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A New Era of Nuclear Criticality Experiments: The First 10 Years of Planet Operations at NCERC

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Abstract — *Planet is a vertical-lift assembly machine currently located at the National Criticality Experiments Research Center (NCERC) at the Nevada National Security Site. In the past, Planet resided at Technical Area-18 in Los Alamos, New Mexico, as part of the Los Alamos Critical Experiments Facility (LACEF). Following the de-inventorying of LACEF, the Planet assembly was relocated to NCERC in 2008 and became fully operational in June of 2011. The Class Foils experiment, which involves stacking highly enriched uranium foils to obtain a critical configuration, was the first critical experiment performed on Planet. As a major component of the Nuclear Criticality Safety Class taught for the U.S. Department of Energy (DOE) Nuclear Criticality Safety Program, the Class Foils experiment allows personnel from all over the DOE complex to handle nuclear material and to complete the approach to critical safely and successfully. This paper describes the Planet vertical assembly and recent engineering upgrade and a selection of the experiments that have been performed on Planet since its transition to NCERC 10 years ago.*

Keywords — *Planet, criticality experiments, critical assembly machine, National Criticality Experiments Research Center, benchmark experiments.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Planet is a general-purpose, vertical-lift assembly machine comprised of an upper stationary platform and a lower movable platen. The Planet assembly machine was originally built as an alternative to the Comet vertical assembly machine, which was being routinely used for weapons-related experiments during the 1980s (Ref. 1). The primary purpose of Planet is to conduct critical experiments by remotely bringing together two halves of a critical assembly into a critical configuration. Gravity is used to provide a passive shutdown mechanism. The simple, yet effective, vertical lift allows for a wide variety of potential designs and is able to meet varied experimental needs.

Critical experiments are used to determine critical masses of fissile and fissionable material (uranium, plutonium, neptunium, etc.). They support the nuclear data and criticality safety communities by providing a capability to test the integral neutron cross sections of various materials of interest. The results of critical experiments are used to improve and validate

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nuclear cross-section databases in order to design processes that remain safely subcritical. Critical experiments are also utilized to validate computational methods for nuclear transport codes and algorithms and to provide a valuable tool for the operation and testing of novel reactor materials or prototypes.

Following more than 20 years of operation at the Los Alamos Critical Experiments Facility (LACEF), Planet was disassembled in 2005, refurbished, and moved to the National Criticality Experiments Research Center (NCERC). On June 15, 2011, Planet was the first of the four critical assembly machines from LACEF to achieve criticality at NCERC. The other three machines followed over time. Since beginning operations at NCERC, Planet has been used for performing benchmark experiments for nuclear data validation, training classes for nuclear criticality safety practitioners, and testing of novel reactor materials. Subcritical, critical, and supercritical experiments have been evaluated for the International Criticality Safety Benchmark Evaluation Project[2] (ICSBEP). Figure 1 shows the number of operational days per year for Planet over the past 10 years at NCERC. Recent experiments are discussed in more detail in Sec. IV.

II. MACHINE OVERVIEW

The Planet assembly is divided into two major components as shown in Fig. 2. These components are the stationary support structure and the drive assembly. The stationary support structure consists of the platform, the columns, and the base of the assembly. The drive assembly consists of two back-to-back hydraulic rams and a moveable platen, lifted by stepper motor–driven jack screws.

The stationary support structure can support up to 907 kg (2000 lb) of weight. Planet's support structure is highly customizable and can be modified to fit most experimental needs. There are multiple experiment-specific top plates that can be installed, and the vertical support columns can be extended to increase the height of the top platform and allow for larger configurations to fit on the lower platen.

The drive assembly operates sequentially to raise the lower platen upward toward the top platform. First, the secondary hydraulic ram is raised, with a travel distance of 2 in. Then, the primary hydraulic ram is raised, with a possible travel distance up to 16 in. This travel distance depends on the experiment configuration and is adjusted by the operator prior to beginning operation. In the transition from LACEF to NCERC, the secondary hydraulic ram was added so that the Planet assembly complies with the ANSI/ANS-1-2000 (R2019), "Conduct of Critical Experiments,"[3] requirement of two independent safety SCRAM mechanisms. Each hydraulic ram is an independent safety shutdown mechanism. Withdrawal of either of the two hydraulic rams will bring the system subcritical.

Once the hydraulic rams are on their in-limits, the platen is raised by four jack screws driven by a stepper motor. This fine control movement of the platen is customizable and allows for platen movement speeds as low as 0.001 in./s. The operator can also select the gap distance at which the slowdown will start. The platen can travel up to 8 in. using the stepper motor.

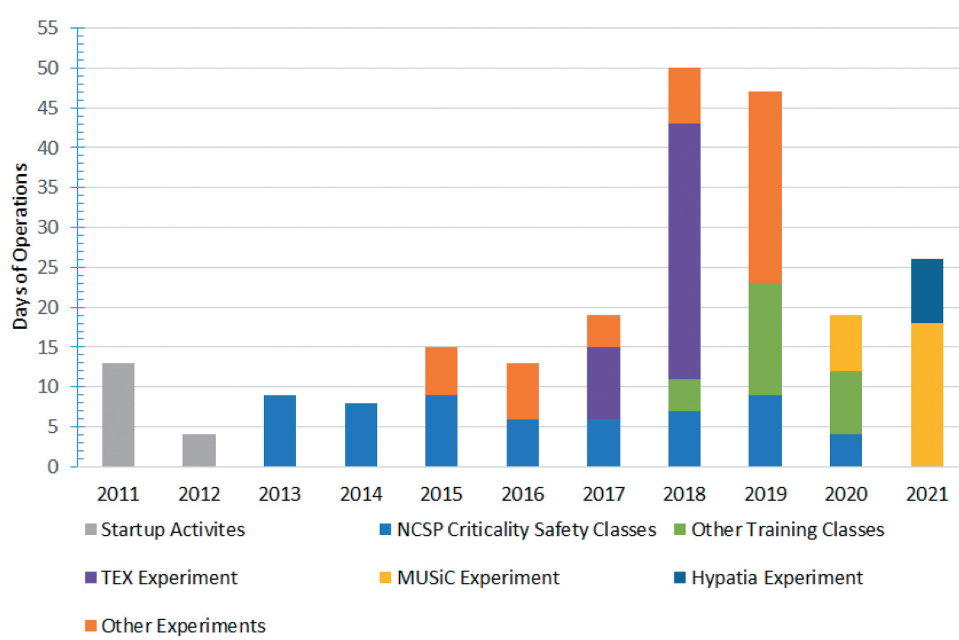

Fig. 1. Planet operations at NCERC.

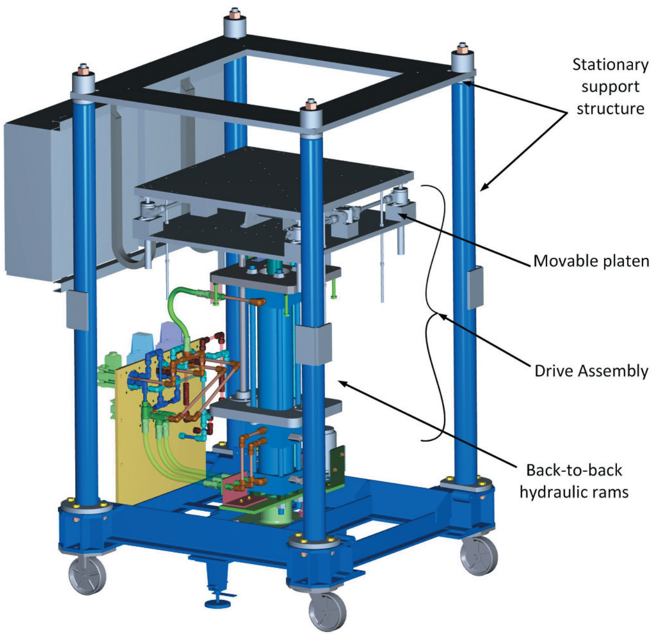

Fig. 2. Planet vertical assembly machine.

