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# Safety Considerations for the Addition of 1S and 2S $UF_6$ Cylinder Contents and Air Transport Capability for the Versa-Pac

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## 1 Abstract

The Versa-Pac is a certified Type A fissile packaging (USA NRC Certificate # USA/9342/AF-96), which has previously been used for the transport and disposal of waste materials. Continuous content additions have improved the versatility of the package resulting in expanded uses for the industry. The Versa-Pac is used directly or in conjunction with a pipe container (legacy 2R vessel), poly bottles, and a variety of other containers, inserts and vessels. An expansion of the authorized contents in the Versa-Pac aids the nuclear industry with the shipment of front-end feed materials in support of high assay low enriched uranium (HALEU) fuel development. The 2019 NRC license amendment adds new drop testing results and updated thermal analysis to support new contents, which include 1S and 2S $UF_6$ cylinders, increased payload mass, expanded $^{235}U$ enrichment loading, and the allowance to transport the package via air for any approved content. The addition of these capabilities for the Versa-Pac has presented a unique set of challenges in developing the safety basis for the package. The development of insulation and confinement components was required to satisfy all regulatory and ANSI N14.1 / ISO 7195 cylinder requirements. Additional consideration was also given to both criticality safety and public exposure due to the risks associated with air transport.

## 2 Introduction

The Versa-Pac is a drum-style package that has been used to store, transport, and/or dispose of uranium materials in almost any form at any U-235 enrichment. The Versa-Pac is a Type AF package, designed to provide familiar, simple-to-use packaging with economical and versatile options for miscellaneous uranium contents and wastes. Figure 1 shows an exploded view of the Versa-Pac design and Figure 2 shows an array of Versa-Pac packages staged at the completion of fabrication activities.

The contents permitted in the original Versa-Pac package license were initially restricted to uranium compounds at any enrichment limited based on a criticality analysis modeling 100 wt% $^{235}U$. While this initial license provided significant flexibility in the form and enrichment of the contents, it was limiting in terms of the allowable mass of fissile material in the package. Therefore, the package license was revised in 2015 to add an enrichment curve with set mass limits for a number of enrichment bands (i.e. ≤5 wt%, ≤10 wt%, ≤20 wt%, and ≤100 wt%) and introducing a new 5-inch pipe component to restrict geometry of the fissile material in the package. For this content expansion, the structural integrity of the 5-inch pipe container and its ability to provide geometric confinement for the fissile material, was demonstrated through drop testing of the component and the criticality analysis was expanded to analyze lower enrichments and the 5-inch pipe configuration. There were no new or unique methods or additional considerations required. The efforts required were relatively straight forward, and there were no significant challenges presented in demonstrating package safety and regulatory compliance.

The 2019 licensing activities have expanded the permissible contents to include a lower enrichment band of ≤1.25 wt% and increased the content mass to 158 kg (350 lb). These additions to the license were made via the same methods as before, with a supplemental criticality analysis and new drop testing. The base Versa-Pac and 5-inch pipe fissile limits are listed in Table 1.

**Table 1 – Versa-Pac Content Limits**

| Enrichment (wt% $^{235}U$) | $^{235}U$ Mass Limit (g) | |
|---|---|---|
| | Base Package | With 5-inch Pipe |
| ≤ 100 | 350 | 695 |
| ≤ 20 | 410 | 1,215 |
| ≤ 10 | 470 | 1,605 |
| ≤ 5 | 580 | 1,065 [1] |
| ≤ 1.25 | 2,000 | - |

Notes: [1] Limited by the volume of the 5-inch Pipe

Additionally, due to increased industry demand, the Versa-Pac license was amended by the NRC in 2019 to allow for the transport of small $UF_6$ cylinders (i.e. 1S and 2S cylinders) and to allow for air transport of the package. For these additions there were new confinement, criticality, and general public safety considerations necessary.

