USEC PERFORMS SUCCESSFUL ANALYTICAL TESTING OF PADUCAH TIGER OVERPACK

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INTRODUCTION/BACKGROUND

USEC performed several finite element analyses (FEAs) of the Paducah Tiger Overpack—the protective overpack used to ship ten-ton, ANSI N14.1 type 48X cylinders containing enriched uranium hexafluoride (UF_6)—to supplement the original test data for a renewal application for the package's certificate. The FEA also was used as a basis to increase the authorized UF_6 capacity. During the process, USEC determined that the package would be enhanced by the addition of an aluminum stiffening plate placed inside the overpack in front of the cylinder valve. By adding the plate for extra valve protection, USEC successfully updated a nearly 30-year-old package design. This plate also promoted even distribution of heat across the cylinder head during the 800° C thermal event in spite of the heavy damage within this localized area experienced in the drop test.

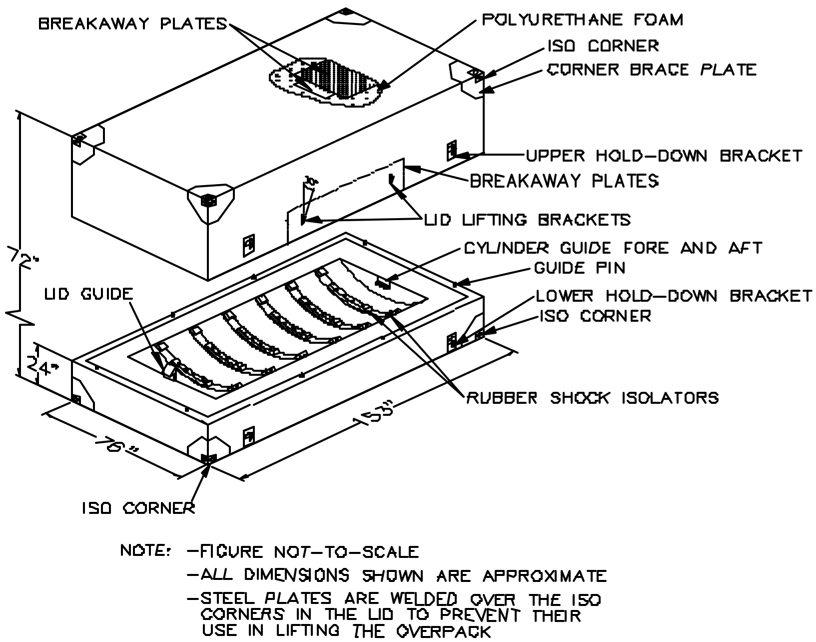
The Paducah Tiger overpack has been used for nearly 30 years to ship ten-ton UF_6 cylinders from the Paducah Gaseous Diffusion Plant to the Portsmouth Gaseous Diffusion Plant. During this time, the Paducah plant operated as the front end of the uranium enrichment process, enriching uranium from the natural assay of 0.711 weight % ^{235}U to approximately 2 weight % ^{235}U, then sending it to Portsmouth to be further enriched to customer specifications. As USEC ceased enrichment operations at the Portsmouth plant in June of 2001, the Paducah Tiger is now used to ship UF_6 enriched to 4.5 weight % ^{235}U to the Portsmouth plant for purification and laboratory analysis before the material is delivered to the customer. The Paducah Tiger is certified under the Nuclear Regulatory Commission (NRC) regulation, 10 CFR 71, as a Type A-Fissile package. USEC's Paducah Tiger overpacks can be shipped by both rail and truck.

DESIGN OF THE PADUCAH TIGER OVERPACK

The overpack consists of a steel outer skin and inner liner, with polyurethane foam filling the void space. High-density foam is used along each edge and at each corner of the lid and body for rigidity, while low-density foam is used for the remainder of the overpack. A square tubing space frame reinforces the mating surfaces for the lid and body of the overpack and serves as the mounting point for the closure devices. Rubber shock isolators bolted to the inner liner support and align the UF_6 cylinder within the overpack. Stainless steel breakaway plates are attached to the inner surface of the outer skin on the top, bottom, and sides for puncture protection. On the valve end of the overpack, a stainless steel valve-protector plate is attached to the overpack skin to provide increased puncture resistance. Closure mechanisms, attachment points for a tamper-indicating device, lifting points, and tie-down features also are included. Figure 1 shows a diagram of the Paducah Tiger. The overpack provides impact and thermal protection for the UF_6 cylinder, which serves as the containment boundary for the radioactive material. The 48X cylinder shipped in the Paducah Tiger may contain up to 21,030 pounds of UF_6 enriched up to 4.5 wt % ^{235}U.