The total travel distance of the moveable platen (hydraulic rams plus stepper motor) is approximately 26 in. The maximum lifting load on the platen is 453 kg (1000 lb). Modifications to the Planet assembly at NCERC include a leveling upgrade and the addition of a load cell, to improve benchmark quality and performance. In 2020, a load cell was installed to measure the weight loaded onto the platen and to verify complete closure between the upper and lower stacks. When the bottom stack is raised into contact with the upper stationary stack, the load cell registers the force applied and displays this measurement to the operators. Leveling bases were added to the support columns, allowing for the columns to be adjusted to be perfectly vertical. Leveling assemblies were also added at the top of the columns to allow any top plate to be adjusted perfectly horizontal for each experimental configuration. A leveling plate mounted on the movable platen similarly allows for fine adjustments to make the movable platen parallel to the top plate.

Planet can be configured to accommodate experiments in different ways. The most common method is to split the critical experiment into two parts. The top portion is supported by the upper stationary platform while the bottom portion sits on the moveable platen. Bringing the lower portion to meet the upper stationary portion can achieve a critical configuration. Another common method is to place a heavy outer reflector on the upper stationary platform and a central fuel column on the moveable platen. As the moveable platen is lifted toward the upper stationary platform, the central fuel column is inserted into the heavy outer reflector, and a critical configuration can be achieved.

II.A. Measurement Instrumentation

Planet operations are monitored using a standard set of neutron detectors as required by ANSI/ANS-1-2000 (R2019). Additional instrumentation supporting specific experiments may also be deployed. The standard set of detectors includes startup counters, linear channels, and log-N's. These detector systems are located externally to Planet and rely on monitoring neutron leakage from the experiment. Experimental temperatures during a Planet operation are monitored by resistance temperature detectors, which provide indication of ambient and assembly temperatures.

The startup counters are ^{3}He tubes operated in pulse mode, providing the lowest range indication of neutron flux within the assembly. Linear channels are compensated ion chambers that overlap the startup counter range and provide indication of neutron flux within the assembly over six decades of range. Log-N's are compensated ion chambers used as input sensors to the SCRAM system. Operators select the log-N trip level based on expected conditions for each experiment.

The startup counters operate in pulse mode. They are used in operations when the neutron count rate is low, such as during hand-stacking, approach-to-critical operations, or low-power critical or supercritical operations. These systems become saturated when a ^{3}He tube exceeds a count rate of approximately 50 000 counts/s. The startup counter detectors are located on portable stands and can be moved around the experimental area to measure the neutron leakage from an experiment at the desired distance and orientation.

The linear channels operate in current mode and are used to collect experimental data during operations. They are used in operations when the neutron count rates are high enough to saturate the startup channels, typically in middle- to high-power critical or supercritical operations. The linear channel detectors are in fixed positions on wall locations, 3 to 5 m from Planet.

The log-N's also operate in current mode. As part of the SCRAM safety system, they allow for the operation to be terminated if the measured leakage exceeds a preset level. The log-N's are not connected to a computer and are not used to provide experimental data. The log-N detectors are in fixed positions on wall locations, 3 to 5 m from Planet (in the same locations as the linear channels).

III. PLANET HISTORY AT LACEF

The earliest remote critical experiments performed on a critical assembly were from 1947 to 1955 at the Los Alamos site Technical Area-18. These experiments continued the work of the Manhattan Project. Later, the site transitioned to experiments focusing on chain reaction systems, nuclear criticality safety, neutron multiplicity measurements (such as Rossi-alpha), and nuclear propulsion programs. Several critical assemblies were designed to support these programs. One of those was the Planet critical assembly, built in the 1980s (Ref. 4). Some of the most interesting experiments performed on Planet while it was operated at LACEF are summarized below.

III.A. Beryllium Reflected Plutonium Experiments

The Beryllium Reflected Plutonium (BeRP) experiments were conducted in 1986 on the Planet assembly. These experiments determined the precise beryllium thickness required to attain criticality when reflecting a 4.5-kg alpha-phase plutonium sphere. This sphere is known as the BeRP ball for its initial use in this experiment and is still in use today.[5] This series of experiments was accomplished by surrounding the BeRP ball with different thicknesses of beryllium reflectors until delayed critical (k_{eff} of 1) was attained. The BeRP experiment configuration consisted of the plutonium core nested inside of the bottom beryllium hemishell and placed on the lower movable platen with the top beryllium hemishell held up with post extensions on the top spider-type platform as shown in Figs. 3 and 4. An ICSBEP benchmark evaluation, PU-MET-FAST-038, was published using the data from this experiment.[5]

III.B. Plutonium Sphere Reflected by Highly Enriched Uranium

The Plutonium Sphere Reflected by Highly Enriched Uranium (HEU) experiment campaign was conducted in 2003. It consisted of the alpha-phase plutonium BeRP ball surrounded with HEU Rocky Flats shells,[6] shown in Fig. 5. The experiment provided data to determine how well the Monte Carlo N-Particle® (MCNP®)[a] transport code,[7] in conjunction with uranium and plutonium cross sections, could reproduce the experiment. An ICSBEP benchmark evaluation, MIX-MET-FAST-013, was published using the data from this experiment.[6]

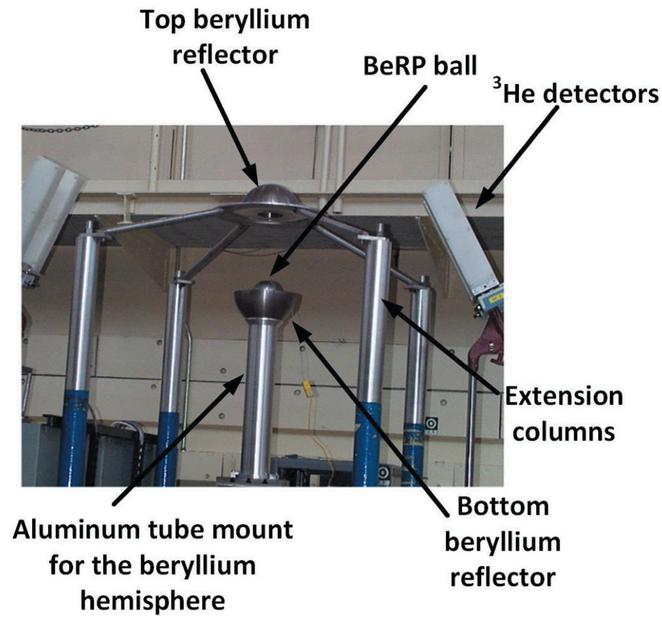

Fig. 3. The BeRP experiments mounted on Planet.

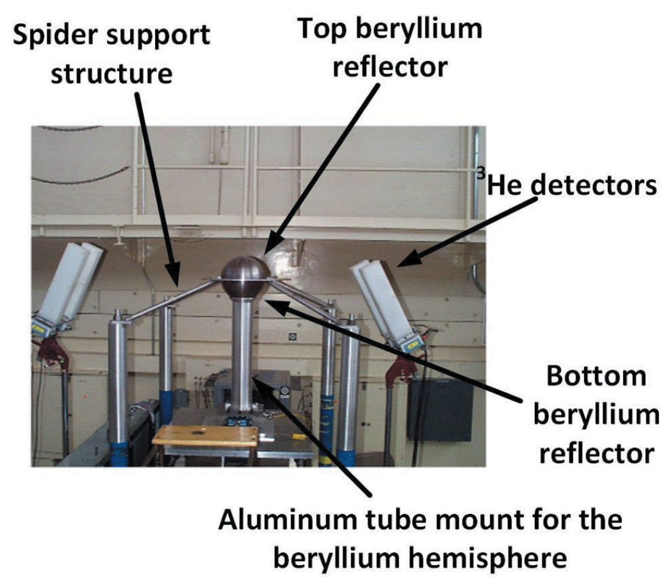

Fig. 4. Alignment of the BeRP experiment on Planet.

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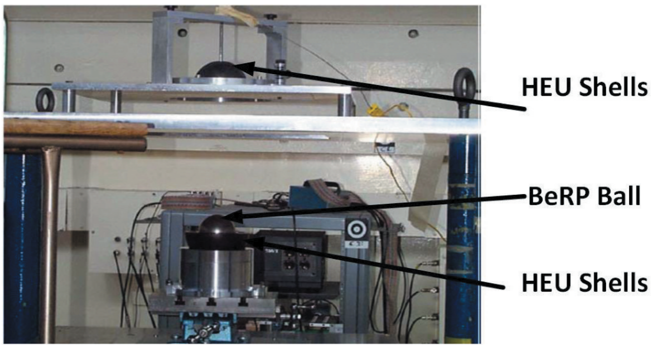

Fig. 5. BeRP ball surrounded by HEU shells.