To add 1S and 2S cylinders as acceptable contents it was necessary to demonstrate the ability to meet the ANSI N14.1 thermal and mass requirements and justify the confinement of material in the cylinder for criticality and material compatibility concerns. To add shipments via air as a permissible mode of transport, consideration for the enhanced accident testing and the hazards from a potential release of material was required. Both of these additions presented challenges for demonstrating regulatory compliance and general safety of the package, beyond the efforts of previous content additions.

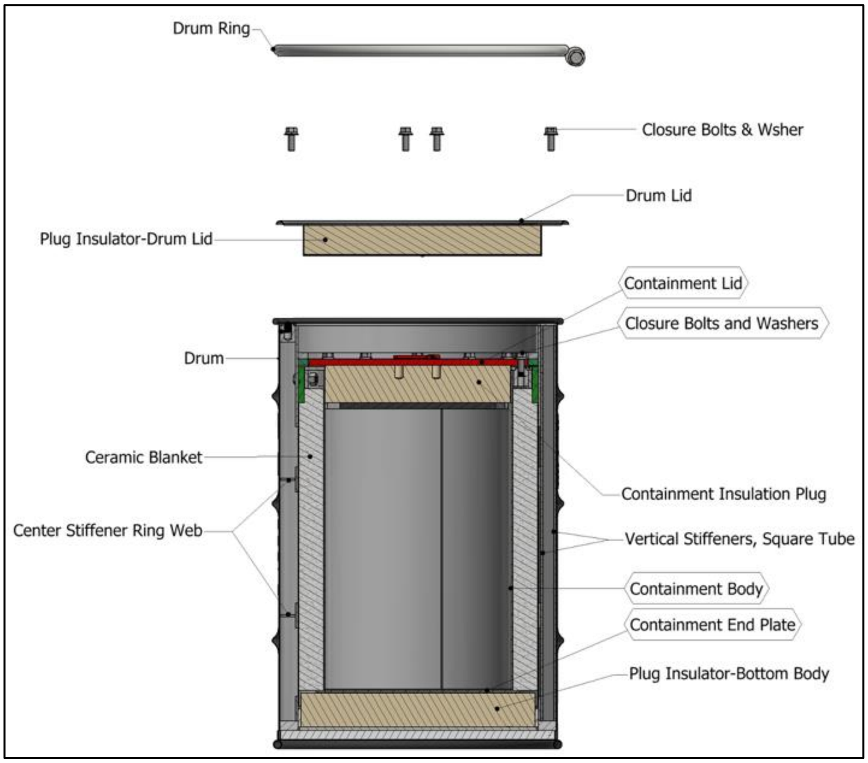


**Figure 1 – Versa-Pac Package Exploded View**

**Figure 2 – Fabricated Versa-Pacs**

## 3 1S/2S Contents

ANSI N14.1 [1] standard 1S and 2S cylinders are utilized to transport small quantities of $UF_6$ (1 lb. and 4.9 lb. respectively) at any $^{235}U$ enrichment. These cylinders consist of a Nickel or Nickel-Copper Alloy cylinder with hemispherical ends and a threaded valve for filling and emptying. A cross-sectional view of example cylinders is shown in Figure 3 [1]. As the cylinders contain fissile material, criticality calculations are required. Additionally, because $UF_6$ and potential HF acid impurities are corrosive materials, which could cause a chemical reaction with the Versa-Pac packaging if released from the 1S/2S cylinder, the fissile material must remain confined in the 1S/2S cylinder for containment purposes and compliance with 10 CFR 71.43(d). New structural and thermal evaluations are also necessary to support the confinement assumptions in the criticality analysis and demonstrate that the corrosive materials are retained in the $UF_6$ cylinders.