Figure 1 -- Paducah Tiger Overpack

The aluminum stiffening plate and 48" cylinder have been eliminated from this figure for clarity.



ORIGINAL TESTING OF THE PADUCAH TIGER

The Paducah Tiger was designed and tested in 1971 using the International Atomic Energy Agency regulations, Safety Series No. 6 (SS6) as a guide.[1] During the initial design process, a prototype for the Paducah Tiger was built for physical testing, the results of which were used to optimize the design. The physical testing was performed based upon the SS6 sequence of a 30' drop followed by a 40" puncture test, and concluding with a fire test. The prototype was drop and puncture tested twice prior to the fire test to examine the damage resistance of design variations in different parts of the prototype. The first sequence of drop and puncture testing was performed by dropping the overpack on the upper edge nearest the cylinder valve and puncture testing on the top center of the overpack. The second series of tests dropped the overpack on the bottom edge opposite the cylinder valve and puncture tested the bottom center. Although both series of tests were performed sequentially as required by SS6, the locations chosen did not necessarily consider the effects of cumulative damage, *i.e.*, the location chosen for the puncture test may not have been the worst-case location, given the damage experienced during the drop test.

The Energy Research and Development Administration—predecessor agency of the Department of Energy (DOE)—certified the Paducah Tiger for use in 1974. The NRC certified the overpack in 1978. The DOE also issued a CoC for the Paducah Tiger for its operating contractors. From 1978 until 1996, both the DOE and the NRC issued concurrent certificate renewals for the overpack, with the NRC certificate revised to incorporate changes requested by the DOE.

When USEC began operations in 1993 pursuant to the Energy Policy Act of 1992, preparations were made to transfer certification of the Paducah Tiger solely to NRC. In 1996, the DOE certificate was allowed to expire and the NRC assumed sole jurisdiction over the Paducah Tiger. The NRC indicated that the existing safety documentation, although adequate for transition of regulatory jurisdiction, would need to be updated prior to certificate renewal in November 1998.

SAR HISTORY

The purpose, scope and format of the original SAR written in 1975 for the Paducah Tiger were consistent with the standard DOE practice at the time. The SAR was written as an informational document, and verbatim compliance with its statements was not expected. Rather, compliance with the in-plant operating procedures was expected, and these were included as appendices to the SAR. The purchase specifications also were included as an appendix, with all the attendant detail (such as overpack color) that is not significant from a safety perspective.

During the process of obtaining initial certification of the Paducah Tiger, a question was raised regarding the ability of the valve end of the overpack to protect the cylinder valve from a puncture. To address this question, a supplement to the SAR was prepared in 1977, incorporating an analysis of the effects of a puncture test on the valve end of an undamaged overpack. As a result of this analysis, the stainless steel valve-protector plate described above was added to the outer skin of the overpack's valve end to prevent the puncture pin from tearing through the outer skin. Based on the results of that analysis, the NRC certificate number USA/6553/AF was issued.

As USEC transitioned to a new regulatory environment in the early 1990s, verbatim compliance with safety documents became paramount. Having the plant operating procedures in the SAR became cumbersome because changes in the procedures required NRC approval and a revised certificate. Therefore, a supplement to the SAR was incorporated in 1997 that specified more general operating procedure steps, concentrating on the safety-significant portions of the operation.

Over the nearly 30 years of operation of the Paducah Tiger, multiple issues arose that required the creation of additional conditions of certification and accompanying CoC revisions. For example, the overpacks were built with ISO connectors on each of the corners, but they were later determined to be unsuitable for use as lifting or tie-down points. The connectors, therefore, were modified and the CoC was revised accordingly. Other changes to the CoC were associated with the fact that the overpacks were procured in multiple lots, in different years and with different sets of design drawings for each lot. Still other changes were made for ease of operations or repairs, such as moving the gasket from its original location on the overpack lid to the body of the overpack.

