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

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Abstract — *The Flattop critical assembly was built and operated from 1958 through 2004 at the Pajarito Site (Technical Area-18), home to the Los Alamos Critical Experiments Facility. Flattop was disassembled in 2005 and refurbished over the course of 3 years. In 2008, Flattop was installed in the National Criticality Experiments Research Center (NCERC) located in the Device Assembly Facility at the Nevada National Security Site. Startup of Flattop with a uranium core occurred in 2011. This paper details the first 10 years of Flattop operations at NCERC (2011–present).*

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

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

I. INTRODUCTION

Flattop is a simple, fast benchmark critical assembly with one-dimensional geometry consisting of a spherical fissile core surrounded by a 1000-kg spherical natural uranium (NU) reflector. The two available cores of special nuclear material (SNM) are highly enriched uranium (HEU) metal (uranium 93% ^{235}U by weight percent) and delta-phase plutonium metal (plutonium 4.8% ^{240}Pu by weight percent). The reflector consists of two movable quarter-spheres and a stationary hemisphere.

Flattop is the descendant of an experiment performed on Topsy, an NU-reflected pseudospherical fissile core comprising cubes.[1] Originally assembled in the late 1950s, Flattop was used to develop and to validate nuclear data and simple one-dimensional, two-region computational modeling. Most components of Flattop have remained unchanged since its inception. The range of experimental capabilities is fairly narrow given its fixed geometry. However, this makes it excellent for validation and comparison of results obtained over several decades. Foil activation measurements performed at Technical Area-18 (TA-18) and the National Criticality Experiments Research Center (NCERC) compare favorably, demonstrating the reliability of the results and emphasizing the necessity for the unique capabilities of Flattop. Flattop is the last such assembly of its kind in the United States.

Flattop was disassembled at the Los Alamos Critical Experiments Facility (LACEF) in 2005 and achieved first critical at NCERC on November 29, 2011. Since

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then, Flattop has been used in an assortment of experiments and training classes in support of criticality safety and nuclear data validation. Figure 1 shows the number of days of operation over the past 10 years at NCERC. The experiments are discussed in more detail in Sec. V.

II. MACHINE OVERVIEW

As mentioned, Flattop consists of a spherical fissile core surrounded by a spherical NU reflector. Figure 2 shows a cutaway view of the Flattop critical assembly. Figure 3 is

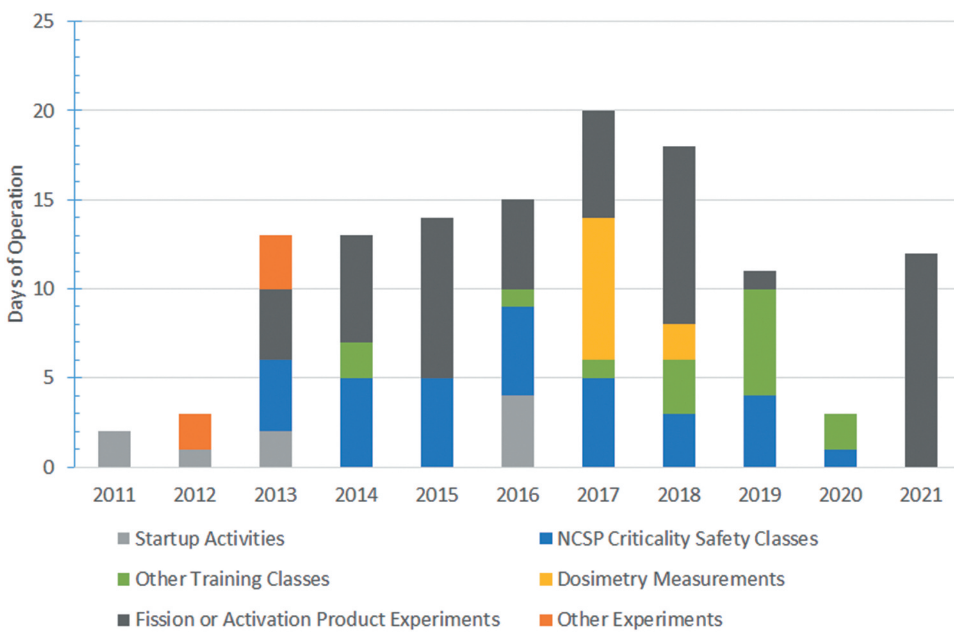


Fig. 1. Days of operation by year for Flattop.