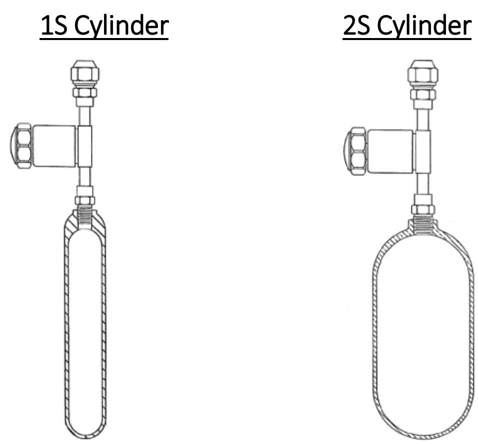


**Figure 3 – 1S/2S Cylinders**

### 3.1 Criticality Calculations

The criticality safety calculations to support the 1S/2S contents are relatively straight forward. For Normal Conditions of Transport (NCT) it is assumed that the fissile $UF_6$ material remains confined inside the 1S or 2S cylinders. The restrictive geometry is modeled as a simplified right circular cylinder bounding the dimensions of a standard 1S/2S cylinder. For Hypothetical Accident Conditions (HAC) it is assumed that the fissile contents are entirely released from the cylinders. Although the valves are qualified to prevent leakage into or out of the cylinder, it is assumed that all fissile material is optimally moderated by water in the cylinder for both NCT and HAC. Sensitivity studies analyzing different geometric arrangements, moderation ratios, and fissile compounds were included in the analysis to demonstrate compliance with all regulatory requirements. The fissile material limits are based on restrictions set on the number of cylinders at the two enrichment levels, as shown in Table 2. Additionally, to maximize the allowable contents, for the 100 wt% $^{235}U$ enrichment cases the previously qualified 5-inch pipe component was utilized. This allowed for some geometric confinement during HAC, without the added challenges of qualifying the standardized 1S/2S cylinders for a 30 ft drop.

The Versa-Pac does allow for the transport of both 1S and 2S cylinders in the same package and a number of cylinders that exceeds the allowed quantity in Table 2, as long as the mass of the fissile contents doesn't exceed the base package limits of Table 1.

**Table 2 – 1S/2S Cylinder Content Limits**

| Enrichment Limit (wt% $^{235}U$) | Cylinder Type | Number of Cylinders |
|---|---|---|
| ≤ 20 | 1S | 7 |
| | 2S | 2 |
| ≤ 100 | 1S | 1* |
| | 2S | 1* |

Note: *in 5-inch pipe

### 3.2 Structural Analysis

To support the assumption that the 1S/2S cylinders retain all fissile material during NCT in the criticality analysis and for containment, it was demonstrated that there is sufficient impact protection to the cylinders for a regulatory 4 ft. drop. From a structural standpoint, 1S and 2S cylinders are small light cylinders that are limited to gross masses of 2.75 and 9.1 lbs, respectively. The inner liner used for insulation of the 1S/2S cylinders is a polyethylene foam that is machined to provide a close fit for the cylinders (further discussed below). This liner also provides additional structural support to protect the cylinders from any significant impact loads from a 4 ft. NCT drop. Based on the light weight of the filled cylinders, and the structural support provided by the Versa-Pac and supplemental polyethylene foam liner, it was demonstrated that neither the cylinder nor the valve would sustain any significant damage during a drop event allowing for the loss of material.

For a 30 ft. HAC drop, it was determined that demonstrating the survival of the 1S/2S cylinder would be a significant challenge. To demonstrate the survival of the cylinder and valve, especially at the threaded connection, would require significant effort and cost. Physical drop testing would require the fabrication of replica 1S and 2S cylinders, shoring components, and a Versa-Pac package. Additionally, physical drop testing would require justification for the bounding drop orientation along with consideration for any possible combination of cylinders as well as arrangements and orientations of the cylinders in the package. An analytical justification could require some benchmarking, justification for all modeling parameters, and the added scrutiny of a regulatory review. For these reasons it was decided that the assumption would be made in the criticality analysis that the material could be released from the cylinders during HAC.

During the development of the criticality analysis it was noted that for the higher enrichments (100 wt%$^{235}U$) the assumption of release of material into the Versa-Pac cavity was problematic. A solution was found in utilizing the 5-inch pipe component (shown in Figure 4) that had already been designed, tested, and incorporated into the license. For enrichments above 20 wt%$^{235}U$, the requirement was added that for any 1S or 2S cylinder to be loaded into a 5-inch pipe prior to loading the contents into the package. This allowed for geometric restriction of the fissile material during HAC while avoiding the added efforts to analyze the structural behavior of the1S/2S cylinders from a 30 ft. drop.

