Sloped Bottom Tanks and Areal Density – Part I: Case Study in H-Canyon Decanter Controls

Tracy Stover, John Lint, Meagan Strachan

Savannah River Nuclear Solutions, LLC, Savannah River Site, Aiken, SC 29803, Tracy.Stover@srs.gov

INTRODUCTION

Part I of this topic introduces a practical case which led to a more fundamental question of physical behavior. That question was investigated in Part II.

In the uranium separations and purification process used in Savannah River Site's H-Canyon, following chemical separation in the mixer-settler banks, solutions enter decanters for additional hold up time. This allows the trace amounts of organic solvent entrained in the acidic aqueous solution to decant and be removed from the bulk solution. Before this analysis, the product decanters were subject to a single parameter fissile concentration limit of 11.5 g U-235/L during operation of the upstream processes. However, once the upstream processes completed, the decanters were subject to a single parameter mass limit (700 g U-235) for interim storage. The decanters are large industrial scale process vessels that are either 13,500 L or 21,000 L in volume. The concentration limit is acceptable for operation but the single mass limit during interim storage is very restrictive, requiring the U-235 concentration to be as low as 0.03 g U-235/L. Meeting this single mass limit resulted in multiple flushings of the decanters into downstream tanks during their hold-up period. This unduly taxes the system and operators while generating excessive volumes of dilute solution that must later be re-concentrated. Operations asked criticality safety for some relief.

The technical safety requirements for H-Canyon include single parameter limits in the form of mass (700 g U-235), concentration (11.5 g U-235/L), and areal density (0.40 g U-235/cm^2), all of which are based on ANS 8.1 guidance (Ref 1). The first two already apply to the decanters during various states of operation. This specific request tended toward establishing a mass limit for the decanters larger than 700 g U-235, and more aligned to the areal density value. There was one issue however.

The application of areal density limits as they are generally understood is to project the fissile mass of a system (single container or array) onto a surface. This projected mass is then comparable to an infinite slab of a certain thickness, which is well understood and characterized by experimental data and well simulated by most modern computational programs. The underlying assumption is that the surface the mass is projected onto is a plane orthonormal to the remaining two dimensions of the system. The decanters have a sloped bottom (Fig. 1).

The practical question that arose was to whether a mass limit based on areal density could be safely applied to a tank with a slight slope (3.125%) on the bottom. Investigation of this question resulted in a new mass limit for the decanter process vessels to reduce strain on the system and operations.

Computational modeling was performed using KENO-VI in the SCALE 6.1 code package, validated for site processes in Ref 2.

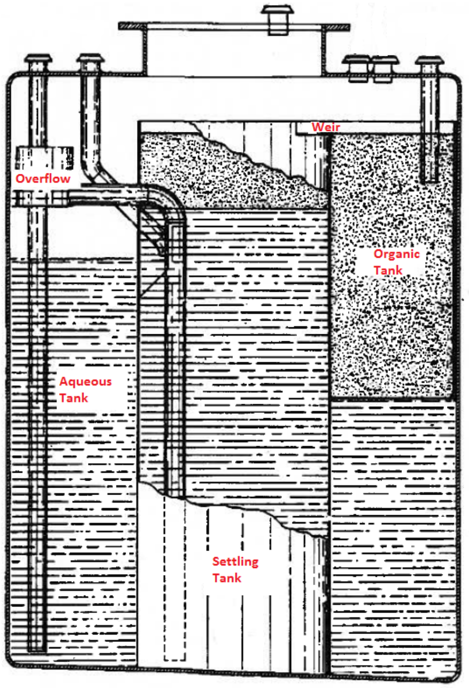

Fig. 1. Generic diagram of H-Canyon decanter.

DESCRIPTION OF THE WORK

Process Description

By nature of the process, a small amount of organic solvent (consisting nominally of 7.5 vol.% tributyl phosphate and 92.5 vol.% normal paraffin) is entrained in the bulk aqueous uranyl nitrate and nitric acid solution leaving the separations process. To separate, and also recover this solvent, a decanter is used to provide hold up time for the solution before it is moved to further downstream processing. The product decanters come in two sizes, one that is 8 feet in diameter and one that is 10 feet in diameter, and both 11 feet maximum outer height.

