Concrete Reflected Cylinders of Highly Enriched Solutions of Uranyl Nitrate” ICSBEP Benchmark: a Re-Evaluation by Means of MCNPX Using ENDF/B-VI Cross Section Library

Cruzate, J.A. and Carelli, J.L.

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CONCRETE REFLECTED CYLINDERS OF HIGHLY ENRICHED SOLUTIONS OF URANYL NITRATE” ICSBEP BENCHMARK: A RE-EVALUATION BY MEANS OF MCNPX USING ENDF/ B-VI CROSS SECTION LIBRARY

Cruzate, J.A. and Carelli, J.L.

Nuclear Regulatory Authority
Argentina

jcruzate@arn.gob.ar ; jcarelli@arn.gob.ar

ABSTRACT

This work presents a theoretical re-evaluation of a set of original experiments included in the 2009 issue of the International Handbook of Evaluated Criticality Safety Benchmark Experiments, as “Concrete Reflected Cylinders of Highly Enriched Solutions of Uranyl Nitrate” (identification number: HEU-SOL-THERM-002)[4].

The present evaluation has been made according to benchmark specifications [4], and added data taken out of the original published report [3], but applying a different approach, resulting in a more realistic calculation model. In addition, calculations have been made using the latest version of MCNPX Monte Carlo code, combined with an updated set of cross section data, the continuous-energy ENDF/B-VI library. This has resulted in a comprehensive model for the given experimental situation. Uncertainties analysis has been made based on the evaluation of experimental data presented in the HEU-SOL-THERM-002 report.

Resulting calculations with the present improved physical model have been able to reproduce the criticality of configurations within 0.5%, in good agreement with experimental data. Results obtained in the analysis of uncertainties are in general agreement with those at HEU-SOL-THERM-002 benchmark document. Qualitative results from analyses made in the present work can be extended to similar fissile systems: well moderated units of ^{235}U solutions, reflected with concrete from all directions. Results have confirmed that neutron absorbers, even as impurities, must be taken into account in calculations if at least approximate proportions were known.

Key words: International Criticality Safety Benchmark Evaluation Project (ICSBEP), Criticality Benchmark Experiments, High-Enriched Solution Systems, criticality calculations with MCNPX, ENDF/B-VI validation.

1. INTRODUCTION

A total of 76 critical experiments were performed in the mid-1970s at the Rocky Flats Plant, which was operated at that time by Rockwell International. In those experiments, critical heights at room temperature were determined for high-enriched uranium solution in various containers and under various conditions of neutron reflection [1,2,3]. Fourteen of those critical experiments were considered acceptable for use as benchmark experiments, and so were included in the 2009 issue of the International Handbook of Evaluated Criticality Safety Benchmark Experiments, as “Concrete Reflected Cylinders of Highly Enriched Solutions of Uranyl Nitrate” (identification number: HEU-SOL-THERM-002) [4]. In these experiments, each involving a single reflected tank containing highly-enriched uranyl nitrate solutions, the critical height was determined by linear interpolation between slightly supercritical and slightly subcritical states. The tanks were cylindrical in shape and placed at different locations in a concrete reflector. Critical configurations had height-to-diameter ratios less than 1.2, and uranium concentrations varied between 59.65 and 334.77 grams per litre.

In the HEU-SOL-THERM-002 report an evaluation of experimental data was performed. In the calculation model presented in this document, several items were justifiably neglected, for the sake of simplicity. The effects on k_{eff} of omitting these items were calculated using the TWODANT two-dimensional code, with 44-group ENDF/B-V cross sections. The calculated effects were then summed to get corrections to the benchmark-model k_{eff} values, and combined quadratically as additional uncertainty. Also, in the same document, calculated k_{eff} values were given for each of the cases considered, for three different combinations of codes and cross sections: KENO with 16 Group Hansen-Roach models, KENO with 27-Group Scale models and, MCNP with continuous Energy ENDF/B-V cross section library.

This work presents a theoretical re-evaluation of the original experiments, according to benchmark specifications and added data taken out of the original published report [3]. In contrast with the analysis made in the benchmark itself, the present evaluation has been made applying a different approach: in the base cases no items have been omitted or neglected, and the calculated effects on keff values have been taken as uncertainties. Also, calculations have been made using the latest version of MCNPX Monte Carlo code [5,6], combined with an updated set of cross section data: the continuous-energy ENDF/B-VI library.