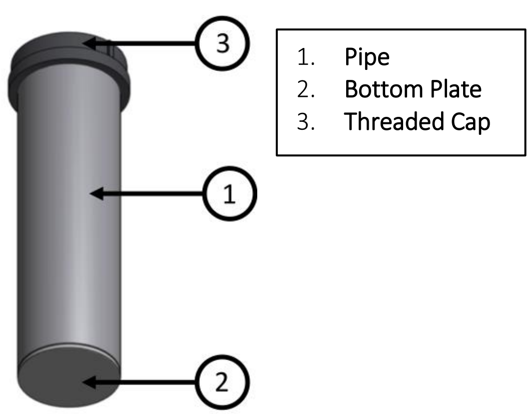


**Figure 4 – 5-inch Pipe**

### 3.3 Thermal Analysis

In support of the criticality analysis and for containment purposes an analysis was required to show that the temperatures at the cylinders would not exceed their set temperature limit, to demonstrate the ability of the 1S/2S cylinders to retain all fissile material during NCT. The temperature limit of 250°F for both 1S and 2S cylinders for all NCT and HAC is provided in Table 1 of ANSI N14.1. Although survival of the 1S/2S cylinders is not required during HAC for the criticality safety analysis, it is analyzed to alleviate concerns for any possibility of a violent rupture of the cylinder damaging the Versa-Pac inner cavity structure and affecting containment of fissile material. The base HAC thermal analysis calculated a maximum temperature of 430°F in the inner cavity of the package. Therefore, to meet the temperature limit of 250°F as specified in ANSI N14.1 for 1S/2S cylinders it was determined that an insulating liner is necessary.

As the $UF_6$ contents do not generate a significant quantity of heat, the only concern is heat entering the package from the insolation or fire applied to the outer package surfaces. To provide the required additional insulation, a parametric study was conducted using the ANSYS code [2] to determine the minimum thickness of polyurethane foam required on all sides to reduce the inner temperature to below the 250°F limit for both NCT and HAC. The minimum thickness required was determined to be 2 inches of 9 PCF polyethylene foam. The results of the HAC fire thermal analysis for the base Versa-Pac model (no liner) and the model that includes the 2-inch polyurethane foam liner are shown in Figure 6 and Figure 7, respectively. The maximum temperature at the inner surface of the 2-inch thick polyurethane foam liner is 243°F. Using this minimum required outer thickness of the liner between the cavity wall and 1S/2S cylinders as the only requirement for the foam liner leaves flexibility for the cutouts in the inner portion of the liner to allow for a variable number and arrangement of cylinders, while providing the minimum required insulation. Additionally, this outer layer of foam provides some impact protection for the cylinders to support the structural analysis of the cylinders during NCT. An isometric view of a Versa-Pac package with a fabricated insert to transport 3 2S cylinders and 1 1S cylinder is shown in Figure 5 .