Multiple repairs had been performed on the overpack, each of which required CoC revisions, resulting in a certificate with numerous conditions and references. Problems also were identified regarding the CoC's reference to ANSI N14.1's specifications. Because historical practices allowed compliance with the intent of ANSI N41.1, rather than a verbatim compliance, the proscriptive nature of the ANSI standards created problems once verbatim compliance became a requirement. (For example, the ANSI specification for the solder used to tin the threads on the cylinder valve and plug referred to a non-existent alloy.) The end result of these changes was an outdated SAR that required many supplementary documents and analyses to describe its technical basis.

Many of the Paducah Tiger overpacks had experienced corrosion and pitting on the bottom of the overpacks, as well. This condition may be due to prolonged contact with wet surfaces as rainwater became entrapped between the overpack and the transporting railcar or trailer surface. USEC developed a repair method to weld an additional stainless steel sheet over the bottom of the overpack to restore the skin to its original minimum thickness. Because the stainless steel sheet would add weight to the package, thus affecting the package's behavior during the hypothetical accident conditions, USEC evaluated those effects. During that evaluation, and the incumbent research into the historical documentation, USEC discovered inconsistencies in the historical analyses.

The physical testing performed on the prototype Paducah Tiger had used a cylinder filled with a simulated payload of 20,011 pounds—about 1,000 pounds lighter than the 21,030 pound maximum fill limit of the UF_6 cylinders. Further, the 1977 analytical testing used a package weight ~7,000 pounds lighter than the allowable maximum gross weight.[2] USEC discovered this in 1998 and stopped shipments of the overpacks, pending resolution of these issues. USEC used an FEA to replicate the 1977 puncture analysis of the valve end of an undamaged overpack with a gross weight of 38,000 pounds.[3] NRC approved the new analysis and resumption of shipments but then required an analysis of the HAC, to consider the effects of cumulative damage of the tests.

PREPARATION OF A REVISED SAR

USEC had begun to rewrite the SAR for the Paducah Tiger in 1997 to support an application for certification renewal.[4] USEC was preparing a SAR that would meet current standards and expectations, *i.e.*, follow the guidance of NUREG-1609, *Standard Review Plan for Transportation Packages for Radioactive Materials*. The revised SAR would contain the proper level of detail, eliminating the unnecessary, non-safety significant detail contained in the old SAR. The revised SAR would also put into one document all the information necessary to support the CoC, *e.g.*, the appendices, supplements, and other analyses that had been added over the years.

Midway through development of the revised SAR, USEC discovered the inaccuracies in the historical testing and analyses. USEC had not planned to perform new analyses but had rather planned to simply revise the SAR to meet the NUREG-1609 format. Once the weight issues arose, USEC decided to reanalyze the drop/puncture testing through the FEA. New thermal analyses were not performed because the overpack damage resulting from the FEA was bounded by the damage done to the prototype overpack. Additional thermal analyses were performed later to support operational changes associated with the cessation of enrichment operations at the Portsmouth plant.