The decanters are divided into three internal sections (Fig. 1). The combined solution enters the inner or center chamber, also called the settling section. The heavier aqueous solution settles to the bottom, flows to the outer chamber by gravity head pressure, and from there is jetted to downstream tanks. The small amounts of the lighter organic solvent floats to the top of the settling section and overflows past a weir into the organic collection tank. The organic collection tank is a small tank near the top which spans approximately ¼ of the radial arc outside the inner chamber and about ½ of the height of the tank. From there the solvent is either air lifted back to the mixer settler or collected for reuse or disposal.

Modeling and Assumptions

The decanters were modeled per their design drawings using generic stainless steel and the geometry specified in Table I. To simulate the tank bottom slope, the rotated wedge macro-body available in SCALE was used. The wedge was assumed to be solid steel though in reality there is an air pocket beneath the decanter. The solid steel was shown by computation to be more conservative than air or water beneath the decanter, reflection outweighing parasitic absorption.

Table I: Decanter Dimensions

Dimension	**8x11 Decanter**	**10x11 Decanter**
Outer Height	334.3275 cm	334.3275 cm
Outer Diameter	243.84 cm	304.8 cm
Wall Thickness	1.27 cm	1.27 cm
Slope Rise	7.62 cm	9.525 cm
Inner chamber distance from top of tank	25.4 cm	25.4 cm
Inner chamber outer diameter	104.14 cm	142.24 cm
Inner chamber wall thickness	0.635 cm	0.635 cm
Inner radius	120.65 cm	151.13 cm
Inner height	331.7875 cm	331.7875 cm
Outer Radius	121.92 cm	152.4 cm
Inner chamber outer height	308.9275 cm	308.9275 cm
Inner chamber inner radius	51.435 cm	70.485 cm
Inner chamber outer radius	52.07 cm	71.12 cm
Cross sectional area of the inner chamber	8311.27 cm^2	15607.86 cm^2

Since the inner chamber is the one that will be first filled with fissile solution before overflow into either remaining chamber occurs, it is that portion of the tank that will be limiting to operation. The 0.40 g U-235/cm^2 areal density limit was applied to the cross sectional area of the inner chamber of each decanter resulting in a mass of 3324.5 g U-235 for the 8x11 decanter and 6243.1 g U-235 for the 10x11 decanter. The fissile solution is modeled as 73 wt.% enriched uranium, a parameter protected by the H-Canyon process flowsheet limits and criticality controls. While the solution is typically dilute uranyl nitrate, no excess nitrate beyond that bonded to the uranium is assumed to conservatively eliminate the slight poisoning effect of nitrogen. The solution is assumed to be free of aluminum, silica, iron, fission products, and tranusranics which are effectively removed in the upstream process.

Solution containing the areal density based fissile mass is placed in the inner chamber of the decanter diluted to the point of filling the inner chamber, which for either decanter is approximately 1.3 g U-235/L, and then concentrated to near the precipitation limit of uranium in nitrate solution, 650 g U-235/L. Water reflection is assumed around the inner chamber and above it and outside the decanter. This bounds air which would normally fill that space, concrete below the decanter, and any thin layer of organic that may be above the solution.

Since the dilution problem is parameterized in concentration and solution height, it is necessary to have a mathematical means of translating between the two, i.e. volume calculations are needed. At levels higher than upper side of the bottom slope, the volume of solution in the bottom head is easily calculated as a half cylinder the diameter of the inner chamber and of a height equal to the rise of the tank between the lower and upper end of the sloped bottom. Then the remainder of the solution is calculated as a right circular cylinder. As the solution concentrates, it eventually becomes flush with the upper end of the bottom head slope. Once it passes below that threshold, the solution takes on the shape of a truncated circular wedge (Fig. 2).