III.C. Jupiter Icy Moons Orbiter Experiment

The National Aeronautics and Space Administration's Jupiter Icy Moons Orbiter project was to design a space-reactor power system to explore several of Jupiter's moons. Critical experiments were designed to address the uncertainty in the neutron cross-section data of refractory materials under consideration for the reactor design including rhenium, molybdenum, tantalum (Ta) 2.5 wt% tungsten (Ta-2.5 W), and niobium 1 wt% zirconium (Nb-1Zr). Eight to ten experiments were designed, but only one was taken to critical in 2004. Figure 6 shows the Nb-1 wt% Zr experiment mounted on the Planet assembly. An ICSBEP benchmark evaluation, HEU-MET-FAST-047, was published using the data from this experiment.[8]

III.D. Westinghouse-Idaho Nuclear Company Slab Tank Experiments

The Westinghouse-Idaho Nuclear Company (WINCO) slab tank experiments provided benchmark data for highly enriched uranyl-nitrite solutions stored in thin rectangular slab tank arrays isolated from adjacent tanks by moderating and neutron absorber materials. For the experiment, short, cylindrical slab tanks were mounted on both the upper stationary platform and the lower movable platen, as shown in Fig. 7. The platen was raised, and delayed critical was attained with a 9.8-cm air gap between the tanks. This series, conducted in 1988 and consisting of approximately 30 delayed critical experiments, utilized a variety of absorbing and moderating materials between the tanks.

There were also experiments performed using the source jerk and the Rossi-alpha techniques to characterize subcritical configurations. For the source jerk measurements, a neutron source was placed between the tanks and ejected rapidly into a shielded storage container. Neutron detectors (^{3}He) placed above and below the tanks recorded the fluctuations in the neutron population at different degrees of subcriticality. The data were analyzed with different source jerk methods.[9] The effective delayed neutron fraction and prompt neutron decay constant at delayed critical were estimated using the Rossi-alpha technique for subcritical measurements.[10] An ICSBEP benchmark evaluation, HEU-SOL-THERM-038,

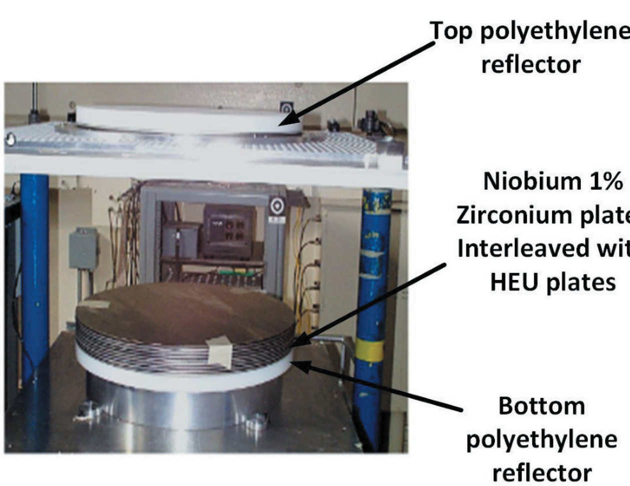

Fig. 6. Niobium 1 wt% zirconium fueled by HEU plates.

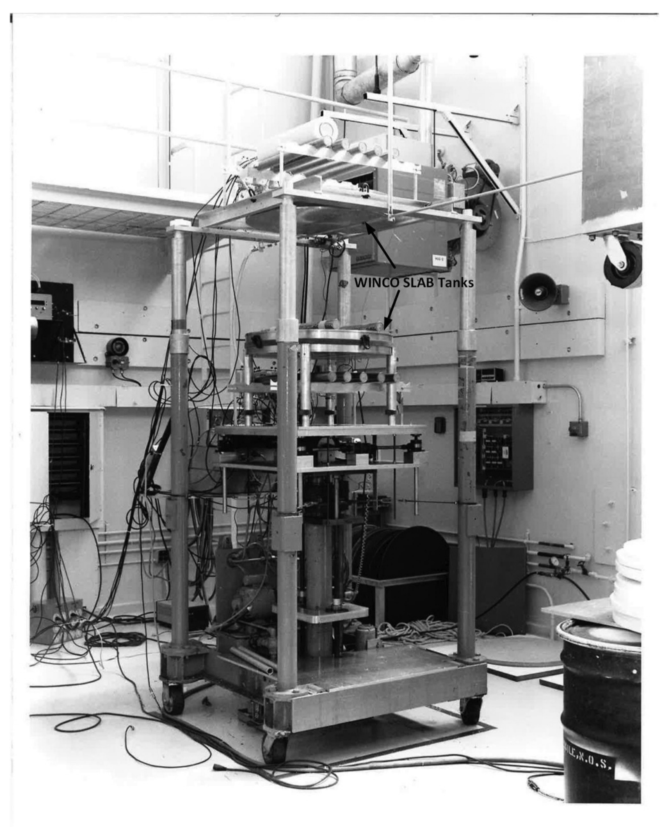

Fig. 7. The WINCO slab tanks mounted on Planet.

was published using the data from this experiment including both critical and subcritical configurations.[11]

III.E. Neptunium Critical Experiment

A series of critical experiments was performed in the early 2000s to estimate the critical mass of ^{237}Np (Ref. 12) using a 6-kg sphere of neptunium (named the Np Sphere). The Np Sphere was cast and clad at Los Alamos National Laboratory (LANL) in 2001 (Ref. 13). The experimental configurations included surrounding the Np Sphere with HEU shells (shown in Figs. 8 and 9), in addition to using reflector materials such as polyethylene and stainless steel.

A typical 3000 MW(thermal)/1000 MW(electric) nuclear reactor produces on the order of 12 to 13 kg of neptunium in 1 year (Ref. 14). Neptunium in irradiated fuel elements may be separated and stored in liquid solutions or, for longer-term storage, converted into oxides and metals. There was uncertainty of the critical mass for neptunium oxides and metals.[15] This knowledge was needed to determine mass storage limits and optimize configurations for disposition of materials containing neptunium.

Nuclear data evaluators utilized the critical experiment results, coupled with MCNP simulation results, to update ^{237}Np neutron cross sections, based on ENDF/B-VI.8 (Ref. 16) nuclear data at the time. From this work, the bare ^{237}Np critical mass of 57 $\pm$ 4 kg (Ref. 12) was estimated. This experiment continues to be used for nuclear data validation, with the latest cross-section data estimating a bare critical mass of ^{237}Np to be 59.59 kg (ENDF/B-VIII.0), 58.7 kg (ENDF/B-VII.1 and JENDL-4.0), and 63.8 kg (JEFF-3.1) (Ref. 17). An ICSBEP benchmark evaluation, SPEC-MET-FAST-008, was published using the data from this experiment.[18]

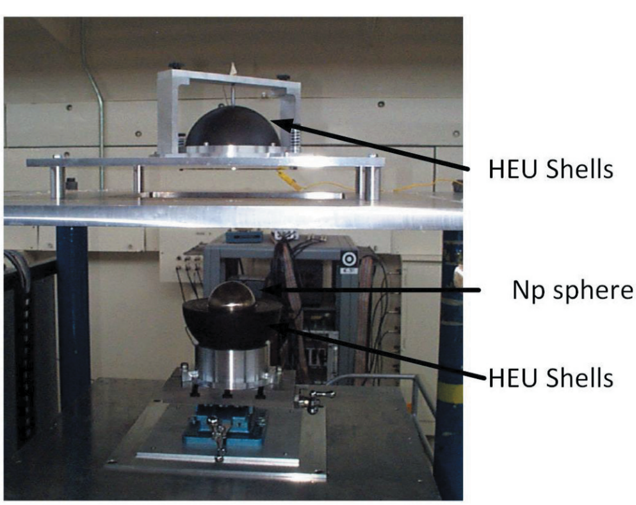

Fig. 8. Neptunium critical experiment on Planet.