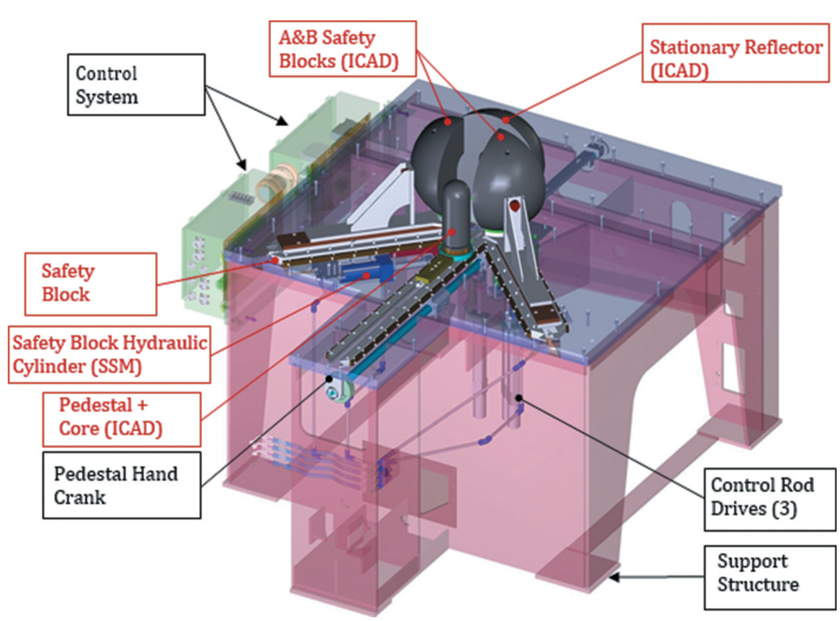


Fig. 2. Flattop critical assembly components.