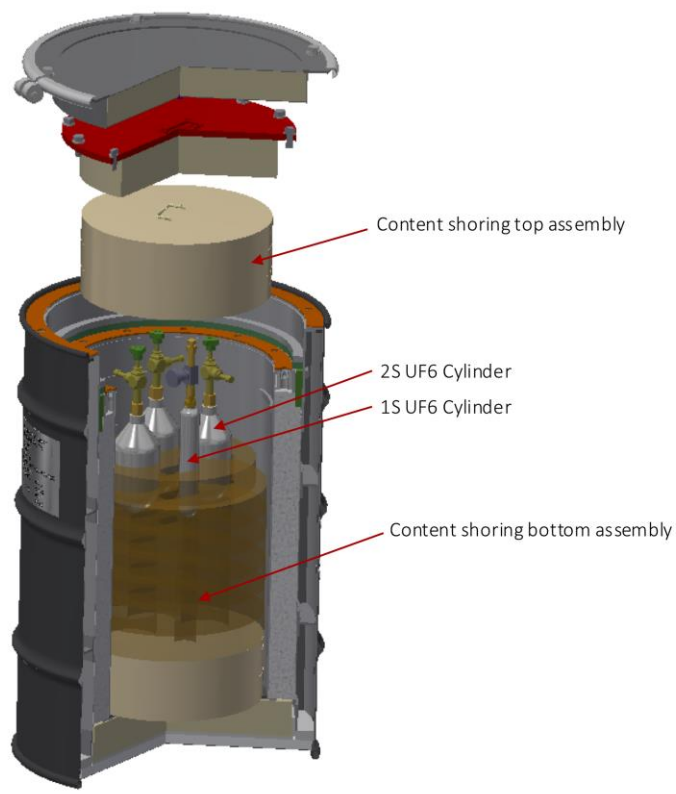


**Figure 5 – 1S/2S Example Foam Insert**

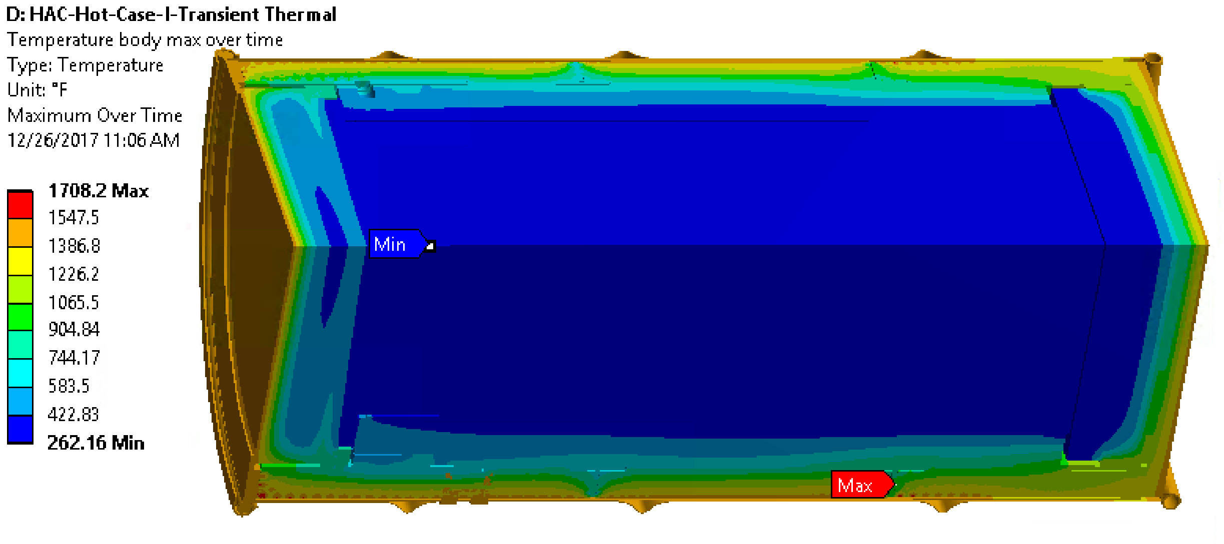


**Figure 6 – HAC Base Thermal Evaluation**

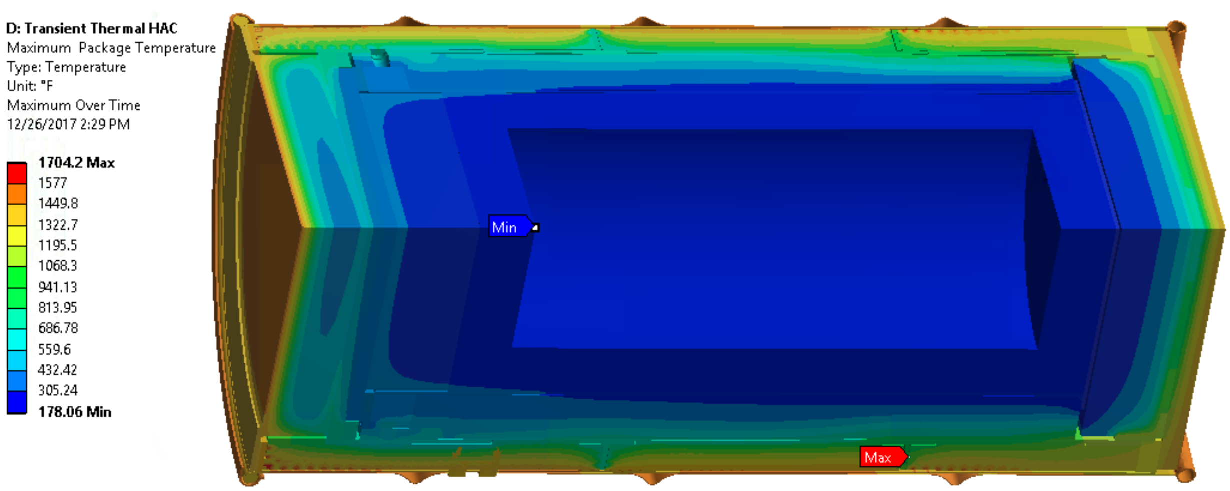


**Figure 7 – HAC Foam Liner Thermal Evaluation**

## 4 Air Transport Content Analysis

To meet the customer request to add the option for air transport of fissile material for the Versa-Pac, the enhanced packaging requirements of 10CFR71.55(f) were applicable. It was immediately evident that the analysis for the 90 m/s drop required in 10CFR71.55(f)(2) would present significant challenges in trying to defend both the survival of the containment and the post drop test state of the packaging. However, the alternative approach is to avoid any additional package testing and assume that the package itself is destroyed and all fissile contents are released. The specific wording of the regulation states: "The package must be designed and constructed, and its contents limited, so that it would be subcritical…". By assuming that the contents are released from the packaging and reconfigure into the worst-case arrangement in the air transport criticality analysis, the content limits are set such that the regulatory requirement is met. Although this approach is not practical for every package, for a smaller package like the Versa-Pac it allows for shipments of fissile material by air that far exceed the exempt quantity limits of 10CFR71. Based on the criticality analysis, the air transport fissile limits for the Versa-Pac are set as listed in Table 3. For any shipment of the Versa-Pac by air, the $^{235}U$ limit is set based on the lower value between the air transport limit listed in Table 3 and the base analysis limits listed in Table 1.