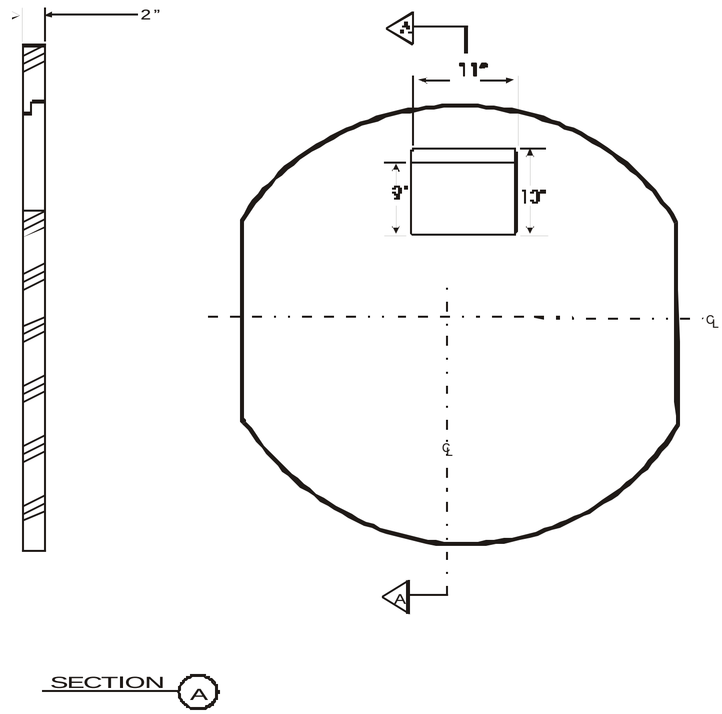
FINITE ELEMENT ANALYSIS

The FEA performed in 1998 took into account the cumulative effects of the HAC discussed in 10 CFR 71.73.[5] The results of this investigation prompted the addition of a two-inch-thick 6061-T651 removable aluminum stiffening plate (Figure 2) to be installed between the valve end of the 48X cylinder and the end of the overpack. This plate incorporates a hole that is necessary to prevent damage to the cylinder valve as the cylinder may move during the drop and puncture tests. Subsequent plans to cease enrichment operations at the Portsmouth plant required additional analyses performed in 1999 to investigate the behavior of a partially filled cylinder during the thermal event.

FEA MODEL DEVELOPMENT FOR DROP TEST MODELING

To accurately predict the behavior of the Paducah Tiger during the drop and puncture tests, the FEA model needed to include many of the overpack's fabrication details and predict cylinder movement during the tests. Stress-strain diagrams for the low and high density foam were developed, as was modeling of the body and lid mating components and shock isolators. Due to symmetry, it was only necessary to model one half of the overpack.

Figure 2 -- Aluminum Stiffening Plate



Development of bounding stress-strain diagrams was one of the greatest challenges, because four different types of polyurethane foam had been installed in the overpacks over their 10-year procurement.[6] Polyurethane foam is an anisotropic material, *i.e.*, its material properties are dependent on direction. The original procurement documents indicated that crush strengths could differ by as much as 25% between samples tested perpendicular to the direction of rise and samples tested parallel to the direction of rise. Additionally, the orientation of the overpack during foam installation is not known; therefore, to properly bound this condition, properties from the weakest direction (perpendicular to the direction of rise) were incorporated into the FEA.

Another challenge in determining the foam properties came from the fact that only limited test data exist for some of the foam types used in the overpacks. Through extensive discussions with the vendor, USEC developed bounding stress-strain curves for the FEA. These stress-strain diagrams are conservative because they are based on the static crush properties of the foam, while dynamic crush strengths are approximately 30% greater than static crush strengths.

The overpack incorporates a redundant closure system of four ratchet turnbuckles and eight ball lock pins. These features were all modeled, along with the mating components that aid proper orientation of the overpack lid. Finally, the radial shock isolators, consisting of 5-inch-thick curved blocks of EPDM rubber placed around the cylinder, were included in the FEA model. Results of the FEA illustrated that the shock isolators provide little protection during the HAC and were probably designed to minimize acceleration loads encountered only under normal conditions of transport.

INITIAL DROP TEST ANALYSES

A full evaluation of the HAC was performed, with an extensive study investigating three bounding drop cases: a 0° end drop, a 15° degree top edge (which is closest to the cylinder valve) drop, and a center of gravity over the top edge drop (26.7° edge drop). These were performed to determine the worst-case scenario.

After the 30' drop analyses were completed, a 40" puncture analysis was performed for each case. These analyses showed that the pin would not penetrate the " stainless steel valve protector plate, thus protecting the polyurethane foam from being directly exposed to any flames during the fire test. This result was used as the basis for accepting the historical thermal investigation. The FEA also indicated that the interior end plate (adjacent to the cylinder valve) would deflect, thus reducing the amount of clearance between the cylinder valve and the end plate, with a possible contact of the cylinder valve. To resolve this, a removable 6061-T651 aluminum stiffening plate was added between the end of the cylinder and the inner end of the overpack.