2. BENCHMARK EXPERIMENTAL SETUP

Highly-enriched solutions of uranyl nitrate [$UO_2(NO_3)_2$], dissolved in nitric acid and diluted to the desired concentration with water, were used for all of the cases. The uranium was enriched to about 93 weight percent in ^{235}U, and three uranium concentration were used: 59.65, 144.38 and 334. 77 g U per litre (low, medium and high concentration). Each solution contained some impurities, whose elemental concentrations were given with measured uncertainties of about 50%, what reflects the difficulty of measuring such small contributions. Of these, cadmium and boron are expected to be the strongest neutron absorbers. The critical height, at room temperature, was determined in each case by linear interpolation between slightly supercritical and slightly subcritical states.

The tanks used in the experiments were top-opened right circular cylinders. Each had a ~30 cm-long coaxial “tailpipe” of the same material welded to the bottom of the tank. These tailpipes passed the solution to and from the cylinder during experiments. Aluminium alloy AL-6061 cylinders of two diameters were used, as well as one diameter for stainless steel SS-304 cylinders.

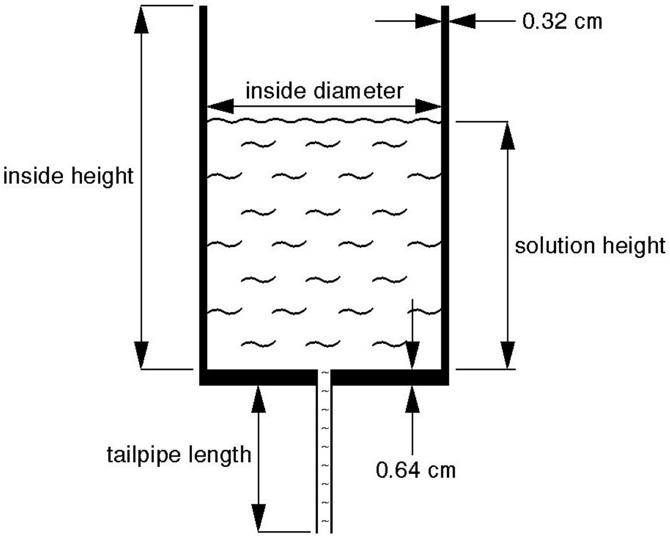

Figure 1: Experimental configuration.

The stainless-steel used had a density of 7.927 g/cm^3, and the aluminium alloy had a density of 2.737 g/cm^3. Because of nitric acid contents, a protective coating of acid-resistant paint (named "Phenoline 300") was applied to the inside of the aluminium tanks. Figure 1 is a sketchy representation of these tanks.

The tanks were located inside a concrete reflector, which geometrically was a thick-walled cubical shell of ~173 cm along its exterior side, with a ~122 cm interior cavity. The reflector was cast in six panels. Figure 2 shows a top view of the experimental configuration, while Figure 3 is a side view.

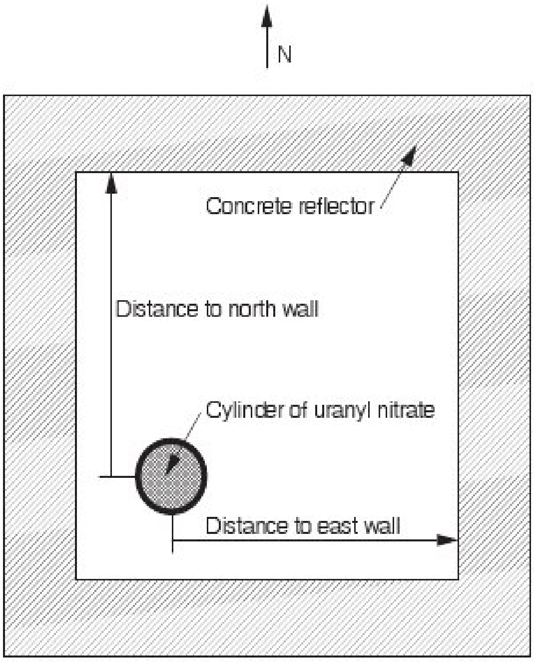

Figure 2: Top View of Experimental Configuration.