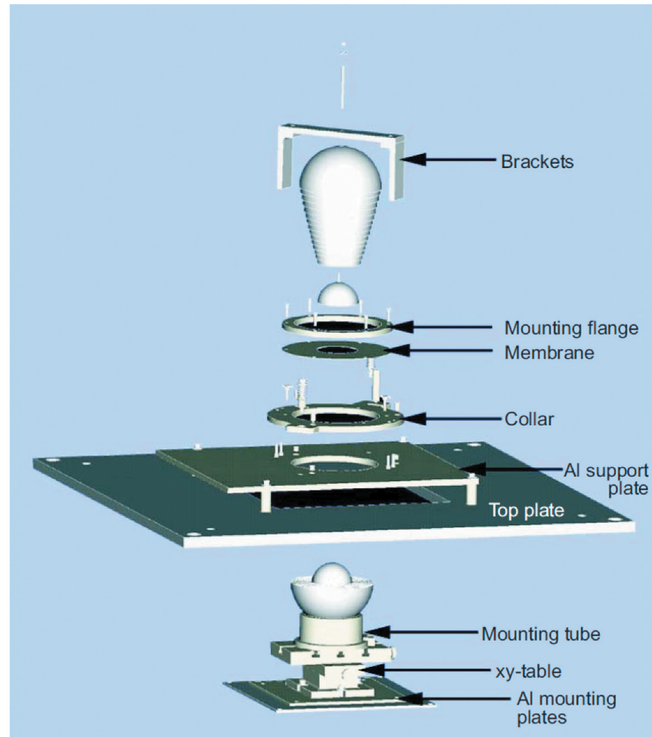

Fig. 9. Neptunium critical experiment on Planet (exploded view).

The Np Sphere has also been used for subcritical benchmark configurations and as a radiation test object component for detector measurements.[19]

III.F. Summary of Benchmark Experiments on Planet

During Planet's more than 20 years of operation at LACEF, 30 ICSBEP benchmarks were conducted using a variety of materials and geometries. Each ICSBEP evaluation has a unique identifier. The identifier takes the following form: (Fissile Material)-(Physical Form)-(Spectrum)-(Three-Digit Numerical Identifier). The Planet benchmarks encompass critical experiments in the PU-MET-FAST (PMF), HEU-MET-FAST (HMF), HEU-MET-THERM (HMT), U233-MET-FAST (U233MF), MIX-MET-FAST (MMF), SPEC-MET-FAST (SMF), and PU-MET-MIXED (PMM) ICSBEP series. The full list of ICSBEP benchmark experiments performed on the Planet assembly is provided in Table I.

Of particular note are several critical experiments performed to validate computational models of fissile material

TABLE I

ICSBEP Planet Benchmarks

Benchmark Name	ICSBEP Identifier	Measurement Year
"Benchmark Critical Experiment of a Plutonium Sphere Reflected by Tungsten"	PU-MET-FAST-005	1958
"Benchmark Critical Experiment of a Delta-Phase Plutonium Sphere Reflected by Normal Uranium"	PU-MET-FAST-010	1958
"Benchmark Critical Experiment of a Delta-Phase Plutonium Sphere Reflected by Beryllium"	PU-MET-FAST-018	1958
"Benchmark Critical Experiments of Uranium-233 Spheres Surrounded by Uranium-235"	U233-MET-FAST-002	1958
"Benchmark Critical Experiments of Highly Enriched Uranium-233 Spheres Reflected by Normal Uranium"	U233-MET-FAST-003	1958
"Benchmark Critical Experiments of Highly Enriched Uranium-233 Spheres Reflected by Tungsten"	U233-MET-FAST-004	1958
"Benchmark Critical Experiment of Highly Enriched Uranium-233 Spheres Reflected by Beryllium"	U233-MET-FAST-005	1958
"Benchmark Critical Experiment of a Plutonium Sphere Surrounded by Highly Enriched Uranium"	MIX-MET-FAST-001	1958
"Plutonium Sphere Reflected by Beryllium"	PU-MET-FAST-038	1986
"Winco Slab Tanks: Two Interacting Tanks of Highly Enriched Uranyl Nitrate Solution with Various Absorber-Reflector Plates"	HEU-SOL-THERM-038	1988
"Subcritical Noise Measurements for Two Coaxial Cylindrical Tanks Containing 93.1% Uranyl Nitrate Solution"	SUB-HEU-SOL-THERM-002	1988
"Polyethylene Reflected and Moderated Highly Enriched Uranium System with Silicon"	HEU-MET-THERM-001	1998
"Polyethylene Reflected and Moderated Highly Enriched Uranium System with Aluminum"	HEU-MET-THERM-008	2000
"Polyethylene Reflected and Moderated Highly Enriched Uranium System with Magnesium Oxide"	HEU-MET-THERM-009	2001
"Polyethylene Reflected and Moderated Highly Enriched Uranium Systems with Gadolinium"	HEU-MET-THERM-010	2001
"2 × 2 Array of Highly Enriched Uranium, Moderated and Reflected by Polyethylene"	HEU-MET-THERM-031	2001
"One Dimensional Array of Highly Enriched Uranium, Moderated and Reflected by Polyethylene"	HEU-MET-THERM-032	2001
"Polyethylene Reflected and Moderated Highly Enriched Uranium Systems with Iron"	HEU-MET-THERM-013	2002
"2 × 2 × 23 Array of Highly Enriched Uranium with Silicon Dioxide, Moderated and Reflected by Polyethylene"	HEU-MET-THERM-014	2002
"2 × 2 Array of Highly Enriched Uranium with Iron, Moderated and Reflected by Polyethylene"	HEU-MET-THERM-015	2002
"Neptunium-237 Sphere Surrounded by Hemispherical Shells of Highly Enriched Uranium"	SPEC-MET-FAST-008	2002
"2 × 2 × 26 Array of Highly Enriched Uranium with Aluminum, Moderated and Reflected by Polyethylene"	HEU-MET-THERM-012	2003
"Polyethylene Reflected and Moderated Highly Enriched Uranium System with Concrete"	HEU-MET-THERM-018	2003
"2 × 2 Polyethylene Reflected and Moderated Highly Enriched Uranium System with Rhenium"	HEU-MET-THERM-033	2003
"Plutonium Sphere Surrounded by Highly Enriched Uranium"	MIX-MET-FAST-013	2003
"Neptunium-237 Sphere Surrounded by Highly Enriched Uranium and Reflected by Low-Carbon Steel"	SPEC-MET-FAST-014	2003
"Niobium - 1wt.% Zirconium Moderated by Polyethylene and Fueled with Highly Enriched Uranium"	HEU-MET-FAST-047	2004

(Continued)

TABLE I (Continued)

Benchmark Name	ICSBEP Identifier	Measurement Year
"2 × 2 × 13 Array of Highly Enriched Uranium with Ni-Cr-Mo-Gd Alloy, Moderated and Reflected by Polyethylene"	HEU-MET-THERM-034	2004
"Neptunium-237 Sphere Surrounded by Highly Enriched Uranium and Reflected by Polyethylene"	SPEC-MET-FAST-011	2004
"TEX Plutonium Baseline Assemblies: Plutonium/Aluminum Metal Alloy Plates with Varying Thicknesses of Polyethylene Moderator and a Thin Polyethylene Reflector"	PU-MET-MIXED-002	2017
"TEX Plutonium Assemblies with Tantalum: Plutonium/Aluminum Metal Alloy Plates with Varying Thicknesses of Polyethylene Moderator, Interstitial Tantalum and a Thin Polyethylene Reflector"	PU-MET-MIXED-003	2018
"One Dimensional Array of Highly Enriched Uranium, Moderated and Reflected by Lucite"	HEU-MET-THERM-004	2019

in contact with waste matrix materials. These experiments provided criticality data to validate models in support of decommissioning activities, the Yucca Mountain disposal facility, and the Hanford waste storage tanks.[20]

This series of experiments utilized the uranium foils presently used for the Class Foils experiment (described in Sec. IV.A). The matrix materials in these experiments included SiO_2, MgO, Al, Gd, CH_2, Fe, and concrete embedded in polyethylene.[21] Figure 10 shows examples of configurations with a variety of matrix materials. In most cases, MCNP simulations overpredicted the reactivity of the experimental configurations. At the time, it was attributed to available thermal scattering law (TSL) treatments of the matrix materials.

