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Development of a Non-Metallic Composite Fuel Support Structure For Transport And Storage

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ABSTRACT

A new package for the transport and storage of CANDU® reactor fuel includes the use of stackable fuel bundle support trays made from lightweight, fiberglass-reinforced plastic resin. Plastic resins with high temperature- and impact-resistance make it possible to design an easily manufactured, close-tolerance fuel tray meeting all the IAEA requirements for transport and storage.

The primary function of the trays during the hypothetical accident is to limit fuel bundle reconfiguration for criticality control. However, the trays must also support and protect the bundles during normal transport, and be easy to use. This paper will discuss the qualification of the material and the design of the trays for normal, accident, and operational conditions of use. Economic aspects of the design for large quantity manufacture will also be discussed.

INTRODUCTION

Historically, the structural components of transportation packages have been constructed from metallic materials (Figure 1). Often the materials chosen were austenitic stainless steels for their resistance to corrosion and to brittle behavior at low temperatures. This paper presents the considerations and testing undertaken to qualify a reinforced polyester material for use as a structural component in a transport and storage package (Figure 2).

The most important considerations were the brittle fracture behavior at high strain rates (accident conditions) along with the material's ability to withstand the temperatures associated with the regulatory fire and in this case the added storage area fire.

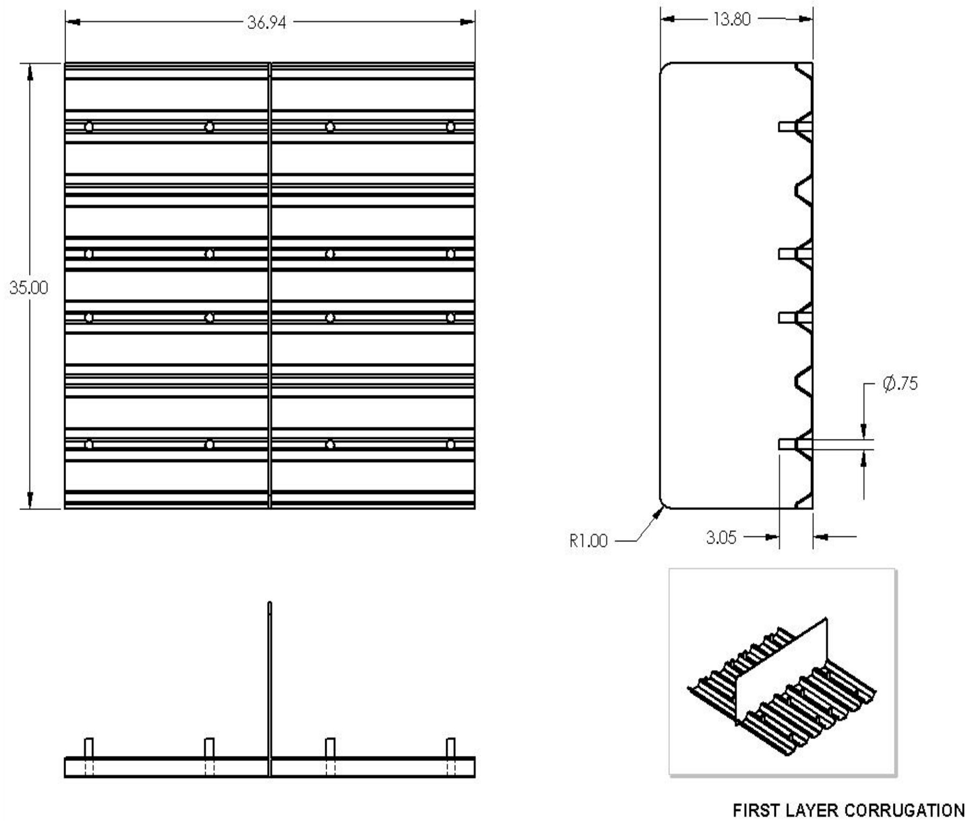

Figure 1- Initial Metallic Trays

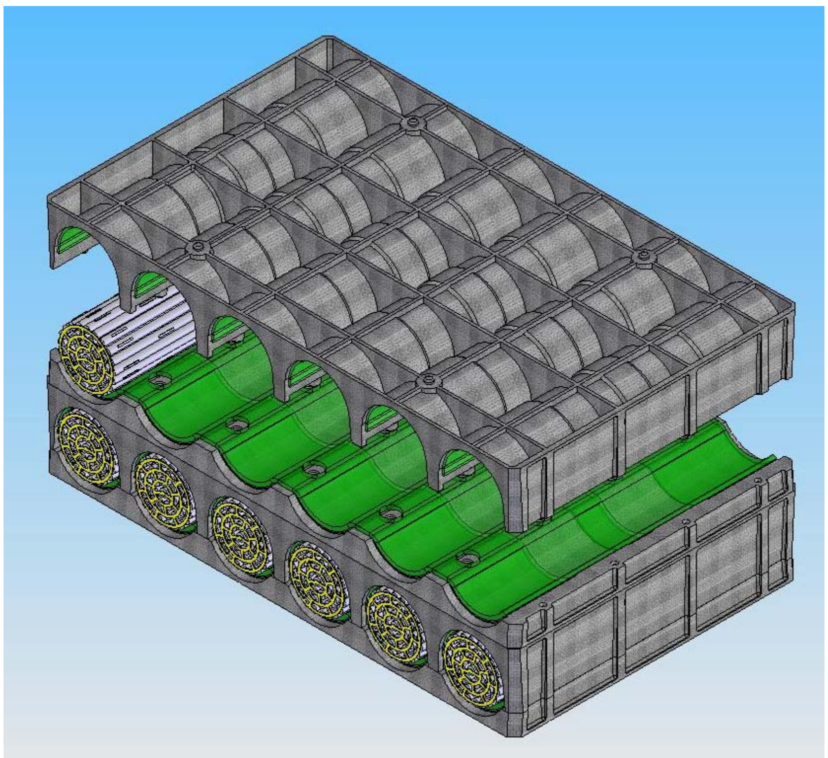

Figure 2- Composite Trays with Fuel Bundles

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DISCUSSION