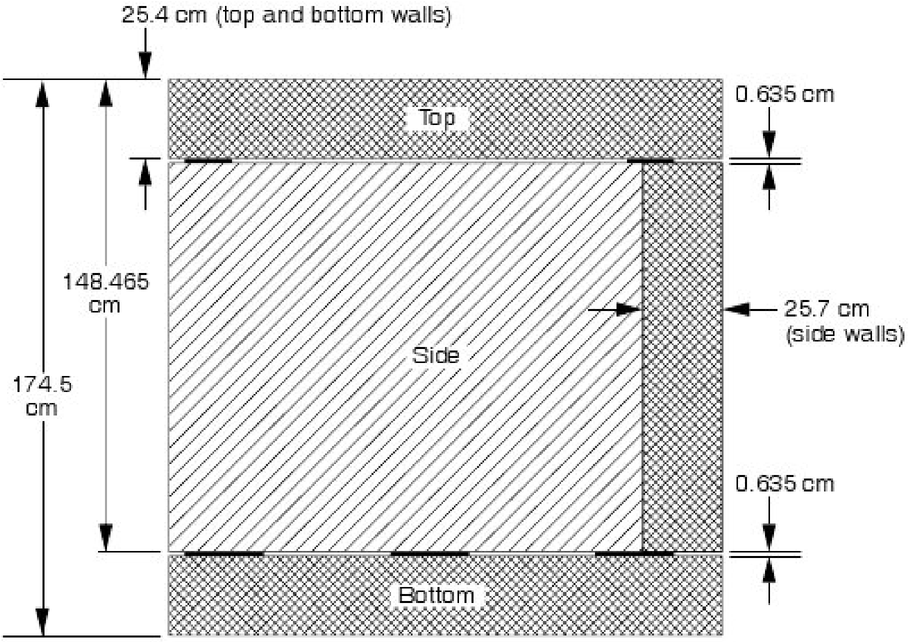

Figure 3: Side View of Concrete Reflector.

The top panel cracked during construction, so it was made safe by surrounding it with a steel compression band. Also in addition to concrete, the six panel combined contained ~11.9 kg of steel reinforcing wire and ~3.9 kg of other embedded steel pieces. This “re-bar” consisted of 0.48 cm-diameter steel rod welded in a rectangular grid-work placed in the mid-plane of each panel during pouring. Both top and bottom panels contained a given number of small holes serving various purposes (to receive the tailpipes, for example). The top had twenty-seven 2.5 cm-diameter holes, while the bottom had four of that diameter plus fourteen of half that size. In the same way each side panel contained one 3.8 cm-square hole at one corner, used as safety drain in the event of uranium solution leak. All holes and embedded material consumed less than 0.25% of reflector volume. All panels, except the top one, were lined with a 0.01 cm-thick vinyl sheet for contamination control.

A type of concrete representative of that used in the nuclear industry was selected for that set of experiments. The amount of water in the initial wet mix was about 9 weight %, being the elimination of this water the only change assumed in the reflector throughout the entire experiment. The experiments with the concrete reflector were performed approximately 4 to 8 months after the concrete was poured. Measurements showed that most of water weight loss occurred before the first experiments. Strong neutron absorbers boron, cadmium and chlorine were present in traces as impurities in concrete composition.

Figure 4 shows an elevation of the reflector concrete shell and its steel supporting structure. The stainless steel tank a few centimetres below the reflectors served as a distribution manifold directing solution to the cylinder as needed.

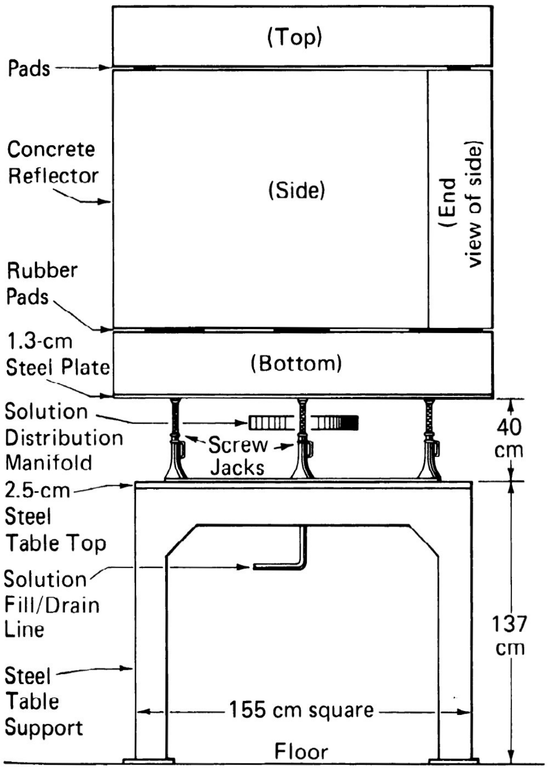

Figure 4: Schematics of the concrete reflector in elevation.

