DESIGN, DEVELOPMENT AND UTILIZATION OF THE NEW LLNL INHERENTLY SAFE SUBCRITICAL ASSEMBLY (ISSA)

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ABSTRACT

Following de-inventory of high security materials from LLNL, a new subcritical assembly for training and detector development purposes was designed and built. This paper describes the safety features inherent in the assembly design and accomplishments related to development, simulation and utilization of the new assembly.

KEYWORDS
Inverse Multiplication, ISSA, Subcritical Assembly

1. INTRODUCTION

De-inventory of high security materials from Lawrence Livermore National Laboratory (LLNL) was completed in September 2012, which required transfer of the Training Assembly for Criticality Safety [1] to the Nevada National Security Site. Consequently, the Nuclear Criticality Safety Division at LLNL decided to build a new subcritical assembly for training and detector development purposes that could be conveniently utilized by laboratory researchers, visiting scientists and students in a low security environment at the main laboratory site.

2. CONCEPTUAL DESIGN

Inherent safety, accessibility, low cost, and simplicity were major considerations identified during conceptual design. The fuel design concept was to use encapsulated fuel to avoid need for establishing a contamination area. Furthermore, the intrinsic radiation present in the fuel and external neutron sources should be strong enough to enable meaningful multiplication measurements within reasonable count times while weak enough to avoid establishing a radiation area and requiring associated controls. The amount of fuel should be limited to preclude any credible risk of a criticality accident. These inherent safety features identified during conceptual design inspired the name Inherently Safe Subcritical Assembly (ISSA). From the outset, the LLNL design goal was to enable a “hands on” student experience rather than student observations of a demonstration by a qualified or licensed operator.

Most importantly, the fuel “attractiveness level” should be as low as possible to minimize security requirements and enable easy access to persons without security clearances including university students. To minimize costs, surplus materials were used wherever possible.

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Simplicity of operations led to consideration of highly enriched uranium fuel in order to minimize the size of the assembly. Furthermore, it was recognized that bundling the fuel elements into subassemblies could minimize the number of fuel handling operations enabling rapid fueling and defueling operations. A literature review led to a design concept of using surplus encapsulated un-irradiated highly-enriched uranium Materials Test Reactor (MTR) type fuel assemblies supported in a simple lattice structure within a cylindrical tank for moderation by water as illustrated in Figure 1, which shows a lattice of SPERT-D fuel elements used in critical experiments at Oak Ridge National Laboratory in 1964-1965 [2].

Figure 1. Design Concept

Two other conceptual design considerations included the desirability of installing a core tank much taller than the active fuel length to enable measurements of higher harmonic flux effects and to elevate the tank above the floor to enable access to the tank bottom for placement of neutron sources away from student handlers and to enable source jerk measurements. An elevated tank is a design feature we noted in the DELPHI [3] subcritical assembly and the Jordan Subcritical Assembly [4].

3. FINAL DESIGN

The final design realized uses up to nine modified surplus MTR type fuel assemblies from the Omega West Reactor (OWR) [5] manufactured by the Naval Nuclear Fuel Division of Babcock & Wilcox (B&W) in Lynchburg, Tennessee. Each assembly contains either 220 or 232 grams of ^{235}U of highly enriched uranium within nineteen curved plates containing either 11.5 or 12.2 grams of ^{235}U in U_3O_8 dispersed in a matrix of aluminum and fully clad in pure aluminum. These assemblies were significantly reduced in size by LLNL to an approximate length and weight of about two feet and twelve pounds for ease of handling.

LLNL modified the original assemblies by removing the aluminum end pieces (i.e., the “nozzles” used in the Omega West Reactor for fuel positioning and handling) and fabricated new aluminum fixtures for the top and bottom of the fuel elements to aid in their placement into the lattice array. Photographs of an OWR fuel assembly modified by LLNL are provided in Figure 2.

