Probabilistic Safety Evaluation of 48-inch Loaded Depleted and Natural UF6 Cylinders Involved in the TS-R-1 Regulatory Fire

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Background

In September 2000, the United States Enrichment Corporation (USEC) submitted an application to the U. S. Department of Transportation (DOT) for a certificate permitting the shipment of the series 48X and 48Y uranium hexafluoride (UF_6) cylinders in their current configuration. Such approval is required under current IAEA regulations.

The IAEA's 1996 Edition of *Regulations for the Safe Transport of Radioactive Material: No. TS-R-1* (ST-1 Revised) contains several changes from the prior Safety Series No. 6. One such change, contained in Paragraphs 629 through 632, is new accident test requirements for UF_6 cylinders containing 0.1 kg or more of material. Particularly affected are those cylinders containing natural or depleted UF_6 since enriched material is shipped with an overpack that affords protection from the accident environment. The tests are pressure, mechanical loading, and thermal exposure. Of these three, the thermal test is the focus of our paper.

The thermal accident test requirements are found in Paragraph 728 of TS-R-1. The acceptance criterion is that the loaded cylinder sustains the thermal test environment, *i.e.*, 800°C plus convection, for 30 minutes without rupture. A significant amount of testing and analysis of bare, *i.e*., no specific thermal protection, cylinders has been performed by various entities but the results have been both marginally conclusive and at times contradictory.

To evaluate the safety of continued shipment of the 48X and 48Y cylinders in their current configuration, USEC used a probabilistic "risk-informed" approach. This was done to determine the reasonableness of such thermal protection measures. We based the assessment on an examination of the probability of occurrence of the thermal environment during transport together with a consideration of several mitigating factors that reduce the risk of shipping bare 48-inch cylinders.

Probabilistic Safety Evaluation and Risk-Informed Discussion

The probabilistic safety evaluation was similar to the probabilistic risk assessment (PRA) that is commonly used in the evaluation of nuclear safety-related issues. Whereas the PRA evaluates radiological consequences, our safety evaluation only examined the expected frequency of occurrence of the aspect-of-interest, in this case, the thermal test environment. No radiological or toxicological assessment was performed.

"Risk-Informed" or risk insight is a relatively new concept accepted by the U.S. Nuclear Regulatory Commission whereby considerations other than purely numerical or analytical results may be used to comprehensively evaluate a risk circumstance. It allows the introduction of less quantifiable factors into the risk decision process. The fundamental safety argument must be soundly based on analyses and tests but the risk-informed elements help put things in perspective for a reasonable decision.

Regulatory Considerations

The implementation of the UF_6 cylinder testing is specified in TS-R-1, which describes the thermal test parameters. Another aspect of TS-R-1 is that the Competent Authority may approve the use of UF_6 cylinders even though they may not meet the requirements of the thermal test. USEC's probabilistic safety evaluation would be used to support such a decision if it could be shown that the expected frequency of occurrence of the fire conditions during transport was acceptably low and that there were other considerations that made the public risk diminishingly small.

Modes Considered

The four modes considered for the evaluation were highway, railroad, ocean-going vessel, and barge. These four modes, or combinations of them, are employed in the transportation of 48-inch UF_6 cylinders both domestically and in international commerce.

<u>Highway</u>: The highway transportation is via legal-weight flatbed truck with shipping attachments mounted or on steamship line chassis with modified ocean containers. One or two cylinders are transported on each truck.

<u>Railroad</u>: The railroad shipment of these cylinders is on flatcars with shipping attachments mounted. Up to five cylinders are contained on one flatcar.

<u>Oceangoing Vessel</u>: The 48-inch UF_6 cylinders are shipped on oceangoing vessels in relatively large numbers. Routine shipments may involve up to 50 cylinders although 15 cylinders are typical. Special shipments on a chartered vessel could include as many as 250 cylinders with 150 cylinders being typical. Cylinders are usually transported in 20-foot flat-rack type ocean containers. Each container holds one cylinder. Ocean containers are shipped on container ships where they are stacked and secured. Special shipments, *i.e.*, exclusive use, may use conventional cargo vessels.

<u>Barge</u>: Barge transport is currently used for domestic shipments of natural UF_6. For shipments originating in Kentucky, cylinders secured to shipping cradles are transported in barges (with up to 75 UF_6 cylinders per barge) via the Tennessee and Mississippi Rivers. Depending on the specifics of each shipment, multiple barges may be used; typical scenarios involve the use of two barges traveling in tandem. The cylinders are subsequently transferred to sea-going vessels in New Orleans for export shipment.