ADDITION OF ALUMINUM STIFFENING PLATE

The aluminum stiffening plate is approximately five feet in diameter and two inches thick, with a hole to provide clearance for the valve during the HAC. Aluminum was chosen for the stiffening plate due to weight concerns. As previously discussed, a full 48X cylinder weighs 25,530 pounds (nominally) and an empty overpack can weigh as much as 14,470 pounds. While historical practice was to ship five loaded overpacks on one railcar, the increased weight of the overpack with the stiffening plate meant that only four overpacks per car could be shipped. To minimize costs, it was imperative that at least four overpacks could be shipped per railcar. The 6061-T651 aluminum is as strong as ASTM A36 steel, has superior corrosion resistance, and yet weighs 60% less than steel. Furthermore, aluminum plates are much easier to handle and fabricate than steel plates of this size.

The addition of this plate did not reduce the inner length of the overpack because the plate was designed to fit into the area previously occupied by the end shock isolators (*i.e.*, the 4" x 4" x 2" EPDM rubber designed to minimize damage to the cylinder during loading). Because the stiffening plate is removable, the cylinder can either be loaded around it or the plate can be installed after the cylinder has been loaded. The aluminum stiffening plate incorporates a 10" X 11" hole in front of the cylinder valve. With the addition of the stiffening plate, the FEA indicated that a minimum clearance of " between the cylinder valve and any other component was maintained during the HAC. Analysis with the stiffening plate installed concluded that the acceleration loads would not challenge the integrity of the cylinder and that the package would meet the HAC of 10 CFR 71.

THERMAL EVENT INVESTIGATION

Prior to ceasing enrichment activities at the Portsmouth plant, 48X cylinders were shipped to Portsmouth for further enrichment and processing to meet customer specifications. These operations allowed the cylinders to be "heeled", *i.e.*, emptied to a net weight of 50 pounds or less. Although enrichment activities have ceased at the Portsmouth plant, it is still necessary to ship product from the Paducah plant for further processing and analysis. Elimination of enrichment activities at the Portsmouth plant included elimination of the equipment used to heel a cylinder before returning it to the Paducah plant.

After transfer operations are complete it is possible for the cylinder to contain as much as 1450 pounds of UF_6. This constraint created a challenge for USEC as the SAR had a minimum fill limit of 12,000 pounds and maximum heel weight of 350 pounds to ensure the cylinder does not hydraulically rupture during the thermal event. The thermal properties of UF_6 are such that it acts as a heat sink during the thermal event and prevents the cylinder contents from exceeding its design pressure. Likewise, nearly heeled cylinders are protected by the fact that approximately 350 pounds of UF_6 (or less) will not exceed the design pressure even if the cylinder contents reach the thermal event temperature, 800° C. Although not thoroughly investigated, cylinders containing between 350 pounds and 12,000 pounds of UF_6 were thought to pose an unacceptable risk of rupturing during the thermal event and were therefore excluded from off-site transportation. Therefore, USEC investigated the thermal behavior of a cylinder containing at least 1450 pounds of UF_6 to assure that it could be safely shipped.

USEC used computational fluid dynamics (CFD) to analyze the reaction of a partially filled cylinder to the thermal event and to provide a technical basis for increasing this maximum heel weight. CFD was selected for its ability to accurately model the behavior of systems during thermal transients. This method also eliminated the need for costly and hazardous physical testing. The CFD consisted of two phases—a three-dimensional heat transfer analysis followed by a two-dimensional fluid flow analysis.

HEAT TRANSFER ANALYSIS

The heat transfer analysis was used to determine the cylinder skin temperature as a function of time during the thermal event. While symmetry arguments could have been used to support use of a two-dimensional model for this phase, USEC used a three-dimensional model to provide a defendable mathematical evaluation. For example, a three dimensional model allowed incorporation of solar insolation data from each side of the package, an important feature, given that the UF_6 could melt at temperatures as low as 146° F and exceed atmospheric pressure at temperatures as low as 125° F. Furthermore, this approach allowed USEC to analyze the behavior of the package in a fully engulfing fire, a task that is difficult to accomplish during physical testing.