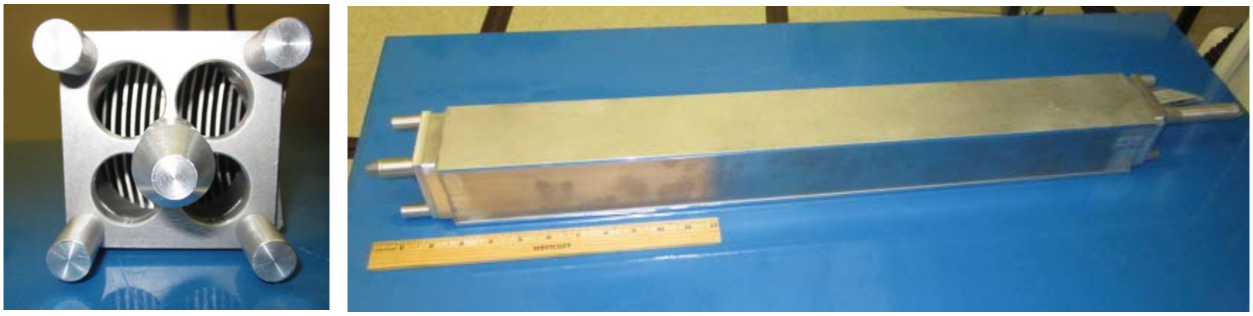


Figure 2. LLNL Modified OWR Fuel Assembly

The design layout of the ISSA is shown in Figure 3. The core tank, shown as the dark gray cylinder in the center of the platform, is a surplus tank used previously for chemical etching. The water dump tank, shown as the white tank to the right of the platform, was previously used on a truck bed for cleaning up large wastewater spills. The overhead crane was excess equipment from another facility. The stairs, railings, platforms and their supports were taken from surplus office trailers.