Shipping Logistics and Matrix

<u>Logistics</u>: For purposes of the study, the logistical network considered was: 1) North America, including transportation to any port, and 2) International from U.S. ports to/from a foreign port. Foreign ground transport was not included.

The study only addressed loaded natural UF_6 shipments in 48X or 48Y cylinders. Empty cylinders were excluded even though “empty" UF_6 cylinders contain a "heel" that is in excess of the 0.1 kg lower limit in TS-R-1. We excluded these because the heels would not fail from over-pressure even under conservative fire temperature assumptions. Also excluded from the study was the domestic shipment of depleted UF_6 cylinders (i.e., "tails") as they represent a different issue for future transportation.

Shipping Matrix: Shipment data of the 48X and 48Y cylinders were gathered from North American conversion and enrichment facilities. The data are reasonable approximations of the actual shipping volume. Table 1 shows a summary of the values used in the study. Some of the values were increased to provide a degree of conservatism and to ensure that the actual values were encompassed.

Table 1
Annual North American Shipping Data for 48-inch UF_6 Cylinders

Transport Mode	Mode-Miles	No. Loaded Trips	No. of Ports of Call
Truck	700,000	2,500	n/a
Rail	45,000	110	n/a
Ocean Vessel	120,000	40	80
Barge	4,200	7	14

Because the actual shippers’ data were upwardly rounded, the total number of cylinders represented by Table 1 is not exact. A reasonable estimate of the Table 1 shipping volume is 4,700 cylinders per year, while the actual number from the survey was about 3,900. The difference between 3,900 and 4,700 is a measure of conservatism in the use of Table 1. The table was used to compute the expected frequencies of an engulfing fire and subsequent cylinder rupture for each of the four modes.

Statistical Data on Accidents

The statistical data on in-transit accidents that involve engulfing fires are sparse. The occurrence of a fire in an accident is a recorded statistic but most post-accident analyses describe the fire environment only in general terms. Important parameters such as fire extent, duration, and temperatures are rarely reported because of the difficulty in gathering such data or making such determination after-the-fact. Much of the statistical data on fire parameters are derived from probability theory using Monte Carlo methods applied to factors that can contribute to the extent, duration and temperature of a fire. The referenced documents below form the basis for our manipulation of parameters and probability distributions. Sandia National Laboratories has engaged in such analyses since the 1970s and we relied on its work for our study.

The application of accident statistics to the shipment of 48-inch UF_6 cylinders is complicated by the fact that the TS-R-1 fire is applied in the absence of any initiating events. In general land transport, however, the fire environment is created by other events, *i.e.*, an impact, crush or puncture of the transport vehicle in an accident. (This is not true for ocean-going vessel where fire is involved in less than 2% of the collisions.) Thus, probability studies tend to examine a sequence of events, one of which is fire. Because each event in an accident sequence has a conditional probability of occurrence, the sequence is far less likely than any one event. In reality there is some dependence between events so singling out one for study, *e.g.,* engulfing fire, tends to overstate its probability; spontaneous fires are extremely rare.

Risk-Informed Considerations

Cylinder Thermal Tests and Analyses: The (French) Institute for Nuclear Safety and Protection, IPSN, has conducted a series of experiments, called the Tenerife Project, to study the fire resistance of large-scale UF_6 transport cylinders.[1] Data from the tests were to be used as input to numerical models for further studies of the fire accident.

The results of the testing program and the associated modeling done by individual countries under an IAEA Coordinated Research Program (CRP) have been inconclusive with respect to the accurate prediction of failure/non-failure. The various entities studying the response of a 48-inch UF_6 cylinder to an engulfing fire have bracketed the 30-minute fire duration with their predictions of cylinder rupture times. The CRP participants, as reflected in meeting minutes, have converged on a range of roughly 25 minutes to 35 minutes as the time to reach the failure threshold. In the absence of other evidence, it is reasonable to think that there is a 50-50 chance of failure. For conditional probability purposes in our study, we assumed that the rupture conditional probability was 0.5 for the land-based modes. For waterborne modes, we assumed a probability of 1.0 because ship fires can have duration's greatly in excess of 30 minutes.