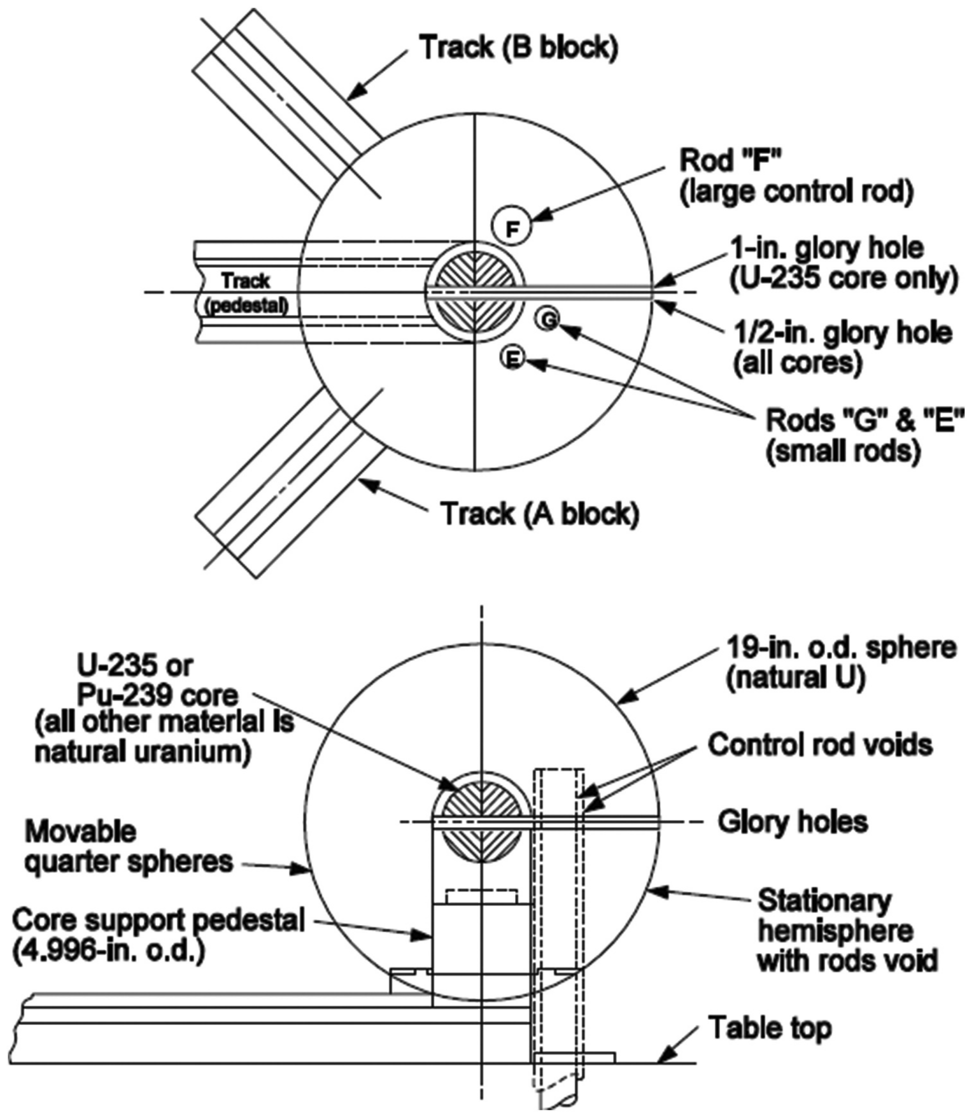


Fig. 3. Flattop critical assembly schematic.

a schematic of the reflector, core, and control rods. Figure 4 presents a cross-sectional view. As seen in Fig. 4, the reflector consists of an ~1000-kg NU metal sphere, which is 19 in. in diameter and is divided into two ~250-kg movable quarter-spheres and an ~500-kg stationary hemisphere. The two quarter-spheres are designated as "Safety Block A" and "Safety Block B." They serve as the safety shutdown mechanisms that can SCRAM the assembly.

Two cores of SNM remain available for experiments. The first core is composed of HEU metal (uranium 93% ^{235}U by weight percent) with a mass of ∼18 kg. The second core is composed of delta-phase plutonium metal (plutonium 4.8% ^{240}Pu by weight percent) with a mass of ~6 kg. Other cores that have been used in past studies include a ^{233}U core and a composite plutonium/HEU core. Each core is supported by its own NU pedestal and covered by an NU "cap." The pedestal and cap form part of the spherical reflector and mate each core to the reflector. The pedestal is mounted on a keyed track and moved by a hand crank (mounted at the edge of the table) in or out of a recessed area in the stationary hemisphere of the reflector. The core cannot be removed from the pedestal once inserted into the recessed area of the reflector. Each core has a central cavity that extends through the stationary (hemisphere) reflector that can be used to introduce fuel or samples for irradiation. This central cavity is known as the glory hole.

Three NU control rods enter voids in the stationary reflector from below (Fig. 4), serving as fine reactivity control. They are designated "Control Rod E," "Control