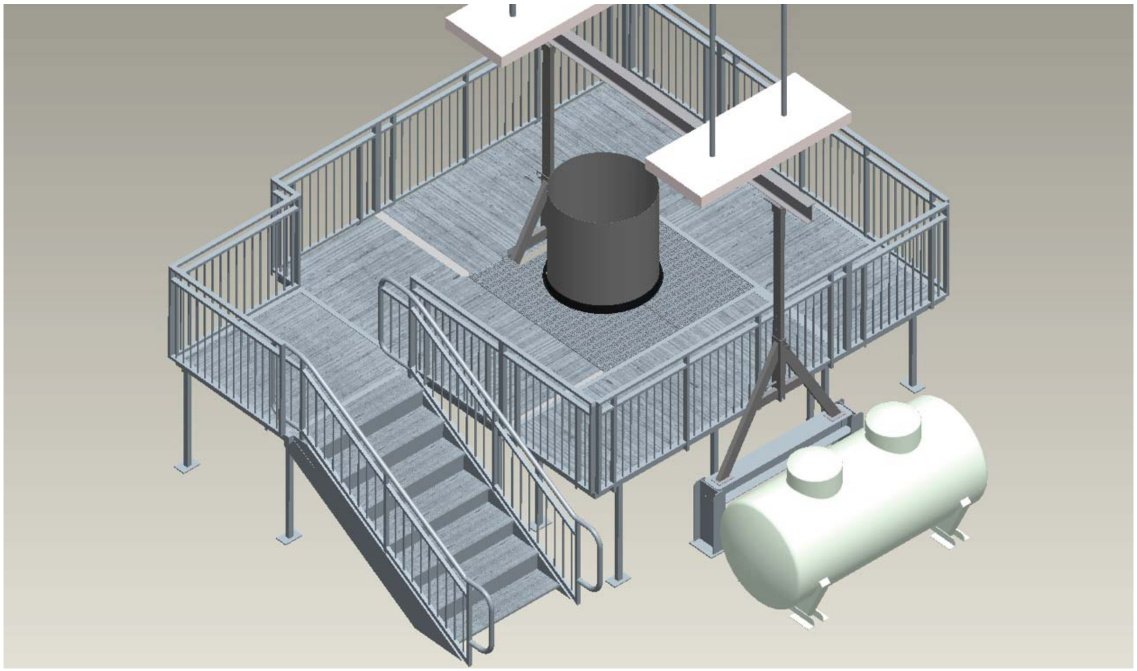


Figure 3. Design Layout of the ISSA

Other repurposed items were ^{3}He detectors taken from health physics survey instruments and eight large ^{3}He detectors recovered from an obsolete multiplicity drum counter. Several 110-gallon DOT-6M/2R obsolete shipping containers were also obtained for fuel assembly storage. Major parts fabricated by LLNL include the tank support stands and seismic restraints, detector tube wells and their supports and the aluminum core lattice. LLNL also fabricated all aluminum "mock fuel" assemblies to original B&W manufacturing drawings. These assemblies are useful in establishing an unmultiplied base count rate for subcritical multiplication measurements. Minor procurements included a water pump and associated piping and controls, drum storage racks and locking drum lids. Eberline model E-600 detectors are used to power and record counts with the small ^{3}He tubes and the large ^{3}He tubes are used with prototype Fission Meters for multiplicity counting. These detectors and ^{252}Cf sources are on loan from other laboratory programs. A photograph of the ISSA "as built" configuration is provided as Figure 4.