Release Mitigation: There are several aspects to release mitigation. One aspect is that if cylinder rupture were to occur, it would not be explosive but rather a ductile tearing followed by rapid depressurization. Depending on the size and location of the rupture, some evidence suggests that in the post-fire period, the contents may solidify and seal the failure site, thus limiting the release. This phenomenon is not a certainty, however.

Another aspect is that the one-inch fill/drain valve is likely to fail under fire conditions and relieve some internal pressure. The valve failure and small leak would thus reduce the potential for cylinder rupture and a large leak. Although there is no consensus whether adequate pressure relief would occur to prevent rupture, tests by both Oak Ridge National Laboratory[2] and the Japanese Central Research Institute of Electric Power Industry (CRIEPI)[3] have shown that valve leakage is an expected occurrence in an engulfing fire. The amount of UF_6 released through a failed valve is minimal. A valve leak has some likelihood of self-sealing in the post-fire period.

Release Consequences: A significant factor in reducing exposure of the general public to the radiological and toxicological effects of the UF_6 is the fact that the engulfing fire with its convective burning may elevate any released material for a wide downwind dispersion. A CRP researcher, Mr.Geoff Bailey of BNFL, has calculated that a 100 to 200 meter elevated release results in a maximum combined ground level dose of hydrogen fluoride and uranium that " … would not be expected to reach a level dangerous to life."[4]

It should be mentioned that another IPSN research program (i.e., PEECHEUR Programme) has simulated the high temperature rupture of 48 inch UF_6 cylinders (but not containing UF_6) and determined that the failure may be smaller and in a different location than predicted by Bailey. Depending on size, location, and release direction, the lofting of UF_6 may be less than Bailey's assumptions. However, it seems certain that some elevation and dispersion will occur due to thermal effects regardless of the scenario.

USEC in its Safety Analysis Report Upgrade for both the Portsmouth and Paducah sites has considered a 48-inch UF_6 cylinder failing in a large fire. It determined that with an 8,000 pound release the 30 mg Uranium uptake threshold occurs only 900 feet from the release point with lower values beyond 900 feet. This suggests that severe toxicological hazard is localized, and that the public at greater distances from the accident is not significantly at risk by a cylinder failure.

Finally, from IAEA and U. S. regulations, the A_2 value for uranium is "unlimited" meaning that from a radiological safety perspective, there is an acceptable public health risk from the total release of the UF_6 in a 48-inch cylinder.

Results Discussion

Analytical Results: Table 2 shows a summary of the results of the probability portion of our evaluation. It shows that the expected frequency of occurrence of an engulfing fire with a subsequent rupture of the involved UF_6 cylinder is extremely low. These tabulated figures are thought to be conservative, *i.e.*, overstating the frequency, for several reasons. The engulfing fire is difficult to produce in tests, thus the size of a real-world fire that could produce the time-temperature-exposure conditions of the regulations would have to be enormous. Such a conflagration is less likely than those defined in the "severe" fire category of the referenced reports.

Table 2
Expected Rupture Frequencies and Intervals
For the Shipment of 48-inch UF_6 Cylinders

Mode	Expected Rupture Frequency per year	Expected Rupture Interval, years
Truck	5.6×10^{-4}	1,800
Railroad	2.6×10^{-4}	3,900
Ocean-Going Vessel		
• At-Sea	2.0×10^{-5}	50,000
• In Port	4.3×10^{-6}	23,000
Barge	3.5×10^{-5}	29,000

Risk-Informed Considerations:

USEC, in its facility licensing submittal to the NRC, adopted a U.S. Department of Energy (DOE) categorization of initiating event frequencies. These were developed to put expected frequencies of site operational conditions into perspective for evaluation purposes. The annual frequency range of 10^{-2} to 10^{-6} is used by the DOE for Evaluation Basis Events, which by definition " *… are not expected to occur during the life of a facility …*" What this means is that analysts only speculate on such occurrences for evaluation purposes *i.e*., there is no basis to believe that they actually will happen. All of the Table 2 transport accident frequencies fall into this Evaluation Basis Events category.

USEC used the transportation hypothetical accident fire as a model for its large on-site fire accident environment. The analyses concluded that the risk to the general public (*i.e.*, outside of the immediate accident vicinity) is within acceptable uptake guidelines. The previously mentioned BNFL study of a UF_6 release in a fire accident reaches essentially the same conclusion.

Other risk-informed considerations mentioned above, *e.g.*, the self-sealing of the failure site and the unlimited A_2 value, suggest that even in the unlikely event of a release due to a fire accident, the radiological and toxicological effects on the general public are acceptably low beyond the immediate vicinity of the event.