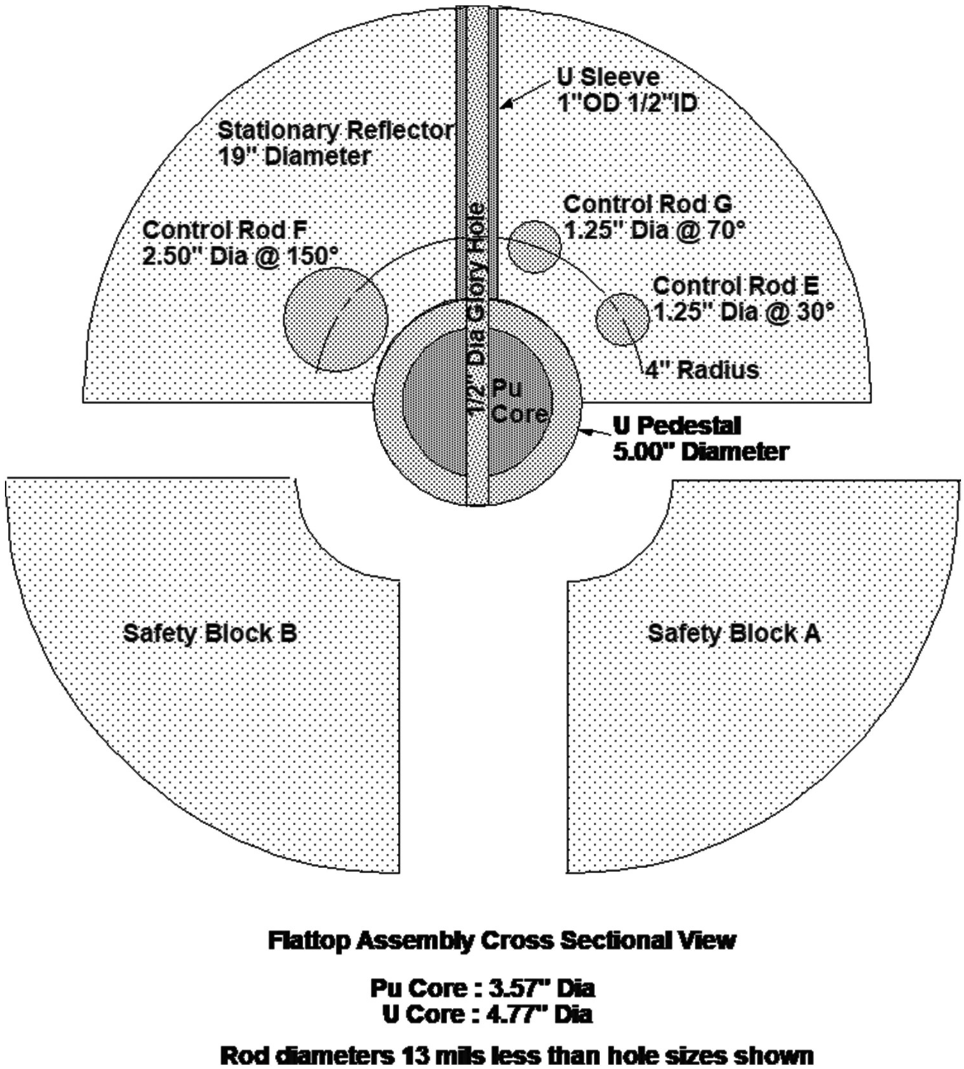


Fig. 4. Flattop critical assembly cross section.

Rod F," and "Control Rod G." Reactivity increases as the rods are inserted (reducing neutron leakage) and decreases as the rods are withdrawn (increasing neutron leakage). Excess reactivity is adjustable by several means: mass adjustment buttons, "beanie" buttons, caps, and glory hole pieces, some of which can be seen in Fig. 5. There are openings for mass adjustment buttons in some pedestals and caps. They can be left empty, filled with NU pieces, or to increase reactivity filled with HEU pieces. One mass adjustment opening can be seen in the cap for the Pu core. Beanie buttons are the curved pieces that can be seen near the ^{235}U core. They exist in both the NU and the HEU versions. There are partial caps for the ^{235}U core made of HEU in addition to NU. Many glory hole pieces exist made of NU, HEU, various enrichments of Pu, and ^{233}U. They come in multiple lengths and have nominal diameters of

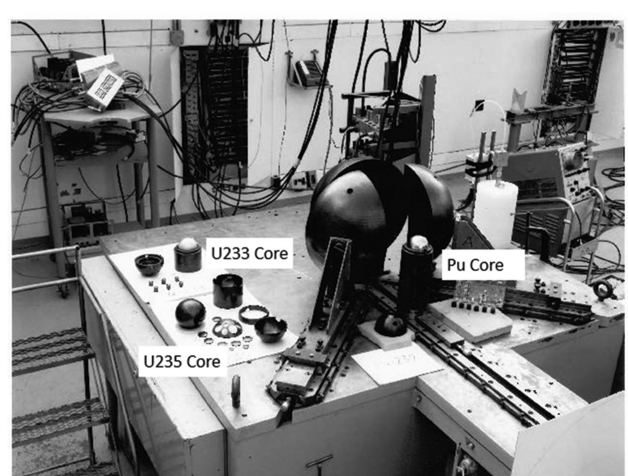


Fig. 5. The Flattop assembly during its time at the LACEF.

0.5 in., and some are formed of split pieces with a small channel in the center.

During operations, the selected core and cap are placed on a pedestal as seen in Fig. 2. The pedestal and core are hand-cranked into a recess in the stationary reflector (Fig. 6). Fuel pieces, samples for irradiation, and custom radiation detectors are inserted (Fig. 7) in the glory hole according to the experiment plan. Once the core is in position, remote operations are established, and the quarter-sphere reflectors (safety blocks) are inserted, enclosing the core. Criticality is attained by inserting control rods until a positive reactor period is achieved.