Traditional package internals or baskets have been limited to metallic components, usually steel (stainless or carbon) or aluminum. For a single or small number of production packages these have proven to be cost effective and have a demonstrated record of surviving accident conditions. Non-metallic materials with superior thermal and structural properties have been developed for use in the automotive, aerospace and defense industries for high temperature under hood components, aircraft structural components and ballistic armor respectively. With the accepted application of non-metallic materials in these industries and applications, their use in transportation packages has become viable. With the proper selection of compounds, non-metallic materials that can survive both impact loads and high temperatures can be used to meet the requirements of a radioactive transport package. The added benefits of using these materials for components with large production quantities is that following qualification of tooling, the parts can be made economically with repeatable geometry ensuring interchangeability.

In a recent package, composite fuel support trays are contained within a double walled cargo assembly (Figure3), used for on site storage, and the cargo assembly is contained within a double walled outer shell for transport (Figure 4). The complete assembly is required to meet the normal conditions and accident conditions of transport (NCT and ACT) as specified by IAEA Transport Regulations, TS-R-1. Additional site specific requirements include a 30 minute, 550°C storage area fire and a 15' drop. Both requirements are for a loaded cargo assembly (the transportation overpack is not present). The heat generated from burning the fuel support trays for an open container during a facility fire was also subjected to limits.

Initial package design relied on traditional (metallic) materials. Problems were encountered with meeting the design weight and cost requirements. Investigations into alternate materials were undertaken and reinforced plastics were proposed initially for their light weight. Several different manufacturing processes were considered to create the desired geometry and structural characteristics. Consideration was also given to the relatively high production for the components due to the dual transportation and storage requirements.