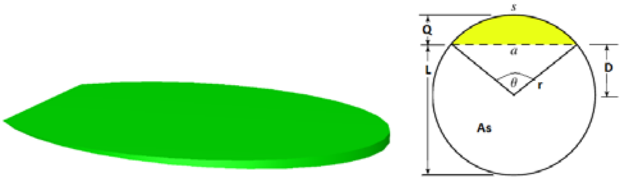

Fig. 2. Truncated circular wedge in 3D (left) and 2D looking down (right).

The volume of partial wedges requires numerical integration up to the depth of the solution, *h*, measured from the deep end of the chamber. Let *l* be the fractional slope of the tank, which for this design is 0.03125. Then the volume of solution, V_S is:

$$V_S = \int_0^h \left\{ \frac{-r^2}{2} \left[\left(2\,\mathrm{acos}\left(1 - \frac{2r - \frac{h'}{l}}{r} \right) \right) - \sin\left(2\,\mathrm{acos}\left(1 - \frac{2r - \frac{h'}{l}}{r} \right) \right) \right] + \left[\pi r^2 \right] \right\} dh'$$

The above expression assumes the bottom of the wedge is the 0 point and yields the volume of the solution. It is not readily back solved for *h*, so if *h* is required an iterative approach is used searching on the resulting V_S.

The volume expression is in principle just the integration of area as a function of solution height. The formula is derived based on the geometry in Fig. 2. The line *a* would be the line the solution makes along the shallower end of the tank, A_S is the total surface area of the solution, which is the area of the circular cross section minus the segment shaded yellow. The area of the yellow segment is $\frac{r^2}{2}(\theta - \sin\theta)$. Therefore the surface area of the solution is

$$A_S = \pi r^2 - \frac{r^2}{2}(\theta - \sin\theta)$$

Knowing that $2r = Q + L$, *L* is determined by the depth of the solution divided by the fractional slope, and that $\theta = 2a\cos\left(1 - Q/r\ \right)$. Letting *h'* be the depth of the solution and the variable in the equation:

$$\theta = 2\mathrm{acos}\left(1 - \frac{2r \quad - h'/l}{r}\right)$$

It is the ability to iteratively go between height, volume, and concentration that allows for the solution composition and dimensions to be set in the SCALE models.

Mechanical Tolerances and Leaks

The full dilution models assumed nominal dimensions of the decanters. To adequately demonstrate that these assumptions do not omit a condition wherein k_{safe} would be exceeded, a selection of branch cases was run. These cases were only examined over the concentration and moderation range where the multiplication peaked, i.e., between 9.2 and 70 g U-235/L.

To show k_{safe} is still met over the range of steel thickness tolerance, all steel in the models was removed and replaced with water. Boundary conditions were retained as in the nominal steel thickness models. To show k_{safe} is still met with regard to the thickness of the bottom head, simulated above by a solid wedge, the wedge was replaced by void. Boundary conditions and the remainder of the steel were retained. To show k_{safe} is still met with regard to the tolerance on the diameter of the inner chamber, the inner chamber was reduced in diameter by 2.54 cm. The wall thickness remained the same. Boundary conditions and the remainder of the steel were retained as in the nominal models. Complementary cases expanding the diameter were not run because these would inherently have lower multiplication due to the larger surface area for neutron leakage.

Additionally, there is a known small leak at the bottom of at least one decanter's inner settling chamber. By design, the overflow to the outer annual chamber (not the organic overflow area) is taken from the bottom of the inner chamber normally driven by gravity head. This means the solution at the bottom of the inner chamber and at the bottom of the outer chamber of the tank are the same. Given time with no transfers in or out of the decanter, both chambers would equilibrate. It is desired then to show the case of having all the solution in the settling chamber bounds the cases with the solutions equilibrated and with all the solution in the outer chamber. Fig. 3 illustrates the two possible configurations. Fig. 3 also illustrates the condition of the solution volume being sufficient for only a partial fill of the bottom of the tank.