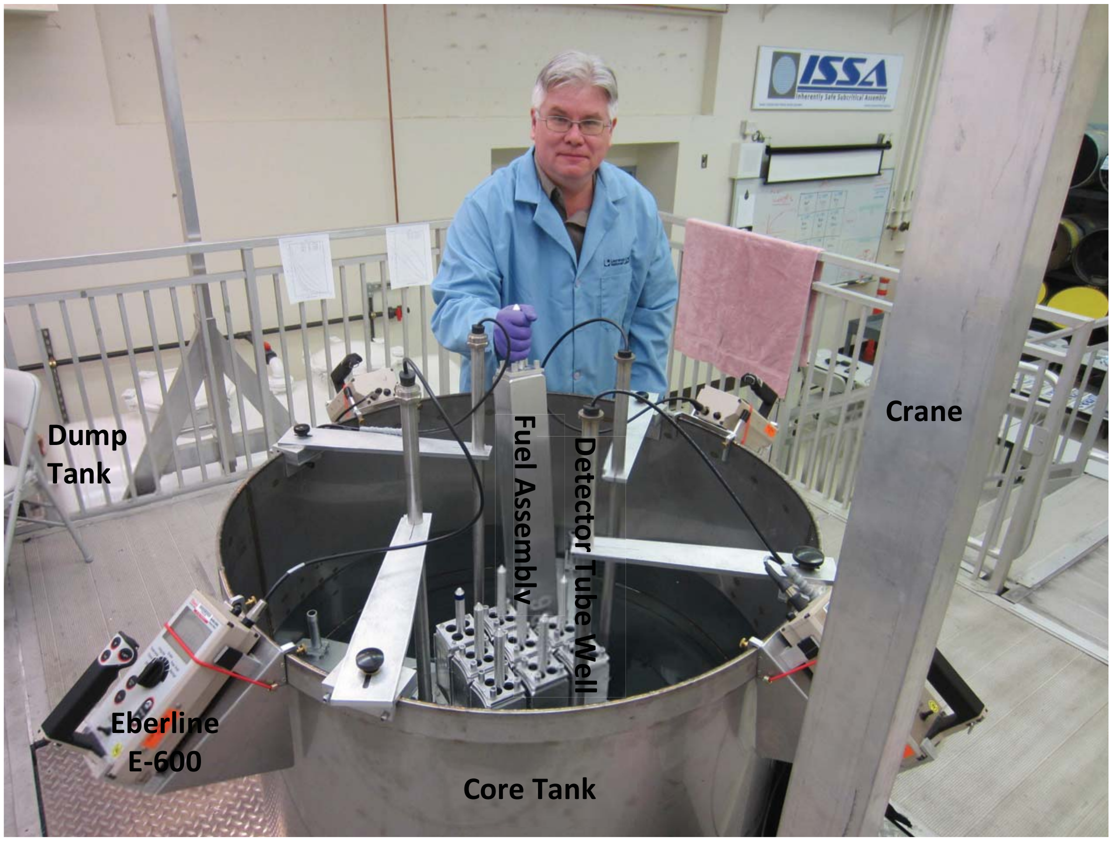


Figure 4. ISSA "As Built" Configuration

4. CRITICALITY SAFETY EVALUATION OF THE DESIGN

Prior to any subcritical measurements, LLNL developed a detailed COG10 [7] model of the "as built" modified OWR fuel assembly and completed a formally documented criticality safety evaluation [6], which is part of the safety basis for authorizing up to nine fuel assemblies outside of DOT-6M/2R storage for placement in the core tank in any arrangement. The upper safety limit of $k_{eff} \leq 0.9654$ developed in this evaluation was based on similar benchmarks using SPERT-D fuel [2]. This subcritical k_{eff} value can be compared to the calculated critical k_{eff} values for the benchmarks, which range from 0.985 to 1.016. Based on COG10 calculations, this range of critical k_{eff} values corresponds to 10.5 $\pm$ 0.5 ISSA fuel assemblies; whereas nine ISSA assemblies at optimum spacing have $k_{eff} = 0.958$, which is below the upper safety limit. A 2-D picture of the 3-D COG10 model geometry for nine fuel assemblies immersed in water is shown in Figure 5.

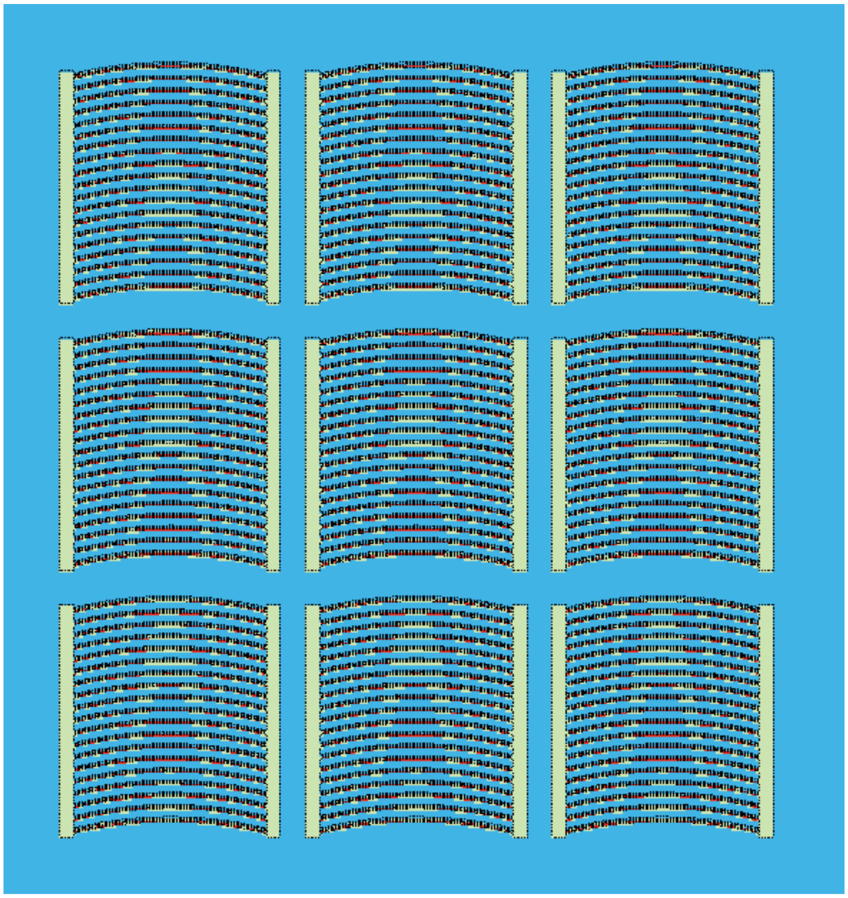


Figure 5. COG10 Model of 9 Modified OWR Fuel Assemblies in the ISSA Array

5. UTILIZATION

The ISSA was designed as a training aid and as a multiplying assembly for the development of detectors including multiplicity detectors such as prototypes for the LLNL-designed ORTEC Model FM-P3 Fission Meter and next generation detectors. As a training aid for the fundamentals of subcritical reactor physics, the syllabus given in Table 1 was as originally envisioned in 2011-2012. Those subjects of the syllabus actually completed and ready to teach are indicated with a check mark. Use of ISSA as a training aid for safeguards measurements is also under consideration.