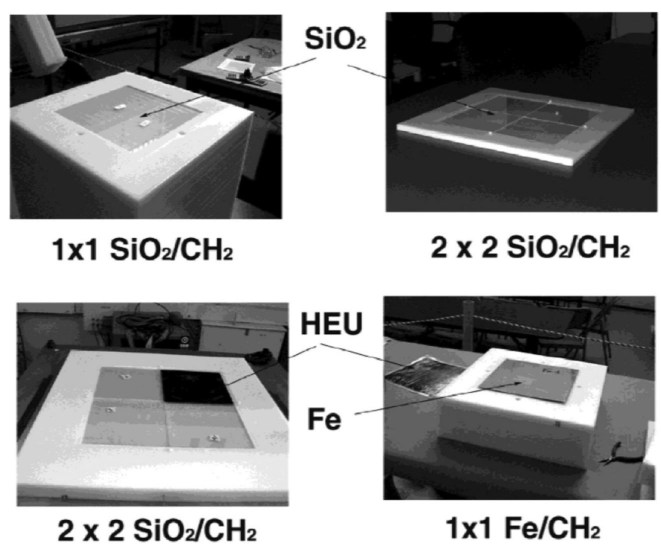

Fig. 10. Some configurations of the HEU/matrix material experiments.

IV. PLANET OPERATIONS AT NCERC

Planet was the first assembly to be taken critical at NCERC with the Class Foils experiment on June 15, 2011. Since then, approximately ten different experiments have been performed using the Planet vertical assembly machine. Figure 1 shows the number of operational days per year spent on each experiment type performed on Planet during the last 10 years. The Planet assembly is often utilized for criticality safety training because of the educational and hands-on opportunities the Class Foils experiment provides. From 2018 onward, the usage of Planet for experiments increased dramatically, with the exception being the year 2020, in which COVID-19 global pandemic restrictions severely impacted the experimental schedule at NCERC.

Sections IV.A through IV.D provide an overview of how experimental data are collected and highlight selected operations that have occurred in the past 10 years.

IV.A. Class Foils Experiments

The Class Foils experiment demonstrates how to safely perform an approach to critical; emphasizes important criticality safety concepts; and provides hands-on experience to workers, managers, and criticality safety professionals. The Class Foils experiments utilize thin

HEU foils, moderated and reflected by hydrogenous materials in order to achieve a critical configuration. Each HEU foil is 93% enriched in ^{235}U, measures approximately 9 × 9 in., and is 0.003 in. thick, with approximately 70 g of HEU per foil (see Fig. 11). The foils are laminated to reduce contamination and the possibility of damage. The moderators and reflectors consist of either high-density polyethylene (HDPE) or polymethyl methacrylate (PMMA) plates. The Class Foils experiments are performed for the Nuclear Criticality Safety Program (NCSP) Criticality Safety Training Classes, held multiple times a year, as well as other training courses for plutonium facility workers and nuclear emergency responders.

While the bare critical mass of HEU is on the order of 50 kg of material,[22] the Class Foils experiments demonstrate how masses of less than 1 kg of HEU can become critical with the addition of moderator material. This allows the criticality safety students to participate in and directly observe the significant effect moderation can have on the critical mass of a system compared to an unmoderated system. See Fig. 12 for the critical mass curve of

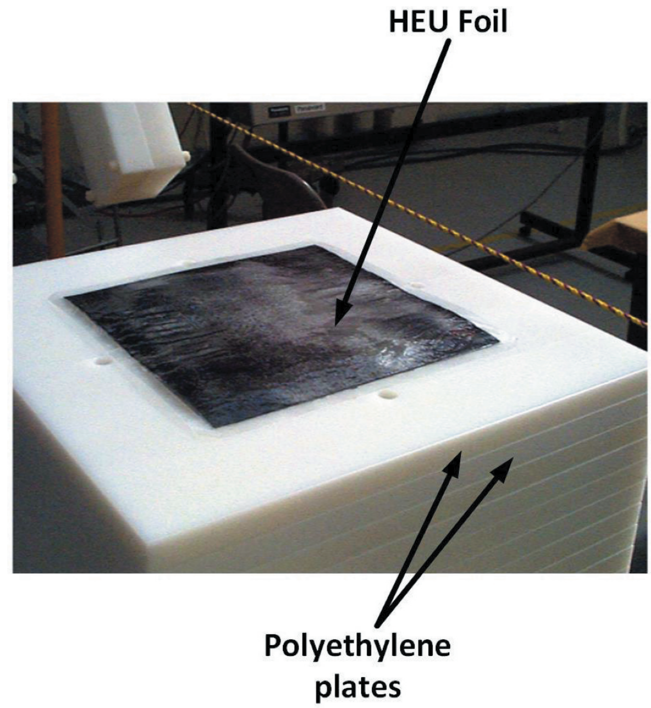

Fig. 11. HEU foil used in Class Foils experiment.

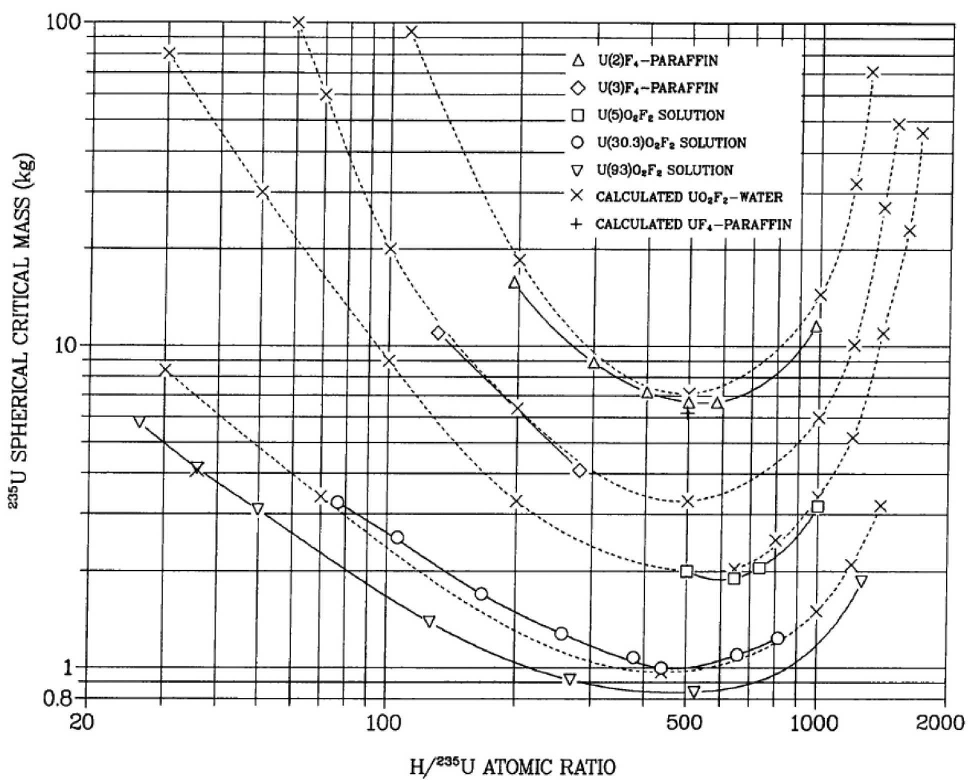

Fig. 12. Critical masses of water-reflected uranium spheres.[22]

^{235}U moderated by varying amounts of hydrogen. The original design for the Class Foils experiment intended the experiment to be approximately at the minimum of the critical mass curve, at approximately a 500:1 ratio of hydrogen to uranium (H/U). In practice, the ratio of H/U varies depending on the type of moderator material used (different materials have a different relative hydrogen content) as well as the thickness of the moderator plates. For the HDPE and PMMA Class Foils experiments, the H/U ratios nominally vary from 800 (HDPE) to 550 (PMMA). Because of the significant moderation, the Class Foils experiment has a fission spectrum similar to a solution system. This is of interest in the criticality safety community because of the use of uranium or plutonium solutions in material-processing applications.