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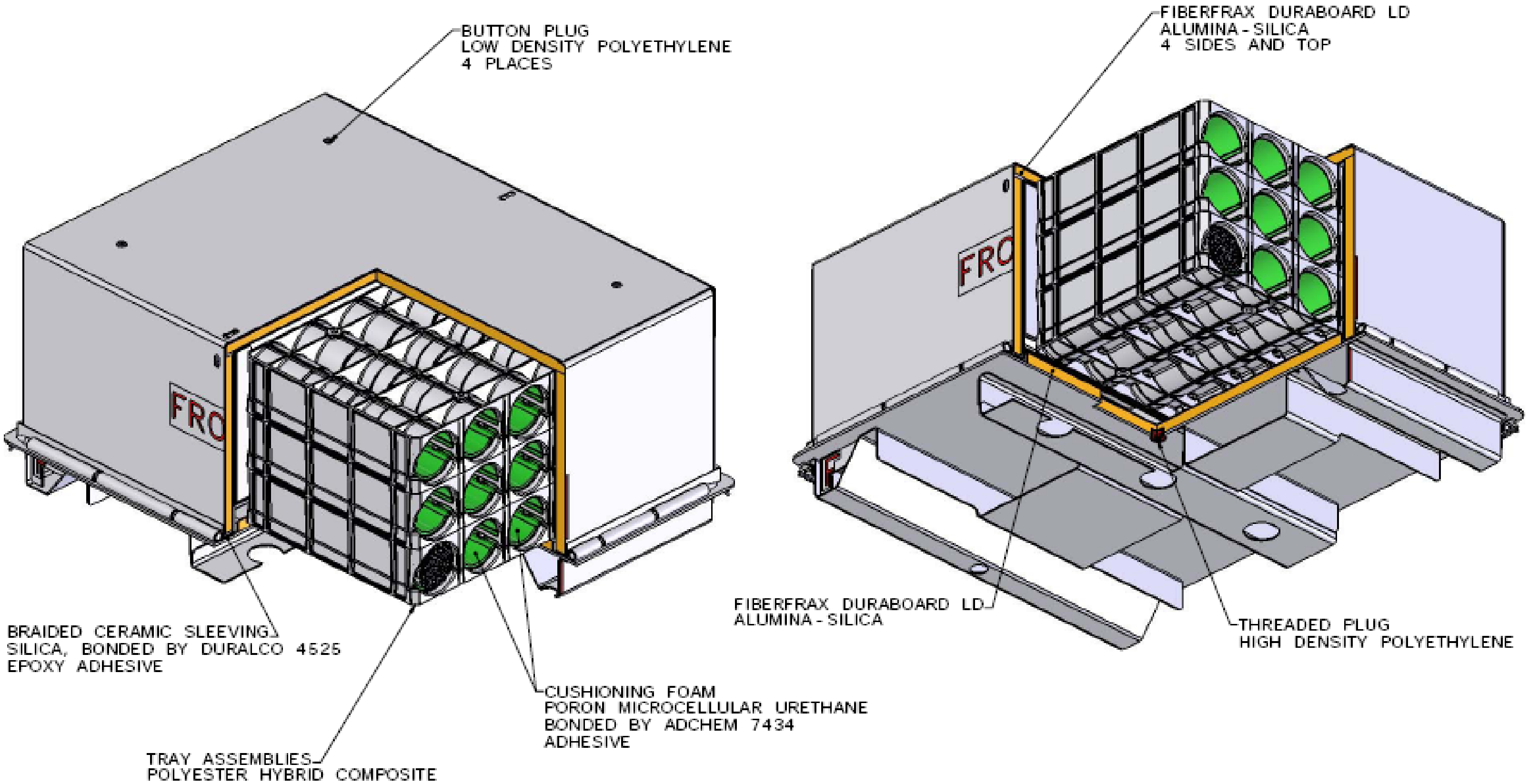