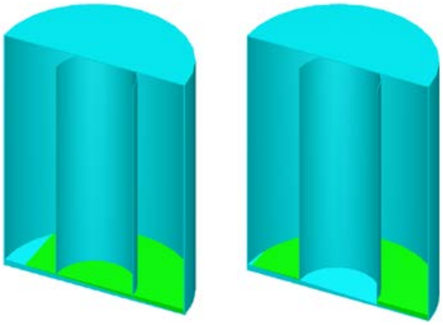

Fig. 3. Decanter Outer Chamber Solution, Equilibrated (l.) and Outer Only (r.)

Determination of k_{SAFE}

A validation for the SCALE 6.1 KENO-VI code for HEU solution systems was included in Ref. 2. Using a conservative bias and an additional subcritical margin, the k_{safe} assumed for this work was 0.9664.

RESULTS

For a fixed fissile mass of 3324.5 g U-235 for the 8x11 decanter and 6243.1 g U-235 for the 10x11 decanter, the solution was shown to remain subcritical through the range of concentrations analyzed (Fig. 4). For the mechanical tolerances investigated (Figs. 5 and 6) and for the leak conditions (Figs. 7 and 8), the solution also remained subcritical over the range of peak reactivity. All eigenvalues shown are best estimate which is k-effective plus two times the statistical uncertainty. The results are subcritical and therefore consistent with ANSI/ANS 8.1 subcritical values for areal density despite the slight slope of the tank.

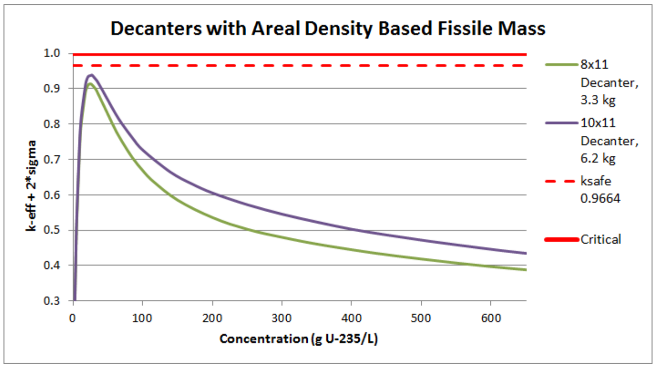

Fig. 4. Decanter Multiplication Factor vs. Concentration

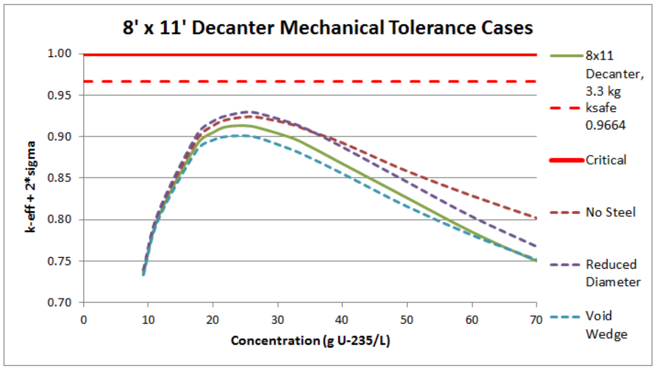

Fig. 5. Decanter Multiplication Factor vs. Concentration for Mechanical Tolerances, 8x11 Decanter

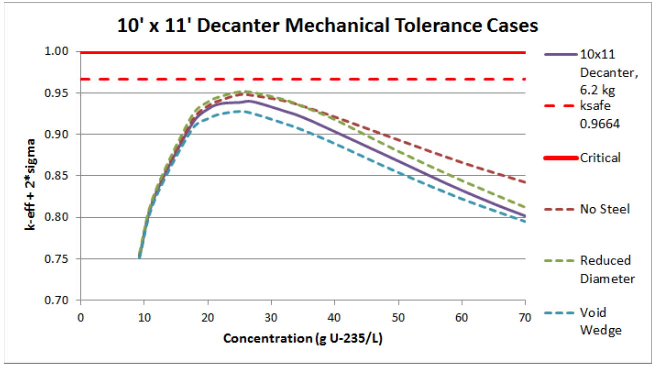

Fig. 6. Decanter Multiplication Factor vs. Concentration for Mechanical Tolerances, 10x11 Decanter