II.A. Measurement Instrumentation

Flattop operations are monitored using a standard set of neutron detectors as required by ANSI/ANS-1-2000 (R2019), "Conduct of Critical Experiments."[2] The standard set of detectors includes startup counters, linear channels, and log-N's. The startup channels are ^{3}He tubes operated in pulse mode, providing indication of neutron flux within the assembly at the lowest levels. Linear channels are compensated ion chambers that overlap the startup channel range and provide power range indication of neutron flux within the assembly. Log-N's are compensated ion chambers used as input sensors to trip the SCRAM system. Operators select the log-N trip level based on expected conditions for each experiment. Resistance temperature detectors provide indication of ambient and assembly temperatures. Core temperatures may increase by hundreds of degrees from fission heating during certain operations. Other instrumentation supporting specific experiments may also be deployed.

Fig. 6. Flattop pedestal and HEU core seated in stationary reflector.

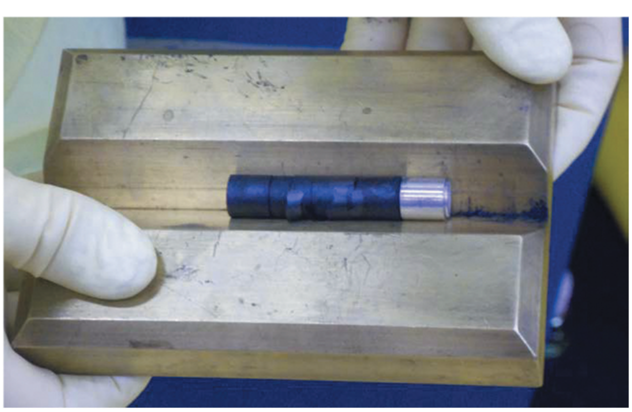


Fig. 7. Flattop HEU fuel pieces and ^{252}Cf ready for loading into the glory hole.

III. FLATTOP HISTORY AT LACEF

Flattop's history can be traced back to the very first critical assemblies.[3] In the early stages of the Manhattan Project, critical configurations were assembled by hand, which proved to be fatal to scientists Harold Daghlian and Louis Slotin.[4] As a result, hand assembly of critical configurations was prohibited, resulting in the development of remote assembly of critical configurations using machines. The original critical assemblies that were operated remotely at LACEF included Topsy, Lady Godiva, Jezebel, and Flattop. Flattop resulted from a series of experiments using blocks of NU surrounding blocks of HEU arranged in a pseudosphere on Topsy. Flattop was designed as a simple one-dimensional experiment to benchmark emerging computer-based modeling. Figure 5 shows the Flattop assembly, three cores, and various mass adjustment pieces during its time at the LACEF. Flattop's first criticality occurred in August of 1958.

IV. BENCHMARKS

During the course of operations at TA-18, Flattop was used to produce five benchmark configurations that varied in material (see Table I). The term "normal uranium" was in common use at the time Flattop was built and was used in the titles of the benchmark evaluations. It is interchangeable with what is now more commonly referred to as natural uranium. These experiments provided simple one-dimensional, two-region problems specifically designed to benchmark computer codes and data. A summary of the critical parameters for the

TABLE I

Summary of Flattop Benchmarks

Title	ICSBEP Identifier	Measurement Year
"Uranium-235 Sphere Reflected by Normal Uranium Using Flattop"	HEU-MET-FAST-028	Mid-1960s
"Plutonium Sphere Reflected by Normal Uranium Using Flattop"	PU-MET-FAST-006	Mid-1960s
"Benchmark Critical Experiment of a Uranium-233 Sphere Reflected by Normal Uranium with Flattop"	U233-MET-FAST-006	1964
"Spherical Composite Cores Composed of Plutonium and Highly Enriched Uranium Reflected by Normal Uranium"	MIX-MET-FAST-002	1960
"Neptunium-237 and Highly Enriched Uranium Replacement Measurements Performed Using Flattop"	SPEC-MET-FAST-003	1994

primary Flattop cores is provided in Table II. Over time, as computing capabilities increased, the focus of benchmark development shifted from providing a single diameter that defined a critical mass (corrected for any variation from spherical) for one-dimensional code validation to providing a detailed model with all physical dimensions. Plans are in place to perform measurements to support the reevaluation of the Flattop benchmarks in this manner.

