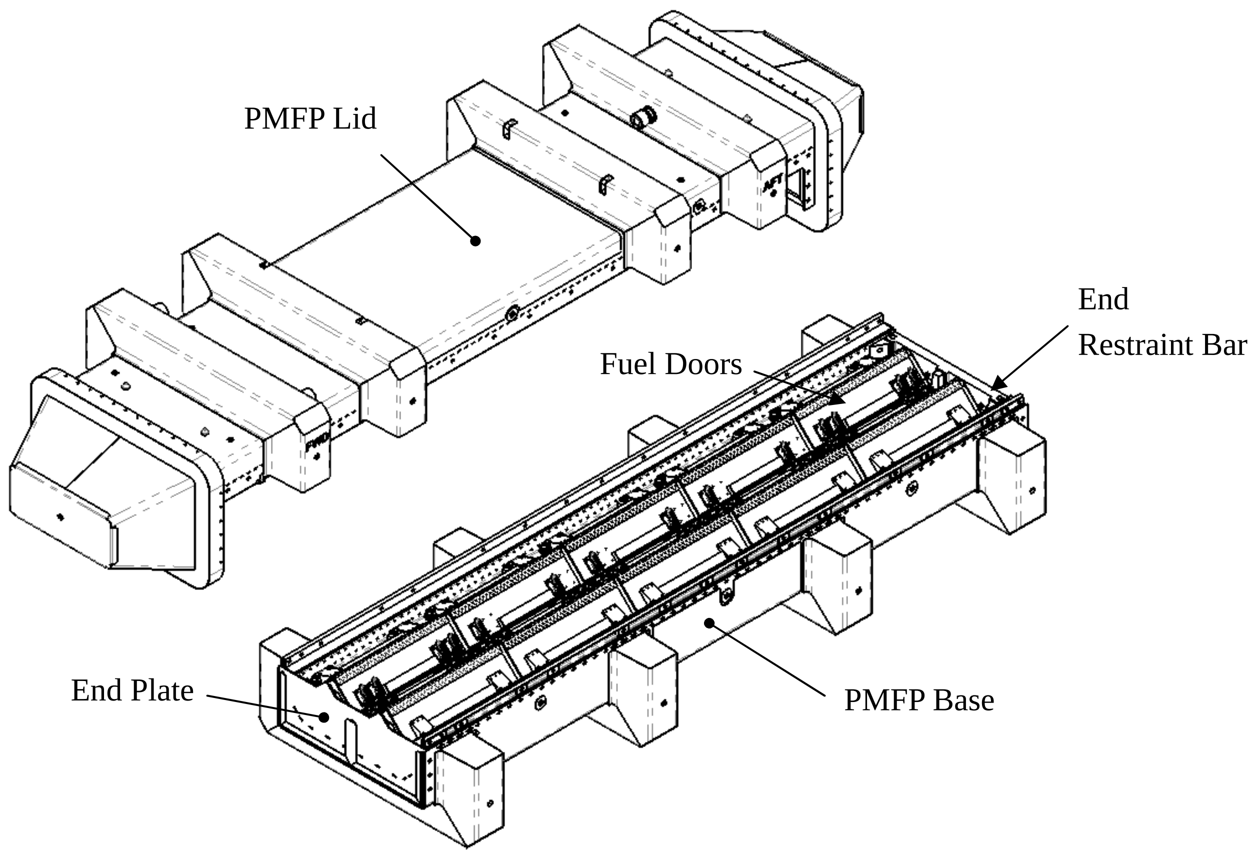


**Figure 2. PMFP Lid and Base**

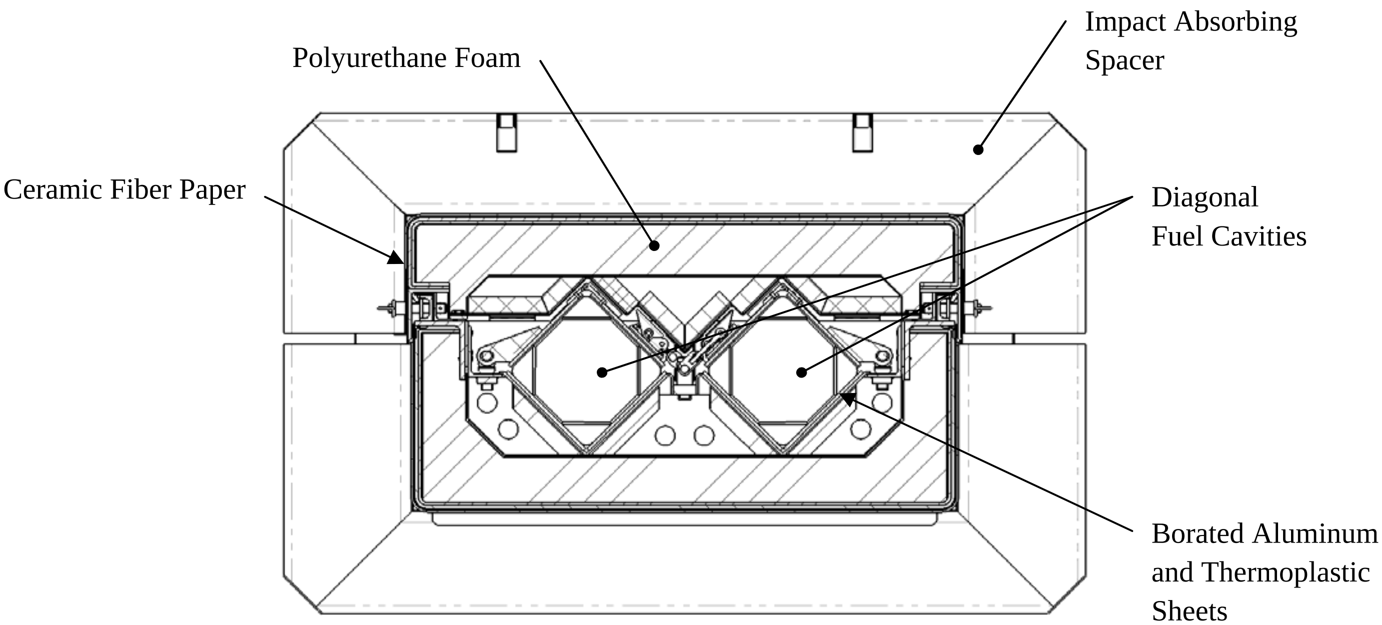