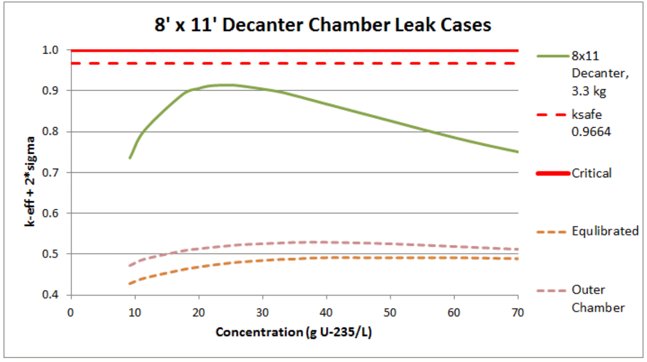

Fig. 7. Decanter Multiplication Factor vs. Concentration for Leak Cases, 8x11 Decanter

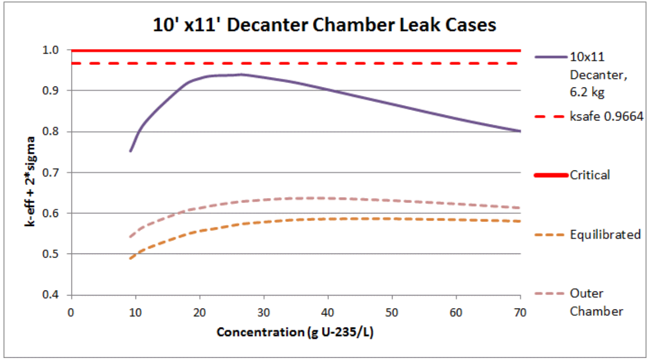

Fig. 8. Decanter Multiplication Factor vs. Concentration for Leak Cases, 10x11 Decanter

CONCLUSIONS AND SUBSEQUENT INVESTIGATION

It was concluded that for this specific case of a decanter with a slightly sloped bottom head that a mass limit based on the areal density applied to the cross-sectional area of the inner chamber could be safely applied. This translates to an approximately 3.3 kg U-235 limit for the 8x11 decanter and an approximately 6.2 kg U-235 limit for the 10x11 decanter, both of which are substantially more than the 700 g limit. This results in less operator action, less waste, and less wear on the system.

The areal density based mass limit worked in this particular case, perhaps because the slope was very slight or perhaps because ultimately there was only a few kg of U-235 in a relatively large area. This prompted further investigation into the more fundamental behavior of such systems. In particular, what does areal density mean in a system where the plane of projection may not be orthonormal to the remaining dimensions of the system? Under what conditions would areal density based mass limits no longer work? Is there a relationship between slope, area, and what may be called a *projected* areal density (PAD) where the plane of projection is not orthonormal to the other dimensions? Is there a conservative adjustment that could be made to the value of the PAD (or a PAD based mass limit) to account for sloped tanks? Such an investigation is the topic of Part II of this work.

ACKNOWLEDGEMENTS

A special thanks goes out to the men and women of engineering and operations for H-Canyon who initiated this work and who keep this national asset going strong. This work was funded by the Department of Energy under the normal operational budget for H-Canyon.

REFERENCES

1. ANSI/ANS 8.1-2014, “Nuclear Criticality Safety in Operations with Fissionable Materials Outside of Reactors”, American Nuclear Society, La Grange Park, Illinois.
2. S. H. Finfrock, et. al, “SCALE 6.1 Validation for SRNS Personal Computers,” N-CLC-G-00166, Savannah River Nuclear Solutions, 2016.