Figure 3- Loaded Cargo Assembly Sectional View

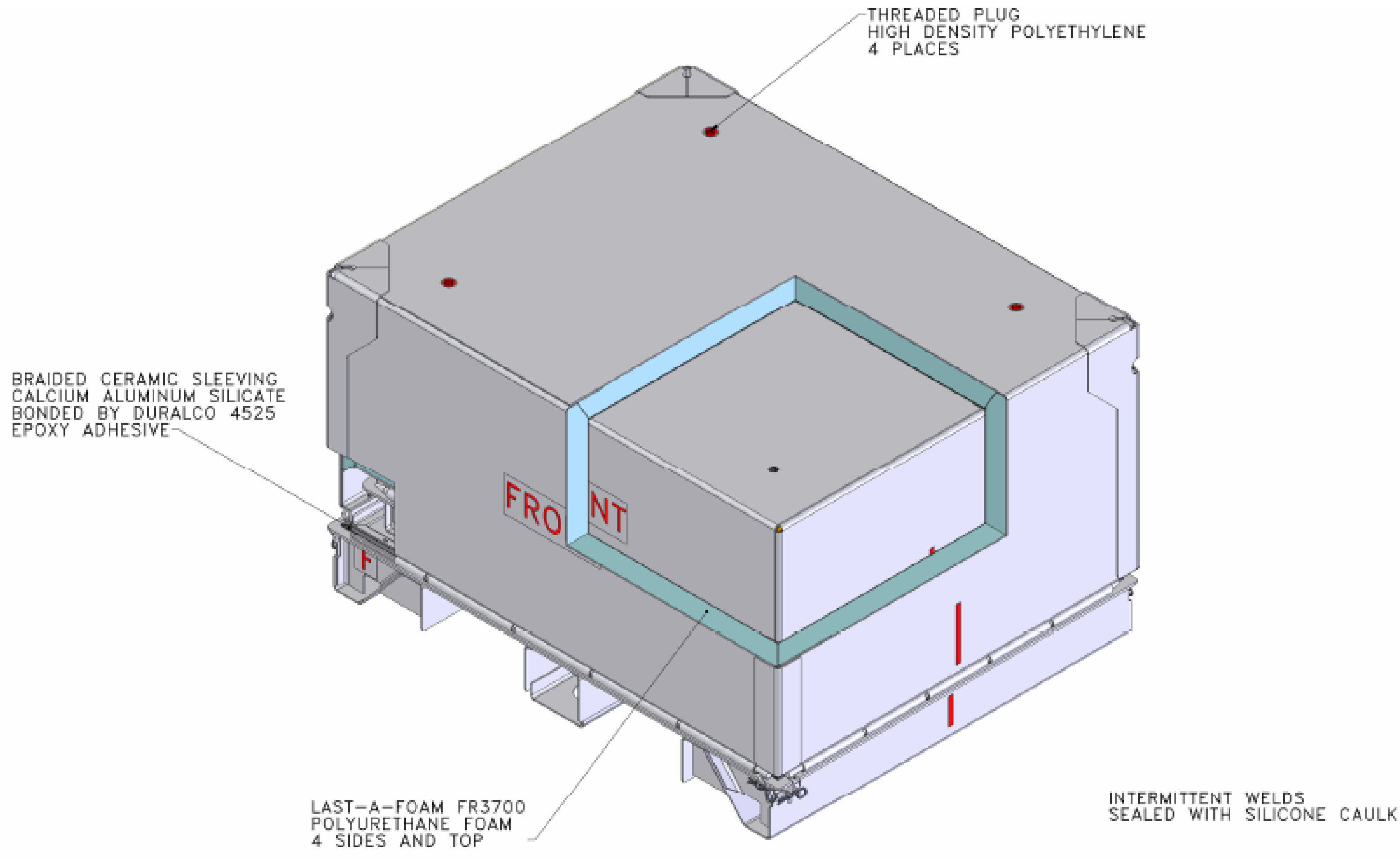

Figure 4- Complete Assembly Sectional View

MANUFACTURING / PROCESSES

Manufacturing methods considered for the fiber reinforced plastic (FRP) fuel support trays were:

1) Traditional wet layup where layers of cloth and mat are spread over a single sided mold and saturated with either polyester (lower cost) or epoxy (higher strength) resin;

2) Resin transfer molding (RTM) where a preformed reinforcement is placed in a two sided tool. With the tool open, resin (again polyester or epoxy) is injected into the mold. The mold is forced closed and the pressure causes the resin to be distributed through the reinforcement;

3) RTM-Lite where the reinforcement is not a preform but laid by hand on a single sided tool. A plastic deformable covering is placed over the reinforcement and resin is added. A vacuum is drawn on the back of the part and the air pressure causes the resin to be distributed throughout the reinforcement;

4) Bulk Molding Compound (BMC) or Sheet Molding Compound (SMC) where logs or sheets respectively of premixed material are placed in a heated two sided mold. The mold is forced closed and the combined heat and pressure cause the material to "flow" through and fill the mold;

5) Epoxy Prepreg where preimpregnated (with a temperature activated resin) cloth and mat is placed on a single sided tool, vacuum bags are applied when the layup is complete and the part and tool are placed in an autoclave and heated under vacuum allowing the material to cure.

For any FRP part, shrinkage is important during manufacture. The part geometry may be easily verified from tool measurements. Following molding, overall part dimensions are used to determine part shrinkage and thus final part dimensions. For example, all part detail is measured on the production tool and includes overall length, width and height. The initial parts are measured for length, width and height. This allows a shrinkage factor to be calculated in each orthogonal direction and the part dimensions may be calculated using the initial tool dimensions and the calculated directional shrinkage.

All of the processes discussed above are able to produce parts of the required dimensions with the required structural and thermal properties. The main consideration as to which process was chosen came down to the required production rates, costs and the testing requirements to ensure these properties were uniform throughout production.

With the potential processes identified, attention was given to which properties were important in making the material selection and how and when these properties would be measured throughout production.

The fuel support trays were determined to be quality category B component for use in criticality control during transport. The requirements for the material properties for this project focus on the ACT as defined by the IAEA and how the material would survive:

1. The material could not spontaneously combust under either accident or storage conditions at the temperatures experienced during either the regulatory fire or the storage area fire.
2. The material must maintain some structural capability when exposed to direct flame.
3. The material must not undergo brittle fracture under normal or accident conditions.
4. The material must be shown to be uniform throughout production.