A three-dimensional, computer-aided-design model of the Class Foils experiment can be seen in Fig. 13. The approach to critical consists of stacking multiple units, each unit consisting of a single laminated HEU foil and a single plastic moderating plate. The Class Foils experiment can be hand-stacked until a neutron multiplication of 10, corresponding to a k_{eff} of 0.90, is reached, as defined by ANSI/ANS-1-2000 (R2019) (Ref. 3). Beyond this, only remote assembly of the stack is allowed. Remote assembly is performed on the Planet vertical assembly machine with some subset of the Class Foils placed on the movable platen and the remainder of the Class Foils placed on the top stationary platform. Criticality is approached as units are added to the stack on the stationary platform.[23]

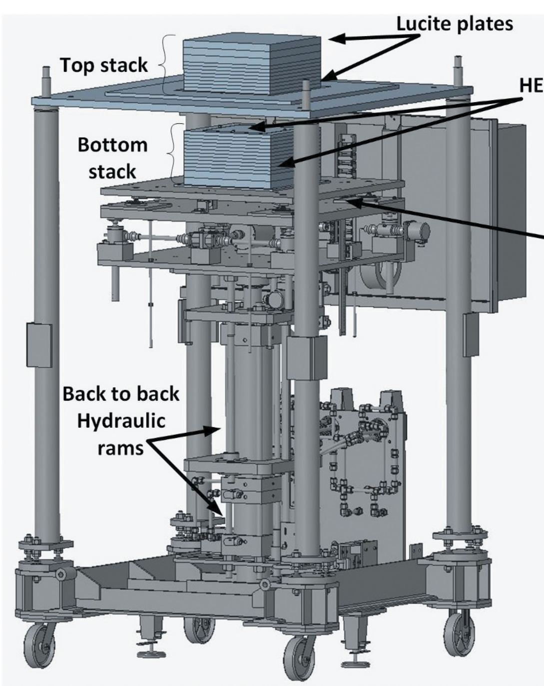

Fig. 13. Class Foils experiment on Planet.

Data taken at NCERC on December 11, 2019, and December 12, 2019, with the PMMA Class Foils experiment have been evaluated as an ICSBEP benchmark by researchers at the Jožef Stefan Institute in Slovenia, HEU-MET-THERM-004 (submitted).

The Class Foils experiment has also been used for Rossi-alpha measurements and calculations,[24] neutron noise measurements,[25] activation analysis studies,[26] and experimental verification of the O'Dell equation.[27] The equation from the O'Dell memorandum states that the multiplication factors for all systems generally obey Eq. (1):

$$k_{eff} = \left(\frac{m}{mc}\right)^{E} \quad , \tag{1}$$

where

m = mass

mc = critical mass

E = exponential constant.

In the memorandum, it was shown that E was 0.3 for metal systems and 0.25 for solution systems. Experimental validation with the Class Foils experiment on Planet showed that $E = 0.3$ was conservative and that $E = 0.25$ for metal systems provided a better fit near $k_{eff} = 1$ (Ref. 28).

IV.B. Thermal/Epithermal Experiments

Thermal/Epithermal eXperiments (TEX) is a series of critical experiments designed and executed at NCERC as a collaboration between LANL and Lawrence Livermore National Laboratory[29] (LLNL). The TEX experiments address nuclear data and validation needs for the criticality safety and nuclear data communities by creating critical experiments that test a wide range of fission energies, from thermal (majority of fissions < 0.025 eV) to fast (majority of fissions > 100 keV).

The TEX-Pu measurements used plates of plutonium originating from the Zero Power Physics Reactor (ZPPR) at the Argonne National Laboratory-West site (now Idaho National Laboratory)[30] with various thicknesses of polyethylene moderators, to create a baseline set of critical configurations (Fig. 14). By using different thicknesses of polyethylene moderators, the neutron energy spectrum of the experiment was changed from fast to thermal, including some configurations of mixed- or intermediate-energy spectra. The thermal and fast configurations are expected to closely match calculated predictions for k_{eff}, as the

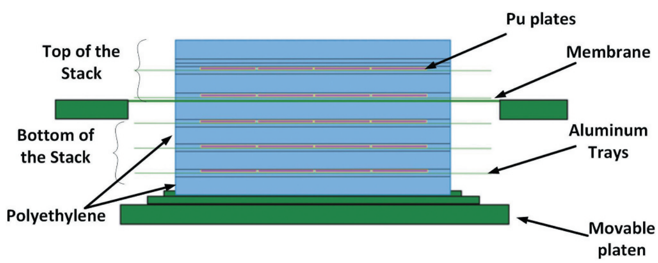

Fig. 14. TEX experiment schematic.

underlying nuclear data in these areas are extensively measured, with a relatively simplistic data structure, and well validated with integral experiments. Larger deviations from predictions are expected for the intermediate and mixed configurations, which have underlying data that are less well understood. These configurations were designed to later incorporate materials of interest (diluents) to generate integral experiment benchmarks.

The first set of TEX experiments was performed on Planet in 2017–2018 (see Fig. 15), and the first diluent material was Ta. Ten TEX configurations were investigated: five configurations with varying thicknesses of HDPE only and then five configurations with varying thicknesses of HDPE with the addition of Ta (Ref. 31). The first five configurations are considered the baseline TEX configurations and have been compiled into an ICSBEP benchmark, PU-MET-MIXED-002 (Ref. 30).

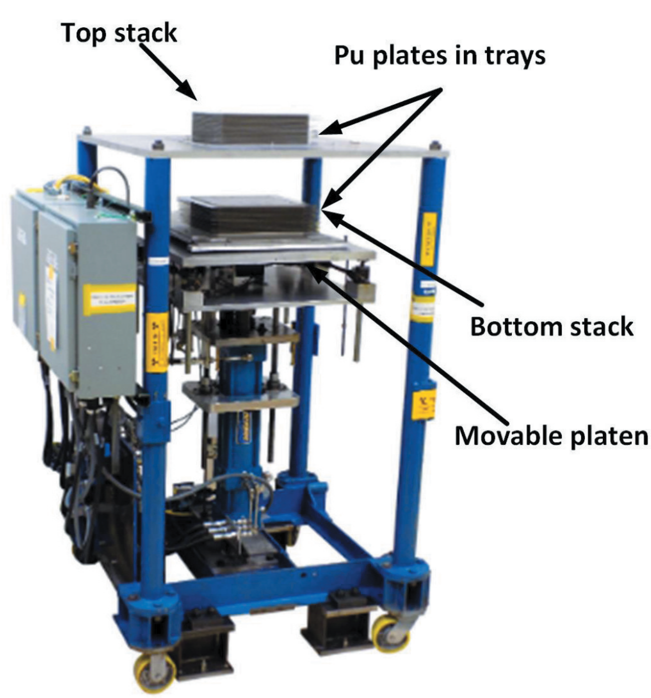

Fig. 15. Planet vertical assembly machine with TEX-Pu experiment.

Sample calculations presented with the benchmark indicate overprediction of k_{eff} for the most intermediate case with modern cross sections. The five configurations including the Ta diluent are compiled into a separate ICSBEP benchmark, PU-MET-MIXED-003 (submitted).

IV.C. Measurements of Uranium Subcritical and Critical Experiment

The Measurements of Uranium Subcritical and Critical (MUSiC) experiment is a series of subcritical and critical configurations of bare, spherical HEU performed between December 2020 and March 2021. MUSiC is a collaboration between LANL and the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN).

The MUSiC experiment series provides experimental measurements to validate various nuclear data for ^{235}U and ^{238}U, including various reaction cross sections and fission parameters such as the average number of neutrons emitted per fission ν. MUSiC also assists in validating and improving subcritical simulation and measurement techniques.

The MUSiC experiment setup consists of stacks of the nesting Rocky Flats HEU hemishells along with aluminum support shells on the interior of the assembly as shown in Fig. 16. Various subcritical and critical configurations were measured with HEU masses ranging from 15 kg to over 60 kg and k_{eff} values ranging from 0.65 to over 1.0. The expected masses and preliminary calculations of k_{eff} values listed in Table II show the span of configurations that were constructed and measured. Final results, including measured values and associated uncertainties, will be included in publications of the data.