ISSA was authorized for use on September 7, 2012 and the first approach-to-critical was completed on September 13, 2012 with typical inverse multiplication curves determined by student measurements as shown in Figure 6. Note that the estimated critical number of ISSA fuel assemblies by extrapolation of inverse multiplication measurements is 11, which is in excellent agreement with COG10 calculations.

Table I. Syllabus

Lectures	Experiments
Basic physics • Inherent sources of neutrons • External neutron sources (^{252}Cf) • Neutron cross sections ✓ Physics of chain reactions • Diffusion and Fermi age theory ✓ Modified one group diffusion equation ✓ Neutron kinetics equation • Statistics of chain reactions Hand calculations • Six factor formula ✓ Diffusion constants ✓ k-infinity, migration area and buckling ✓ Nucleonics data sheet no. 38 ✓ Alpha, k_{eff}, reactivity • Count distributions and Feynman-Y Computer codes ✓ RHEINGOLD (Diffusion) [8] ✓ ARDRA (S_N) ✓ COG (Monte Carlo)	Source multiplication experiments ✓ 1/M vs. mass (or number of assemblies) ✓ Detector placement effectors ✓ Source effects ✓ 1/M vs. moderator height • 1/M vs. pitch • Effect of over/under/optimum moderation • Effect of isolation by water • Effect of neutron poisons (including flux traps and control rods) • Effect of reflector materials ✓ Effect of core shape on leakage • Temperature reactivity coefficient • Fuel reactivity coefficient • Void reactivity coefficient Dynamic experiments • Source jerk • Pulse die-away ✓ Feynman-Y Spatial methods ✓ Buckling and extrapolation length

In the near future LLNL, in partnership with the Institut de Radioprotection et de Sûreté Nucléaire at Fontenay-aux-Roses, France, is planning to develop a subcritical benchmark for ISSA at three or more levels of subcritical multiplication for publication in the International Handbook of Evaluated Criticality Safety Benchmark Experiments. Measured count distributions at the highest level of multiplication attainable in the current design were completed in 2014 to demonstrate feasibility. Typical list mode data for a count distribution and Feynman-Y fit are shown in Figure 7. Preliminary analysis results indicate a multiplication of about 22.5 corresponding to $k_{eff} = 1 - 1/M = 0.955$ [9].

6. CONCLUSIONS

ISSA was developed at low cost as an institutional laboratory asset and is inexpensive to maintain. ISSA is available for "hands on" training and as a multiplying assembly for detector development. Due to inherent safety by design, students and visitors to the laboratory are authorized to handle the fuel, operate the detectors, water pump, etc., and execute all measurements under the supervision of the Responsible Individual. The only student prerequisites are General Employee Radiation Training, which is a read and sign instructional booklet that can be completed prior to visiting LLNL, and a pre-job briefing in the ISSA laboratory on the hazards and controls specified in the authorization basis.