The heat transfer analysis investigated the behavior of cylinders containing 1000 pounds and 1,500 pounds of UF_6. Given the configuration of the package after the drop and impact tests, the valve end of the cylinder was exposed to significantly more heat than the rest of the cylinder. The aluminum stiffening plate unexpectedly increased the performance of the package during the thermal HAC. Because it acted as a radiator, heat was dissipated evenly across the valve-end cylinder head. Without the plate, a large amount of heat would have been concentrated in a small area of the cylinder, *i.e.*, the cylinder valve. The reconfigured package resulted in cylinder skin temperatures of 298° F and 296° F for the 1000-pound and 1500-pound cases, respectively.

FLUID FLOW ANALYSIS

Once the heat transfer analysis was completed and the cylinder skin temperature as a function of time and cylinder location was known, the resulting UF_6 temperature and pressure calculations were done. USEC used a fluid flow analysis to model both the temperature change (examining the convection currents and UF_6 temperatures) and movement during the thermal event. USEC then used these results in conjunction with empirical data to determine the resulting cylinder pressure. By assuming that the UF_6 was liquid at the onset of the thermal event, a considerable amount of conservatism was added because that neglects the heat of fusion. For additional conservatism, the UF_6 liquid was assumed to exist in equilibrium with UF_6 gas as dictated by the phase diagram throughout the thermal event, thus effectively neglecting the heat of vaporization. Finally, even more conservatism was introduced through the assumption that the UF_6

temperature adjacent to the cylinder wall was equivalent to the cylinder skin temperature.

The results of this analysis indicated that a cylinder containing either 1500 pounds or 1000 pounds of UF_6 would not exceed the cylinder design pressure. Furthermore, the analysis indicated that a cylinder containing 1500 pounds of UF_6 would exhibit a pressure of 177 psig and a slightly lower internal temperature than one containing 1000 pounds of UF_6, thus indicating that hydraulic rupture of a cylinder in the overpack may not be credible. These results form the technical basis for shipping the overpack with a cylinder containing 1475 pounds of UF_6 (which allows a 25-pound margin of safety).

CONCLUSION

USEC successfully performed analytical testing of the Paducah Tiger overpack. The work was part of two separate programs: (1) to revise the SAR for the overpack used to ship enriched UF_6 from USEC's Paducah plant to its Portsmouth plant and (2) to address changes associated with cessation of enrichment operations at the Portsmouth plant. The Paducah Tiger had been designed, tested and certified in the 1970s and is used today under an NRC certificate.

A finite element analysis was used to address inconsistencies in the original testing and documentation. The package was evaluated to determine the cumulative impact of the drop/puncture tests, which had not been quantified during the certification testing performed in the 1970s. To address those impacts, USEC designed a removable aluminum stiffening plate that is installed between the valve end of the cylinder and the end of the overpack. The analysis showed that by adding the stiffening plate, an adequate clearance between the cylinder valve and the inside of the overpack would be maintained, and the HAC of 10 CFR 71 would be met.

In addition to the drop/puncture test modeling, USEC performed finite element analyses to evaluate the behavior of partially filled cylinders during the thermal HAC. These analyses were done to support operational restructuring within USEC’s uranium enrichment complex. The results indicated that the cylinder pressure would not exceed 88.5% of its design pressure during the thermal event and could be safely shipped with an increase in the maximum allowed heel weight.

ENDNOTES

[1]IAEA Safety Series 6 predated the NRC regulation, 10 CFR 71.

[2]Because many of the historical records were missing, no concrete answers were found as to why the gross weights were assumed to be so low in the 1977 analyses.

[3]The CoC maximum gross weight at that time was 37,500 pounds. The currently authorized gross weight is 40,000 pounds. An overpack weighing 38,000 pounds was investigated in order to ensure operations at that time were adequately bounded.

[4]The existing certificate was to expire in November 1998.

[5]Nuclear Assurance Corporation of Atlanta, Georgia performed all finite element and computational fluid dynamics analyses discussed in this paper.

[6]The foams installed are General Plastics Last-A-Foam series FR-3600, FR-3700, FR-6700 and FR-9600.