Each configuration consists of inner aluminum source holder hemishells surrounded by HEU hemishells and separated into top and bottom stacks. The top stack is placed on the upper stationary platform, and the bottom

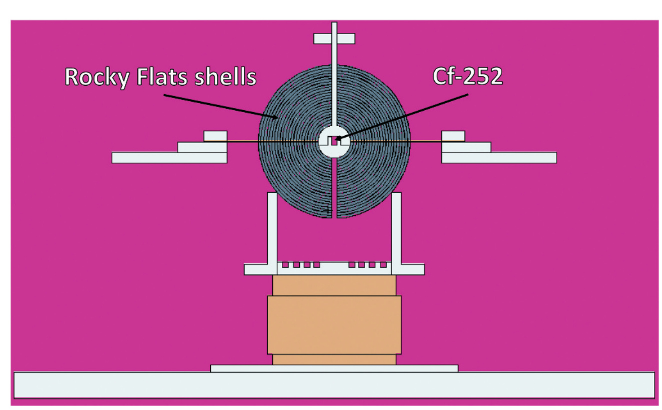

Fig. 16. MUSiC MCNP model.

TABLE II

Mass and k_{eff} of the Subcritical MUSiC HEU Configurations

Configuration	Mass (kg)	k_{eff}
1	13.0428	0.64
2	21.6432	0.74
3	29.0415	0.81
4	37.9617	0.88
5	42.9722	0.91
6	48.4099	0.95
7	54.2785	0.98

stack is placed on the lower movable platen. These two stacks are separated by an aluminum membrane (0.035 in. thick) that supports the weight of the top stack.

The range of reactivities over which measurements were taken during MUSiC provides a unique opportunity to determine the range over which neutron noise techniques such as Feynman variance-to-mean, Rossi-alpha, and pulsed source can be accurately employed for a bare HEU system. The measurements leveraged several different detector systems that were used for cross-validation and obtaining detector independent results. The detector systems deployed included a NoMAD detector,[32] an array of four small-volume ^{3}He detectors, and an array of eight 5.08 × 5.08-cm cylindrical EJ-309 liquid organic scintillators.[33] The layout of the detectors is shown in Fig. 17. Benchmark evaluations will be developed when the MUSiC experiment data analysis is complete.

IV.D. Hypatia Experiment

Microreactor designers at LANL are considering the use of yttrium hydride (YH_X) due to its ability to retain hydrogen within the material at increased temperatures, in comparison to other hydrided materials.[34] However, no integral experimental data on YH_X could be found. The Hypatia experiment utilized uranium fuel, YH_X, and a beryllium metal reflector to design a critical system. Despite the presence of hydrided material, the system had an intermediate-to-fast neutron energy spectrum. Yttrium hydride cross sections at various temperatures above room temperature, when used in MCNP, indicated that certain configurations containing YH_X may exhibit a positive temperature coefficient of reactivity. Heaters were incorporated in the core to provide data at various temperatures up to 330°C. The experiment was performed at NCERC on the Planet assembly in January 2021 (Ref. 35).

Hypatia was configured with a central fuel column placed on the lower moveable platen and a thick beryllium metal reflector placed on the upper stationary platform. The central fuel column was lifted into the stationary reflector to achieve a critical configuration. Figures 18 and 19 show schematics of the Hypatia experiment. The central fuel column was composed of cylindrical fuel parts, $YH_{1.8–1.9}$ interstitial material parts,

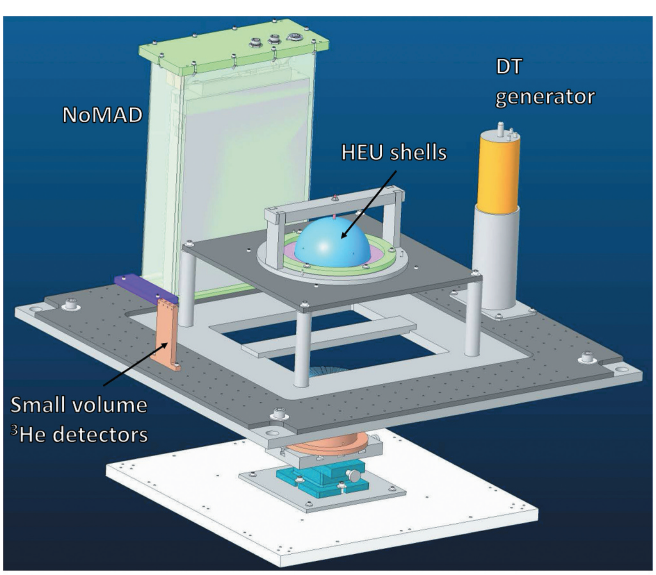

Fig. 17. MUSiC experiment.

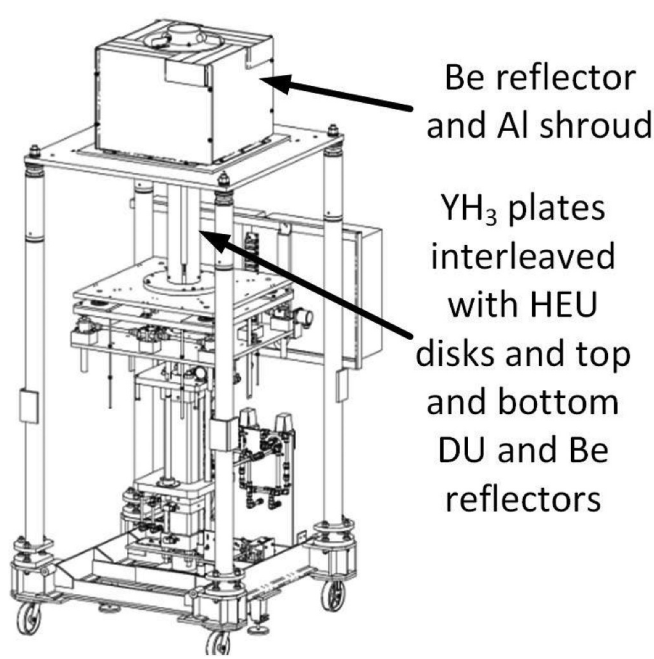

Fig. 18. Hypatia experiment schematic.

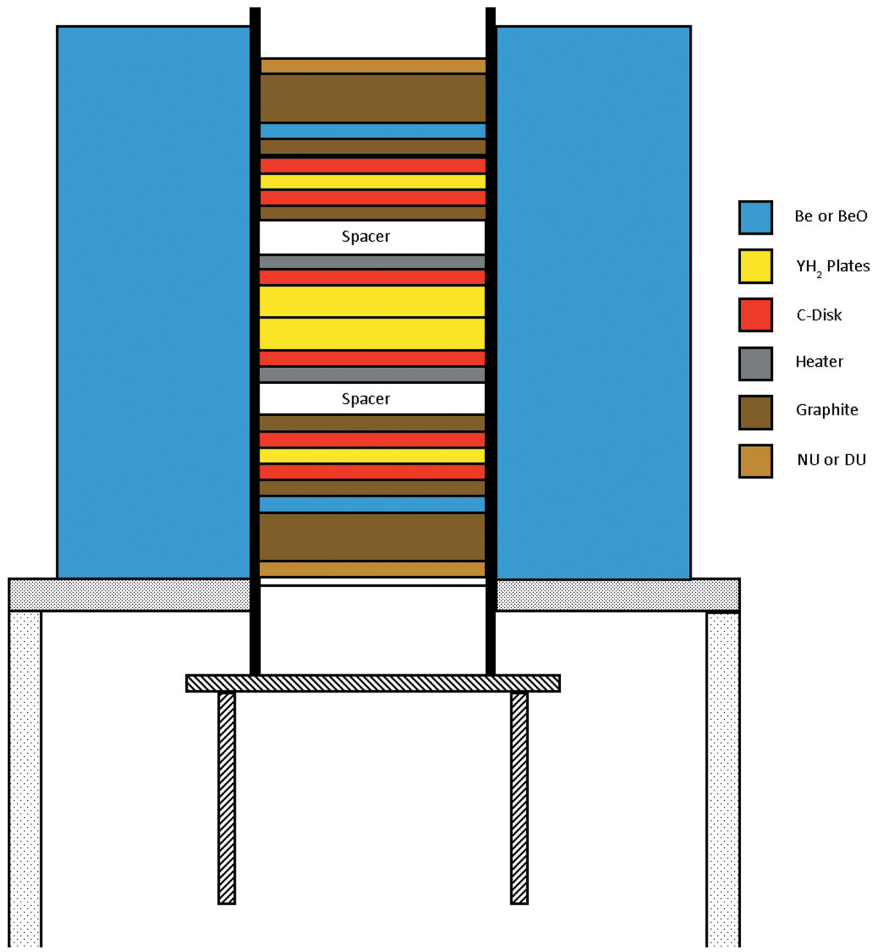

Fig. 19. Hypatia experiment cross-section view.