Table I summarise some important characteristics of the fourteen experiments carried out. More details may be found in reference documents [1,2,3,4].

Table I: Brief description of experimental cases.

Case number	Tank material	Inside diameter (cm)	Uranium concentration (g/cm^3)	Relative tank position
1	SS-304	27.92	144.38	Over the bottom panel
2	SS-304	27.92	144.38	On the bottom panel
3	SS-304	27.92	334.77	Over the bottom panel
4	SS-304	27.92	334.77	On the bottom panel
5	AL-6061	28.01	144.38	Over the bottom panel
6	AL-6061	28.01	144.38	On the bottom panel
7	AL-6061	28.01	334.77	Over the bottom panel
8	AL-6061	28.01	334.77	On the bottom panel
9	AL-6061	33.01	59.65	Over the bottom panel
10	AL-6061	33.01	59.65	On the bottom panel
11	AL-6061	33.01	144.38	Over the bottom panel
12	AL-6061	33.01	144.38	On the bottom panel
13	AL-6061	33.01	334.77	Over the bottom panel
14	AL-6061	33.01	334.77	On the bottom panel

3. MODEL USED AT HEU-SOL-THERM-002

In the HEU-SOL-THERM-002 report, an analysis of experimental data was made. In addition, two-dimensional calculations with TWODANT code, using 44-group ENDF/B-V cross sections from SCALE 4.4, were made for determining the effect of some items on reactivity. Using the results obtained, these items were neglected in order to simplify the calculation model.

In that model, the total measured impurities in solution were omitted, and the effect of including them was calculated for each case. Solution density and measured concentrations were conserved by reducing the water in solution by the mass of the impurity compounds.

Concerning tank materials, the measured weight percentages of all components were used for 304 stainless steel but, in the case of aluminium alloy 6061 only aluminium was used. The k_{eff} effect of adding the other measured constituents for each aluminium-tank case was calculated as an uncertainty, which was found to have a small positive effect and so omitted in the calculation model. Furthermore, the model was simplified by omitting the tailpipes containing fissile solution. As mentioned before, phenolic paint was used to protect the inner surfaces of the aluminium tanks from etching by the acidic solution. However, as remarked in references, tanks sometimes needed repainting due to the paint's gradually wearing away in the acidic solution. No phenolic paint layer was included in this calculation model, and its effect on k_{eff} was calculated by adding it to the initial model.

Regarding concrete, the re-bar region was assumed equivalent to a 0.49-cm-thick region with the given mass and volume of steel homogenized with the remaining volume fraction of concrete, and added at the mid plane of the walls in the models. The effect of adding this region was found to be negligible, so it was no considered in the model. In addition, the small holes at concrete reflector (for detector wiring, etc.) were simulated by reducing volume by approximately 0.25% and, as its effect was found to be negligible it was calculated as an additional uncertainty. The model also excluded the 0.01-cm-thick vinyl sheet of plastic lining the interior bottom and sides of the concrete reflector, which composition was given as that for polyvinylchloride, (C_2H_3Cl). It was assumed that its composition and thickness were not carefully measured, so that the effect of adding this plastic covering was calculated for all cases.

Besides, it was stated that a total of 2746 ppm of impurities were measured in concrete, being the only strong neutron absorbers: 24 ppm boron, 42 ppm chlorine, and 0.28 ppm cadmium, with no uncertainties given. Because of the difficulty of measuring such small amounts and because the main effect of impurities is expected to be from these three absorbers, the entire effect of adding the measured amounts of B, Cd, and Cl to the concrete was calculated as an standard uncertainty.

Finally, as the effect of steel plates below reflector was found negligible, the corresponding effect of adding them was considered as an additional uncertainty. The same result arose for solution distribution manifold and tailpipes welded to the bottom of the tanks.

4. MODIFIED CALCULATION MODEL

As described in the section before, in the calculation model developed at the HEU-SOL-THERM-002 report some items were neglected or omitted, for the sake of simplification. In contrast with this, the present model has been developed applying a different approach: in the base cases no items were omitted or neglected. This resulted in a more realistic calculation model for the given experimental situation. This model has been developed according to benchmark specifications [4], and added data taken out of the original published report [3].