Multiple Cylinders Per Shipment: The frequencies in Table 2, although stated in terms of cylinder rupture, are actually the frequency of the occurrence of the thermal environment on a mode-by-mode basis combined with an assumption that the cylinder(s) being transported are equally exposed to that environment. This is not completely true for all modes; multiple cylinder shipments are less likely to have all cylinders exposed. Although it does not change the fire probability assessment, it may affect the discussion on release of UF_6. This is a modal-specific issue, as described below.

Truck: The assumption used for Table 1 is that one UF_6 cylinder is carried per truck. This maximizes the mode-miles since if two cylinders were assumed, the mode-miles would be one-half of those for one cylinder and the expected rupture frequency would be decreased by a factor of two. The truck scenario is consistent between statistics and releases.

Railroad: The assumption used for Table 1 is that five UF_6 cylinders are carried on one open railcar. Thus, the expected rupture frequency shown in Table 2 is for five cylinders, assuming that all five are simultaneously exposed. In fact, a flatcar is so large that it would take an extraordinarily large fire to fully engulf it and its contents.

Further, with the average train having 67 cars according to DOT figures, there is a probability that the UF_6 car will not be involved, *i.e*., entire trains are never uniformly effected by accident conditions. However, we conservatively assumed that the probability of involvement was unity (1.0) when in reality it is likely to be something like 0.3 in a major accident. The 0.3 conditional probability largely offsets the multiple cylinder consideration. Single cylinder failure out of the total involved is still a reasonable scenario.

Ocean Vessel: The assumption used for Table 1 is that 15 UF_6 cylinders are carried on one containerized cargo vessel for routine shipments and that 150 cylinders are carried on a special shipment chartered vessel.

Cargo Container Vessel: Individual UF_6 cylinders are placed in flatracks, *i.e.*, cargo containers, for the vessel shipments. These containers are carried in large arrays with each container isolating each cylinder from another, as well as isolating it from all other commodities. The opportunity for fire to initiate and spread, let alone effect individual cargo containers, is extraordinarily small. In these cases, the frequency of even a single cylinder being ruptured is apt to be lower than that of Table 2. Assuming a single cylinder ruptures is not unreasonable even though multiple cylinders are on the vessel.

Chartered Vessel: For the chartered vessel shipments, we assumed that UF_6 cylinders are placed in holds below deck, rather than in cargo containers. This is similar to the situation evaluated by Sandia in their work performed in support of the SeaRAM program.[5] The Sandia report shows that fire in one portion of the vessel, including one hold, has a low probability of spreading to other holds especially with the functioning of the fire suppression systems with which most modern freighters are equipped.

Supplementing this is the Sandia project described in a PATRAM 95 paper.[6] This study, which included a simulated shipboard fire, concludes that fire in adjacent holds and fire in the hold containing the radioactive materials package are both significantly less severe than the hypothetical 800° C, 30-minure engulfing regulatory fire. Adjacent hold fires are even less of a thermal assault. Because no other cargo is carried in a chartered vessel, the chance of fire from carried-combustibles is markedly reduced. The Sandia study would suggest that under expected shipboard fires, the rupture probability would be lower than the assumed unity. Thus, the assumption of only one cylinder rupturing, even though multiple cylinders are being carried, is not unreasonable.

Domestic Barge: The assumption used for Table 1 is that a total of 150 UF_6 cylinders are carried per shipment of two barges, each with 75 cylinders strapped to individual shipping skids. These barges are dedicated to the UF_6 cylinders. The barges are moved to their destination port in a string along with other barges. From the standpoint of an engulfing fire, the UF_6 carrying barges have no flammables on board. The cylinders are carried in open wells below the level of the deck. Any fire would have to be enormous to engulf the two UF_6 carrying barges, and even in that case cylinder stowage below the deck level would offer significant thermal protection. Thus, the assumption of one cylinder rupturing, even though multiple cylinders are being carried, is not unreasonable.

Conclusion

USEC concluded that loaded 48-inch UF_6 cylinders can be transported with no specific thermal protection without placing a burdensome health risk on the general public. This conclusion was based on: (1) the low expected frequencies of occurrence of the engulfing fire and subsequent cylinder rupture, (2) the low expectation of general public health risks associated with any fire and post-fire releases and (3) several potential mitigating factors that may limit the release.

References

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