**Table 3 – Versa-Pac Content Limits**

| Enrichment (wt% $^{235}U$) | Air Transport $^{235}U$ Mass Limit (g) |
|---|---|
| ≤ 100 | 395 |
| ≤ 20 | 495 |
| ≤ 10 | 590 |
| ≤ 5 | 790 |

Because it is assumed that the contents can be released from the packaging during an air transport accident, additional safety concerns were raised beyond criticality safety. Since the Versa-Pac is a Type AF package, the contents are always limited to a Type A quantity of radiative material ($\leq A_2$). Therefore, a full release of material from the packaging in HAC is not a concern in terms of the radiological consequences. The primary concern was for the shipment of 1S/2S cylinders by air and the combined possibilities of a violent hydraulic failure of a cylinder and/or the release of corrosive $UF_6$ and HF compounds to the surrounding environment.

To address the hydraulic failure concern of a cylinder, prior fire testing data of bare $UF_6$ cylinders of various sizes [3] shows that explosive failure can occur for cylinders 5 inches in diameter and larger. However, the test report shows that the failure mechanism for small sample cylinders such as 1S and 2S cylinders occurs at the threaded joint or solder between the valve and cylinder. The report concludes that the cylinders did not rupture during either fire test performed. It was also noted that a small cloud of $UF_6$ was released but completely dispersed due to the heat and no contamination was recorded during the post fire examination.