In this model, the compositions for high-enriched uranyl nitrate solutions have been set up according to given data for uranium isotopic distribution, uranium concentration and excess nitric acid. All impurities have been taken into account and were assumed to be those given in references, apportioned according to their typical concentrations. Solution densities have been taken from the corresponding table in documentation.

With regard to tank dimensions, they have been assumed to be those given at tables and corresponding figures. For material composition, given at reference documents, all constituents have been taken into account for both 304 stainless-steel and aluminium alloy 6061. Besides, in all cases tailpipes of the same material have been added according to given geometry and dimensions, as well as phenolic paint of the corresponding thickness in aluminium tanks.

Concrete reflector has been modelled in accordance with given dimensions, and its composition has been assumed that measured after 16 months of curing, taking into account all neutron absorber given as impurities (boron, chlorine and cadmium). The re-bar present in all panels has been included as a 0.49-cm-thick region of homogenized concrete and steel, located at the mid plane of the panels. In addition, the 0.01-cm-thick polyvinylchloride (C_2H_3Cl) layer, lining the interior bottom and sides of the concrete reflector, have been considered as part of the model, being its density 0.91 g/cm^3, as stated in references. This more complete model has also included the steel plates below reflector, the compression band around top panel, and the solution distribution manifold.

Uncertainties analysis has been made based on the evaluation of experimental data presented in the HEU-SOL-THERM-002 report. A brief description of this analysis, together with the study of parameter effect is presented now.

According to references, the reported uncertainties related to solutions represent one standard deviation about the mean for multiple samples. Also, it is stated that the maximum relative uncertainties from the entire series of experiments for the high, medium, and low uranium concentrations were 0.6%, 0.7%, and 2.3%, respectively. In this work, effects of +1% changes in this concentration have been calculated and, following analysis made in HEU-SOL-THERM-002 results for standard uncertainties have been obtained by scaling the effect in order to match the given uncertainties (i.e., multiplying the calculated Δk_{eff} by 0.6/1 = 0.6, and so on). The effect of the uranium isotopic uncertainty has been calculated by increasing the ^{235}U weight percent by twice the standard deviation, and increasing the total of the weight percents of ^{234}U, ^{236}U, and ^{238}U by the same amount, proportioned according to their individual weight percent. The effect of the standard uranium isotopic uncertainty (reported to be one standard deviation) has been obtained by dividing the calculated results by 2.

The largest standard uncertainty in solution density (reported to be 0.0025 g/cm^3) has been taken as the standard uncertainty of the measurement method. The effect of a 0.002 g/cm^3 increase has been calculated for each case, and the k_{eff} effects of the standard uncertainty scaled to 0.0025 g/cm^3. In the same way, the largest measured relative uncertainty in nitric acid contents (reported to be 3.7%) has been taken as the estimate of the uncertainty of the measurement method for all cases. In order to estimate this effect on k_{eff}, a 2% increase in free nitric acid has been calculated for each case, with solution density conserved by decreasing the water. The results have been scaled to the standard uncertainty (i.e., multiplying the calculated Δk_{eff} by 3.7/2 = 1.85). The effect of removing all the nitric acid excess has been also calculated. In addition, the effect of omitting the total measured impurities has been calculated simply by excluding them from the model. As impurities served to both absorb neutrons and displace water, solution density and measured concentrations have been conserved by reducing the water in solution by the mass of the impurity compounds.

The effect of increasing the tank material density by 0.4 g/cm^3 on k_{eff} has been also calculated. Uncertainties in the reported, measured densities have been assumed to be 1 in the last reported digit, so the last results have been scaled to this value. Effect of tank thickness on k_{eff} have been calculated making changes in thickness of +0.1 cm for the side wall and +0.2 cm for the bottom, and scaled then to the standard uncertainties.

The effect of critical height on k_{eff} has been calculated by increasing it by 0.2 cm for each case. Taking into account the different uncertainties associated with critical-height measuring, HEU-SOL-THERM-002 report concluded that critical-height standard uncertainty was 0.11 cm for all cases, so results have been scaled to 0.11 cm in order to obtain k_{eff} standard uncertainty. Effect of solution radius on k_{eff} has been calculated increasing the solution radius by 0.2 cm, and then the results were scaled to the corresponding value for the solution-radius standard uncertainty for each case.