**Figure 3. PMFP Cross-Section**

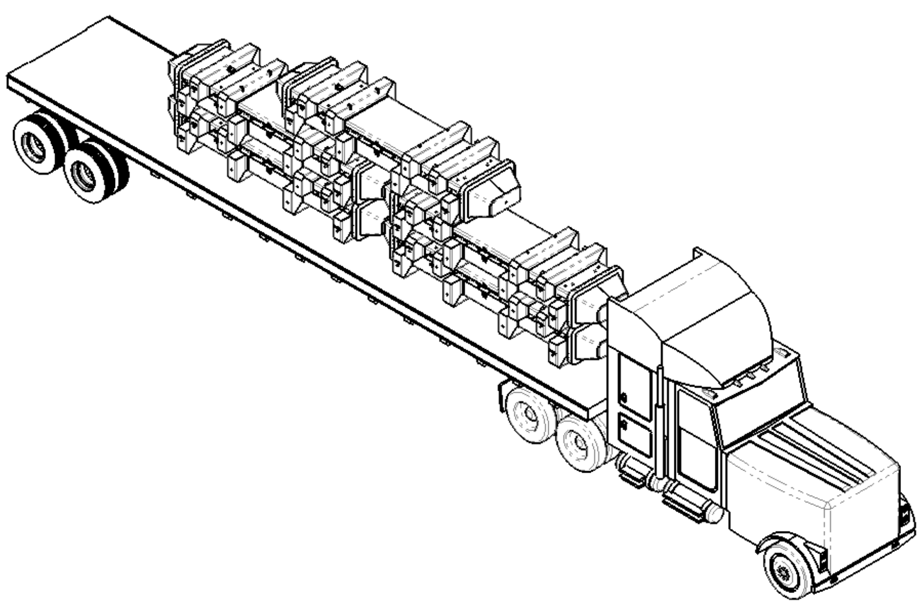

**Figure 4. PMFP - Transport Arrangement**


**Figure 5  PMFP ETU**