Regarding potential public exposure risks from $UF_6$ and other product compounds, the high temperature environment of the fire would evaporate all water, so the $UF_6$ would thermally decompose. The products of this thermal decomposition are $UO_2F_2$, $F_2$, $UF_4$, UOx, and fluorocarbon compounds. All of the uranium compounds would decompose or convert to $U_3O_8$ [4], which is a stable solid. For any material that escapes, complete dispersion of the $UF_6$ vapor by the heat would occur immediately. Once the released material has dissipated, the compounds would be highly diluted. Following the fire, any remaining fumes would cool and condense in the surrounding area. However, the byproducts would be sufficiently dispersed by the fire so that detectable quantities would not be found and not cause an undo safety risk.

In addition to the above discussion, is consideration of the relative hazards to the public in comparison to the hazards posed by an aircraft crash in general. The risk of explosive failure is possible from any combustible or compressed gas material in the aircraft. Also, research into the effects of aviation combustion toxicology shows that hydrogen fluoride, hydrogen chloride and nitrogen dioxide compounds are created during the combustion of polymers used in aircraft construction with nitrogen dioxide compounds having the greatest toxicology risk [5]. Therefore, the relative risk or hazard from an aircraft fire event does not increase the exposure risk to the public or first responders.

## 5 Summary & Conclusions

In summary there can be many unique challenges faced when incorporating new contents into a radioactive material package license. For the 2019 Versa-Pac license revision including the additions of ANSI N14.1 1S/2S $UF_6$ cylinders and the capability for air transport of fissile material, multiple challenges were faced in the development of the safety analyses to support the added contents. The approaches and considerations for developing the safety bases of the added contents while avoiding excessive efforts or costs of physical testing and potentially problematic analytical methods include:

1. Instead of crediting the 1S/2S $UF_6$ cylinders, the HAC analyses assume failure of the cylinders and instead of crediting the Versa-Pac packaging, the air transport accident event analyses assume complete destruction of the packaging. The fissile material limits in all cases meet customer needs and the simplifying assumptions resulted in significant time and cost savings by eliminating the structural and thermal testing and analyses required to justify the survival of these components.
2. The 5-inch pipe container is utilized for shipping 1S/2S $UF_6$ cylinders with higher enrichment (>20 wt% $^{235}U$) fissile material for geometric confinement and criticality safety. As the design of 1S/2S cylinders is set by the ANSI N14.1 standard, the use of the 5-inch pipe mitigates the need to justify the survival of the cylinders during HAC.
3. The design requirements for additional components are based on the minimum requirements to meet the safety limits of the package. For the foam inserts utilized for the transport of 1S/2S cylinders in the Versa-Pac, the sole requirement is that there is 2 inches of foam between the cylinders and the cavity wall. This provides significant flexibility in the possible combinations and arrangements of cylinders and necessary liner designs without analyzing each individually.
4. Consideration was also given to the additional risks of $UF_6$ materials and air transport including the chemical risks involved with HF containing compounds, the violent rupture of a sealed $UF_6$ cylinder, and the release of material during an air transport HAC event. To evaluate this possible scenario, additional analysis and justification was provided to demonstrate that neither the public nor first responders are subjected to undue risk, outside of the HAC event itself.

Future work on the Versa-Pac package includes the addition of increased fissile mass limits to support the transport of TRISO fuel pebbles and the addition of a longer Versa-Pac XL variant to allow for the transport of the larger ANSI N14.1 5A/B $UF_6$ cylinders in support of the HALEU program.

## 6 References

[1] American National Standards Institute, "American National Standard For Nuclear Materials - Uranium Hexafluoride - Packagings for Transport," ANS N14.1, December 2012.

[2] ANSYS, Inc., "ANSYS 17.1," 2017.

[3] Mallet, A.J., "ORGDP Container Test and Development Program Fire Tests of UF6-Filled Cylinders," K-D-1894, Union Carbide Corporation Nuclear Divisiom, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennesee, January 12, 1966.

[4] S. Thein and P. Bereolos, "Thermal Stabilization of UO2, UO3 and U3O8," ORNL/TM-2000/82, 2000.

[5] Chaturvedi, Arvind K., "Aviation Combustion Toxicology: An Overview," Journal of Analytical Toxicology, Vol. 34, January/February 2010.