The effect of elimination of water on k_{eff} has been estimated by adding all initial water and, following reference [4], assuming an standard uncertainty equal to 1/5 the calculated effect of added water. Moreover, calculations with concrete density increased by 2% have been made to estimating the effect on k_{eff}, and the effect of a concrete-density decrease of 0.25% (reported as the standard uncertainty) has been obtained by scaling the results to this value.

The effect of moving the side walls closer to the tank by 1 cm has been calculated. The standard uncertainties for all cases have been calculated by scaling to the assumed uncertainty in position. Finally, calculations have been made in order to the estimate the effect of excluding the following items: vinyl lining from the interior of bottom and sides of the concrete reflector, measured impurities in concrete, compression band at top concrete panel, phenolic paint in aluminium tanks, solution tailpipes, solution distribution manifold, and steel plates below concrete. Also calculations with no concrete reflector were performed in order to determine the relative effects of this reflector.

In this work, all calculations have been made using the latest version of MCNPX Monte Carlo code (i.e. version 2.7E [5,6]). This code allows the development of a complete three-dimensional calculation model, using one of the most up-to-date comprehensive physical models for neutrons. In addition, the code has been combined with an updated set of cross section data: the continuous-energy ENDF/B-VI library. This combination, added to the mathematical model developed in this work, has resulted in a comprehensive representation of the real experimental situation. In MCNPX, effective multiplication factor (k_{eff}) is estimated in three different ways [7]: by collision, absorption, and track length estimators. In addition, these estimates are combined using observed statistical correlations to provide the optimum final estimate of k_{eff} and its standard deviation. This has been the estimate for k_{eff} used in this work.

5. RESULTS AND DISCUSSION.

Using the calculation method mentioned in the section before, the k_{eff}'s for the complete model (i.e. with no items omitted or neglected) have been calculated for each base case in table I. Effects from changes or omission of given items have been estimated by making the proposed variations, and calculating the corresponding k_{eff}'s.

Table II. Calculation results for k_{eff}

Case number	$k_{eff} \pm \sigma$
1	1.0002 ± 0.0066
2	1.0012 ± 0.0073
3	0.9951 ± 0.0081
4	0.9951 ± 0.0071
5	1.0001 ± 0.0075
6	1.0030 ± 0.0067
7	0.9979 ± 0.0045
8	1.0007 ± 0.0056
9	0.9954 ± 0.0095
10	0.9963 ± 0.0105
11	0.9989 ± 0.0069
12	1.0021 ± 0.0058
13	0.9962 ± 0.0053
14	1.0031 ± 0.0073

Experimental uncertainties of reported data and those arising when omitting certain items give rise to an uncertainty in the calculated k_{eff} values. As described in previous section, uncertainties from experimental data have been obtained by scaling the corresponding calculated effect. All estimated uncertainties have been combined with the calculated k_{eff}'s to obtain the benchmark-model one-σ uncertainties for k_{eff} 's. Final results are shown in table II, where resulting one-σ uncertainties include the quadratic combination with statistical uncertainties given by MCNPX.

Table III. Calculated effects on k_{eff}.

Parameter	Parameter variation calculated	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
uranium concentration	+1%	-0.147	-0.057	-0.329	-0.354	0.077	0.057	-0.436
^{235}U weight per cent	+2 sigma	-0.108	0.082	0.131	-0.067	0.137	0.027	0.018
nitric acid	removed	0.808	0.903	1.305	1.122	1.072	0.914	1.276
nitric acid contents	+2%	-0.157	-0.009	-0.014	-0.133	0.153	0.004	-0.062
impurities in solution	removed	0.227	0.450	0.281	0.168	0.547	0.469	0.169
solution density	+0.002 g/cm3	0.016	0.002	0.250	0.216	0.199	0.161	0.078
critical height	+0.2 cm	0.081	0.350	0.356	0.323	0.247	0.252	0.236
solution radius	+0.2 cm	0.781	0.959	1.005	0.790	1.087	0.895	0.876
tank material density	+0.4 g/cm3	-0.042	0.050	0.133	0.064	0.147	0.129	0.032
tank wall thickness	+0.1 cm	0.300	0.373	0.490	0.336	0.271	0.124	0.208
tank bottom thickness	+0.2 cm	0.007	0.044	0.287	0.033	0.132	-0.042	-0.138
phenolic paint	removed	--	--	--	--	0.015	-0.095	-0.096
concrete density	+2%	-0.183	0.121	0.015	0.075	0.178	0.008	-0.025
water in concrete	initial added	-0.215	-0.030	0.027	0.028	0.082	0.008	-0.083
re-bar	removed	-0.149	0.052	0.032	-0.111	0.097	0.028	0.032
impurities in concrete	removed	-0.055	0.162	0.163	0.180	0.113	0.316	0.117
vinyl lining	removed	-0.142	0.069	0.072	0.111	0.087	0.001	0.078
compression band	removed	-0.096	0.063	0.146	-0.075	0.025	-0.011	0.015
concrete panels	removed	-1.522	-7.378	-1.598	-8.978	-1.436	-8.194	-1.911
tank position	1 cm closer	-0.133	0.088	0.035	-0.049	0.078	0.004	-0.048
steel plates below	removed	-0.116	0.031	-0.039	0.066	-0.013	-0.009	0.009
tailpipes	removed	-0.096	0.053	-0.039	0.007	0.119	-0.189	-0.019
solution manifold	removed	-0.176	0.084	-0.013	-0.087	0.047	-0.055	0.033