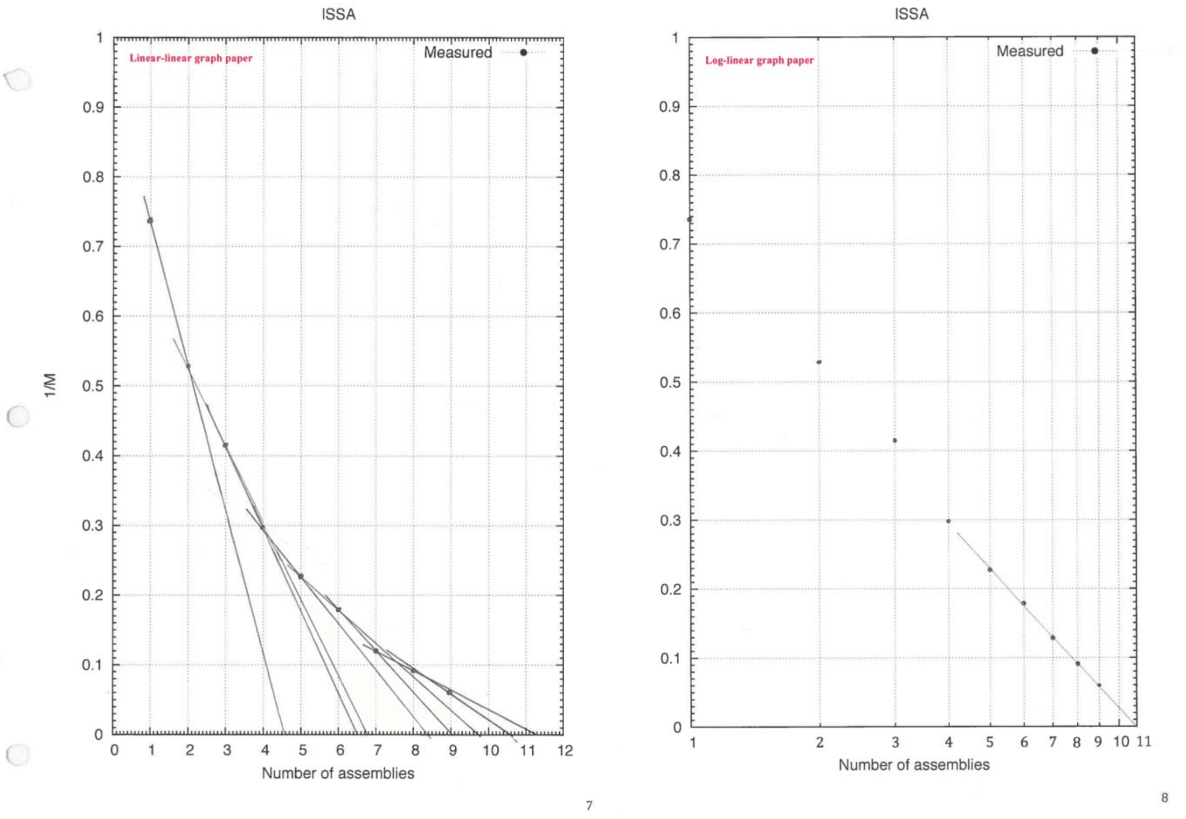
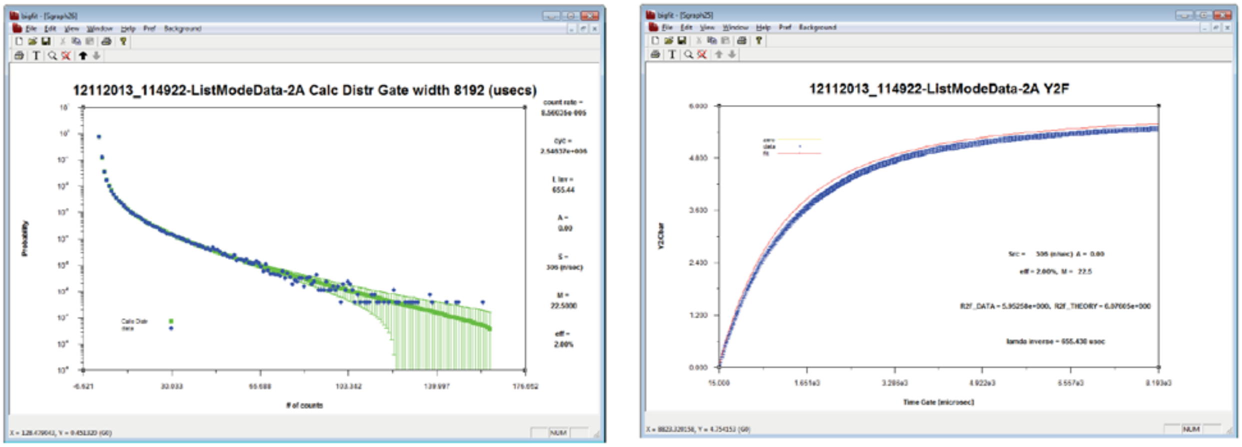


Figure 6. Typical Inverse Multiplication (1/M) Curves



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Src =    306 (n/sec) A = 0.00
eff = 2.00%, M = 22.5
R2F_DATA = 5.95258e+000, R2F_THEORY = 6.07005e+000
lamda inverse = 655.430 usec
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Figure 7. Typical Measured Count Distribution and Feynman-Y Fit at M=22.5

ACKNOWLEDGMENTS

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