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5. The material must maintain the required structural integrity during accident conditions to provide the required criticality control.

As earlier discussed, additional storage conditions were defined where the support trays and fuel were in a closed storage container during a facility fire including a separate requirement where an open storage container was in a facility fire exposing the support trays to direct flame. The closed container storage area fire was determined, by analysis, to expose the support trays to higher temperatures than the regulatory fire when the package does not expose the support trays to direct flame following the regulatory drops. Testing verified the validity of this assumption.

The material properties to be specified and monitored were determined to be:

1. Tensile strength (ASTM D638)
2. Reinforcement (glass) proportion
3. Cure and Gel times
4. Izod Impact Energy, Notched (ASTM D256)
5. Flash and Self Ignition Temperatures (ASTM D1929)
6. Specific Gravity (Relative Density) (ASTM D792)
7. Flame Retardance (UL-94)
8. Total Energy Release when burning (ASTM E1394)

The tests chosen were all standard tests, allowing broad understanding of the test methods, repeatability and ease of finding facilities capable of performing the testing.

The material testing was chosen and used to verify part uniformity as follows: Tensile testing is used in conjunction with the proportion of glass and the relative density to verify the correct resin/glass ratio is maintained; the cure and gel times verify the proper resin/hardener proportions are maintained; a modified flame retardance test is to verify the proper proportion of flame retardant additives has been included. These tests are performed on each material batch. The remaining tests were performed to qualify the material, and when the batch tested properties are maintained, these properties will also be present.

The above tests may be performed for any of the materials / processes discussed. There is some variation in how the tests would be performed and in the test frequency for the material / process chosen. For any of the manual layup processes (Wet Layup, RTM-Lite, Epoxy Prepreg), the layup sequence would require monitoring because the material's structural strength is a function of both the proportion and the orientation of the reinforcement. The remaining processes (RTM, BMC and SMC) generally have randomly oriented reinforcement so the structural strength is generally proportional to the proportion of reinforcement. The strength of the RTM fabricated parts may only be determined post molding because the two main components (reinforcement preform and resin) are separate until molding is complete. For this process as well as the manual processes, a runoff tab or offcut is the easiest method to obtain testing samples. Both the BMC and SMC processes have pre-mixed raw material including both the resin and reinforcement.

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For these processes, test samples may be obtained from each raw material batch and if cured under production processing conditions will yield representative properties.

These final two materials / processes are very similar in that temperature and pressure cause the material to become liquid allowing both to fill the mold. The main difference in the two processes is in the form the raw material takes. In the BMC process, the material is in a cylindrical shape of standard diameters and is cut to length to achieve the desired shot weight. The SMC material is in the form of sheets. The geometry of the support trays is long and wide with a uniform thickness. This geometry lends itself to the SMC form because there are shorter flow lengths (the distance the material must flow to fill the mold). This is important because the larger the flow length, the more orientation is present in the molded part. While both are repeatable, consideration must be taken in design of the parts to minimize the impact of this anisotropy. Minimizing anisotropy was important to this design where design verification was by test in order that drop orientation considerations would not be controlled by anisotropy.

The SMC process was ultimately chosen for the following reasons:

1. Lowest projected cost – including fabrication of two part metallic tooling.
2. Reduced Test Frequency: For this material / process, property testing may be performed on each material batch. The batch size is determined by material shelf life and production rates. The other materials / processes (except BMC) would require additional monitoring and a series of 16 tests per fabrication lot to meet normal sample requirements.
3. Higher Production Rates: A single tool set can be expected to produce 100 pieces / shift. Multiple tools would be required for the other materials/ processes (except BMC) to meet this production rate. This would increase initial tooling cost, tooling qualification and may affect part interchangeability.

Conclusion

Many processes are available to produce fiber reinforced plastic parts meeting structural and temperature requirements for use in radioactive materials packagings. High strength to weight ratios may be obtained at relatively low cost. The manufacturing process chosen may have a large impact on material testing requirements. Initial part geometry verification is ideally based on tool geometry and minimal dimensional verification of the production parts will verify actual part dimensions removing the requirement for extensive dimensional verification for large production runs. FRP lends itself to complicated geometries with a minimum number of components. For a given material, part strength, cost and weight are directly proportional (an increase in part thickness increases strength, weight and material cost). The higher production processes do not lend themselves to rapid changes in geometry due to the tooling used (geometry changes require the tool be taken out of service while changes are made). For this application, SMC was chosen due to reduced material test frequency and lowest projected cost.