Table III. Continued

Parameter	Parameter variation calculated	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14
uranium concentration	+1%	-0.388	0.169	0.248	-0.045	-0.064	-0.463	-0.459
^{235}U weight per cent	+2 sigma	-0.003	-0.022	-0.016	0.121	-0.012	0.013	0.037
nitric acid	removed	1.162	0.493	0.549	1.042	0.911	1.187	1.148
nitric acid contents	+2%	-0.052	-0.087	-0.002	0.025	-0.057	-0.102	-0.077
impurities in solution	removed	0.112	0.818	0.756	0.432	0.309	0.116	0.174
solution density	+0.002 g/cm3	0.083	0.064	0.220	0.271	0.128	0.143	-0.012
critical height	+0.2 cm	0.215	0.076	0.267	0.474	0.392	0.311	0.476
solution radius	+0.2 cm	0.888	0.655	0.627	0.699	0.602	0.631	0.559
tank material density	+0.4 g/cm3	0.069	0.026	0.077	0.173	0.142	0.163	0.117
tank wall thickness	+0.1 cm	0.142	0.010	0.092	0.221	0.046	0.126	0.075
tank bottom thickness	+0.2 cm	-0.091	-0.001	-0.065	0.159	-0.136	0.161	-0.140
phenolic paint	removed	-0.104	-0.046	0.074	0.124	0.029	0.107	0.008
concrete density	+2%	0.025	-0.034	0.040	0.120	0.030	-0.083	0.195
water in concrete	initial added	0.198	-0.070	0.049	0.051	0.180	-0.009	0.366
re-bar	removed	-0.025	0.046	-0.008	0.075	-0.020	0.042	-0.061
impurities in concrete	removed	0.248	0.056	0.253	0.144	0.216	0.131	0.336
vinyl lining	removed	-0.118	-0.074	-0.074	0.064	-0.098	-0.075	-0.116
compression band	removed	0	0.005	-0.027	0.139	-0.033	-0.001	0
concrete panels	removed	-9.754	-1.344	-7.221	-1.636	-11.402	-1.843	-13.674
tank position	1 cm closer	-0.060	0.079	0.058	0	0.073	0	0.123
steel plates below	removed	-0.047	-0.013	0.011	-0.001	-0.021	-0.067	-0.022
tailpipes	removed	-0.242	-0.089	-0.108	-0.003	-0.218	-0.047	-0.354
solution manifold	removed	-0.114	-0.026	0.023	0.057	-0.033	0.047	-0.118

Results of effects on k_{eff} from changes or omission of given items, for the fourteen cases are summarized in Table III. The resulting effects have been calculated as the per cent difference with the associated k_{eff} for base cases.

The results obtained in this work will be discussed now. Because the effects related to solution properties are expected to be the more important, they will be analysed first. It has been found that meaningful variations in uranium isotopic composition produce no significant changes on k_{eff} (up to only 0.13%), so they may be neglected. On the other hand, it has been observed that meaningful variations in uranium concentration produce significant effects, with absolute values ranging from 0.05 to 0.46 %. In consequence, models should include a sensitivity analysis for this concentration. Concerning solution density, it has been found that significant variations increased k_{eff} up to about 0.27%, so it is an important effect to be included in models.