aluminum oxide (alumina) spacers, and axial reflectors (see Fig. 20 for an example of a fuel column configuration). Each cylindrical part had a nominal diameter of 6 in. The entire fuel column was surrounded by a thin aluminum tube that kept the parts aligned and allowed for the fuel column to be lifted into the reflector without catching on any of the reflector components. The fuel components, known as C-discs, are bare HEU metal, with nominal dimensions of 6-in. diameter, 0.5-in. thickness, and masses of approximately 4000 g. In the center of the fuel column were molybdenum cans containing discs of $YH_{1.8–1.9}$. Depleted uranium (DU) metal parts, with nominal 6-in. diameter, 1-in. thickness, were also used. The fuel column contained alumina spacer parts that served two purposes. They thermally isolated the central heated zone from the outer portions of the core. Various sizes of spacer were manufactured. By changing the thickness chosen, the reactivity of the core could be adjusted. The outer reflector was constructed of stacked beryllium metal blocks, held in place by an aluminum shroud as shown in Fig. 21. Beryllium metal axial reflectors had nominal dimensions of 6-in. diameter, 1-in. thickness, and masses of approximately 800 g. The overall outer reflector had a nominal size of 61 cm by 61 × 51 cm. A set of graphite parts was made to transition from the cylindrical central fuel column to the parallelepiped geometry of the outer reflector. They were held in place by graphite rods.

The core was electrically heated (800 W maximum) to the required temperatures, and then the fuel column was inserted into the reflector, and the reactor period was measured to determine the reactivity. The experiment confirmed the positive temperature coefficient caused by the YH_X as predicted by the modeling. Because reactor designs typically need an overall negative temperature coefficient, knowing the positive contribution from YH_X enables designers to determine what compensating mechanisms are needed to maintain an overall negative temperature coefficient.

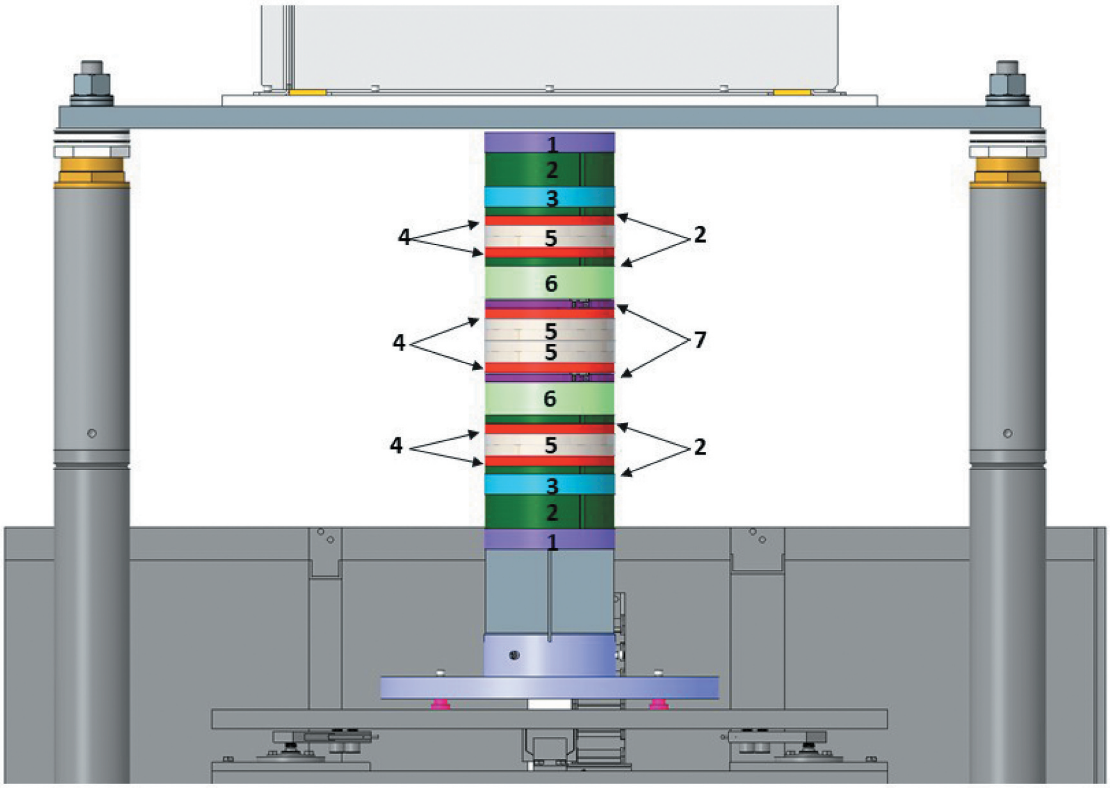

Fig. 20. Hypatia fuel column example loading (“1”: Light purple is DU, “2”: Green is graphite, “3”: Blue is beryllium, “4”: Red is HEU, “5”: Pink is YH_X, “6”: Light green is aluminum oxide spacers, and “7”: Dark purple is electric heaters).

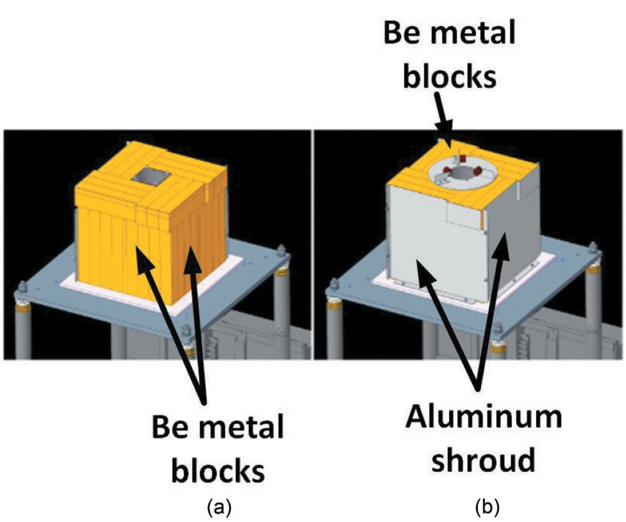

Fig. 21. Hypatia top beryllium reflector (a) without shroud and (b) with shroud.

IV.E. Benchmarks

Of the Planet operations conducted since the move to NCERC, several have been evaluated and included the the ICSBEP Handbook. The TEX-Pu baselines (PU-MET-MIXED-002) have been published.[30] The Class Foils (HEU-MET-THERM-004) experiments and TEX-Pu with Ta (PU-MET-MIXED-003) will be included in the next edition and are listed at the end of Table I. Evaluations of the recently completed MUSiC experiment are in progress.

V. CONCLUSIONS AND FUTURE WORK

Planet is a vertical-lift critical assembly machine relocated from LACEF in New Mexico to NCERC in Nevada. It was the first critical assembly machine to achieve criticality at NCERC, doing so on June 15, 2011. Planet was designed to be highly configurable. Recent upgrades to add leveling and alignment capabilities and the construction of multiple extensions for the vertical supports have made it even more flexible.

Historically, Planet has been used to perform many benchmark experiments, and this use has continued after relocation. At NCERC, Planet has been used to perform two TEX experiments and the MUSiC experiment series. Other experiments, such as Hypatia, are not evaluated within the ICSBEP but provide valuable data such as temperature coefficient of reactivity. Planet is also heavily utilized for the Class Foils demonstrations for the NCSP and other criticality safety training classes.

Future work includes measurements of the prompt fission neutron spectrum using threshold activation foils and other detectors, additional TEX-Pu experiments with thicker moderators to support TSL evaluations, follow-on experiments to Hypatia with additional materials, and experiments to provide criticality safety analysts at the Y-12 National Security Complex and LANL with validation cases for operations involving chlorine in electrorefining and aqueous plutonium chloride processing.

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