Removal of all nitric acid excess has been found to produce increasing of k_{eff} ranging from 0.5 to 1.3%. This effect on k_{eff} is meaningful, so it has been concluded that nitric acid excess must be included in the calculation model. In addition, it has come out that significant variations in this excess (+2%) produce small changes on k_{eff} (up to only 0.16%). Consequently, this variation may be neglected at a first approximation. In regard to impurities, it has been observed that its removal from solution produce a positive effect on k_{eff}, ranging from 0.11 to 0.82 %. References remarked that they represent small amounts, with measuring uncertainties of about 50% and main contribution coming from cadmium and boron. In spite of this, the effect is significant (is the main contribution to uncertainties in cases 9 and 10, as may be seen in table III), so it must be taken into account in the model, or in a sensitivity analysis.

Meaningful variations in critical height have been found to produce important changes on k_{eff} (up to 0.48%). In the same way, significant variations in solution radius have been found to have considerable effect on k_{eff} (ranging from 0.56 to 1.09%). Accordingly, effect of changes in both height and radius of solution should be studied.

It has been found that significant changes in both tank walls and bottom thicknesses produce meaningful effect on k_{eff} , up to 0.49% and 0.28% respectively. Tanks serve to both absorb and reflect neutrons, so the mentioned effects would depend on geometry and should be studied. On the contrary, it has been found that significant changes in tank material density produce no meaningful effects on k_{eff}, so density changes in both steel and aluminium may be neglected. The same result has been obtained for phenolic coating. Taking into account the coat thickness (about 180 µm), it is an expected result. In consequence the phenolic paint may be disregarded in the model.

Concerning impurities in concrete, its removal increased k_{eff} up to about 0.36%. As reflection is expected to be more important with the tank on the bottom panel, and impurities (mainly boron, cadmium and chloride) produce neutron absorption, the effect on k_{eff} is expected to be more significant in these cases; results have confirmed this fact. In regard to addition of initial water contents, it has been found that it produce meaningful effects on k_{eff} (up to 0.36%), more apparent in cases with tank on the bottom panel, as discussed below. Consequently, water content has to be taken into account in the model. Concerning density, it has been found that increasing it by 2% produce small, but meaningful changes on k_{eff} (up to 0.2%). Accordingly this effect must be taken into account if significant changes are possible on concrete density. The effect of moving tanks 1 cm closer to concrete panels has been found to be no more than 0.13% on k_{eff}, which represent only a small contribution to total uncertainties, so it may be neglected. Concerning vinyl lining on concrete panels, as expected because of its small thickness (0.01 cm) it has been found to have no significant effect on k_{eff}. The same result has arisen for re-bar, and for the compression band around the top panel. In consequence these three items may be neglected in the model.

By far the more important effect on k_{eff}, related to concrete, has been found when removing reflector panels. This removal decreased k_{eff} up to about 14%, being the effect more important when tanks were on the bottom panel, as expected because of discussion above. This result is in good agreement with reflecting properties of concrete on neutrons.

No significant effect has been observed when removing steel plates or solution distribution manifold below concrete reflector. Accordingly, they may be ignored in the model. Concerning tailpipes, its contribution was only significant (up to 0.35%) for aluminium tanks, when filled with medium and high enriched solution, and located on the bottom concrete panel.

6. CONCLUSIONS.

Benchmark-model has been re-evaluated using a mathematical model more realistic than that used in SOL-THERM-002 benchmark document. In addition, the most recent version of MCNPX Monte Carlo code has been used, combined with an updated cross section library, the ENDF/B-VI. All this has resulted in a comprehensive model for the given experimental situation. This model has been able to reproduce the criticality of configurations within 0.5%, in good agreement with experimental data.

The results obtained in the analysis of uncertainties are in general agreement with those at HEU-SOL-THERM-002 benchmark document. According to present results, the following items may be omitted, in order to simplify the calculation model: phenolic paint coating on aluminium tanks, vinyl lining on inside surface of concrete panels, steel compression bar around top panel, re-bar into concrete panels, and steel plates and solution distribution manifold below concrete reflector. These items are in agreement with those omitted in the model used at SOL-THERM-002 document.

Qualitative results from analyses made in the present work can be extended to similar fissile systems: well moderated units of ^{235}U solutions, reflected with concrete from all directions. Results has confirmed that neutron absorbers, even as impurities, must be taken into account in calculations if at least approximate composition were known.

7. REFERENCES.

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