IV.A. Uranium-235 Sphere Reflected by Normal Uranium

Experiments were completed in the mid-1960s using a core of HEU metal. Flattop was assembled as described in Sec. II, and an approach to critical was performed. A plot of the inverse multiplication as a function of rod position was used to approach and establish criticality. The critical mass, corrected for the slight gap between the core and the reflector, was determined to be a sphere with a total mass of 17.84 ± 0.04 kg HEU metal, 93.24% enriched, with an average density of 18.62 g/cm^3, and reflected by 18.01 cm (7.09 in.) of NU with a density of 19.0 g/cm^3 (Ref. 5).

IV.B. Plutonium Sphere Reflected by Normal Uranium

Experiments were completed in the mid-1960s using a core of delta-phase plutonium metal, coated with 0.013 cm (0.005 in.) of nickel. Figure 3 shows a schematic of the Flattop assembly and core used in these benchmark experiments. Flattop was assembled as described in Sec. II, and an approach to critical was performed. A plot of the inverse multiplication as a function of rod position was used to approach and establish criticality. Upon correction for the small gap between the core and reflector, the critical mass was determined to be a sphere with a total mass of 6.06 ± 0.03 kg delta-Pu metal, 4.80 wt% ^{240}Pu, with an average density of 15.53 g/cm^3 and reflected by 19.61 cm (7.72 in.) of NU at a density of 19.0 g/cm^3 (Ref. 6).

IV.C. Uranium-233 Sphere Reflected by Normal Uranium

Experiments using a ^{233}U metal core coated with 0.013 cm (0.005 in.) of nickel were completed in 1964. Two configurations were used to determine the critical mass. Flattop was assembled as described in Sec. II, and

TABLE II

Summary of Critical Parameters for Flattop Benchmarks

Core	Enrichment	Mass	Density	Natural Uranium Reflector Thickness	Natural Uranium Reflector Density
^{235}U	93.24 weight percent ^{235}U	17.84 ± 0.04 kg	18.62 g/cm^3	18.01 cm	19.00 g/cm^3
Pu	4.80 weight percent ^{240}Pu	6.06 ± 0.03 kg	15.53 g/cm^3	19.61 cm	19.00 g/cm^3
^{233}U	98.13 weight percent ^{233}U	5.74 ± 0.03 kg	18.42 g/cm^3	19.91 cm	19.00 g/cm^3

an approach to critical was performed. A plot of the inverse multiplication as a function of rod position was used to approach and establish criticality. The critical mass (corrected for core-reflector gaps) was determined to be a sphere of 5.74 $\pm$ 0.03 kg of uranium (98.13 wt% ^{233}U) core with a density of 18.42 g/cm^3 surrounded by 19.91 cm (7.84 in.) of NU at a density of 19.00 g/cm^3 (Ref. 7).

IV.D. Spherical Composite Cores Composed of Plutonium and HEU Reflected by Normal Uranium

Several more complex benchmark experiments were completed in October of 1960 using a composite core of alpha-phase plutonium metal and HEU metal. During these experiments, a solid sphere of plutonium [coated with 0.013 cm (0.005 in.) of nickel] was used with shells made of HEU and NU as shown in Fig. 8. Hemishells, rings, and caps (Fig. 9) of HEU and NU were used to adjust reactivity for three different plutonium cores. Metal alpha-phase plutonium from various burnup targets was fabricated into ~1612-g metal cores with ^{240}Pu content of 2.34%, 4.73%, and 16.1% (atom percent). For these experiments, critical was determined based on the mass of HEU required. Critical configurations are outlined in Table III (Refs. 8 and 9).

IV.E. Neptunium-237 and HEU Replacement Measurements

Between October 1994 and May 1995, a unique set of benchmark experiments was completed using ^{237}Np. Rather than a direct measurement of critical mass, the difference in reactivities resulting from three different experiments was used to estimate the critical mass of ^{237}Np. In these experiments, the central cavity of Flattop alternately contained a canned ^{237}Np sample, an HEU sample, and an empty aluminum can. As a result of these

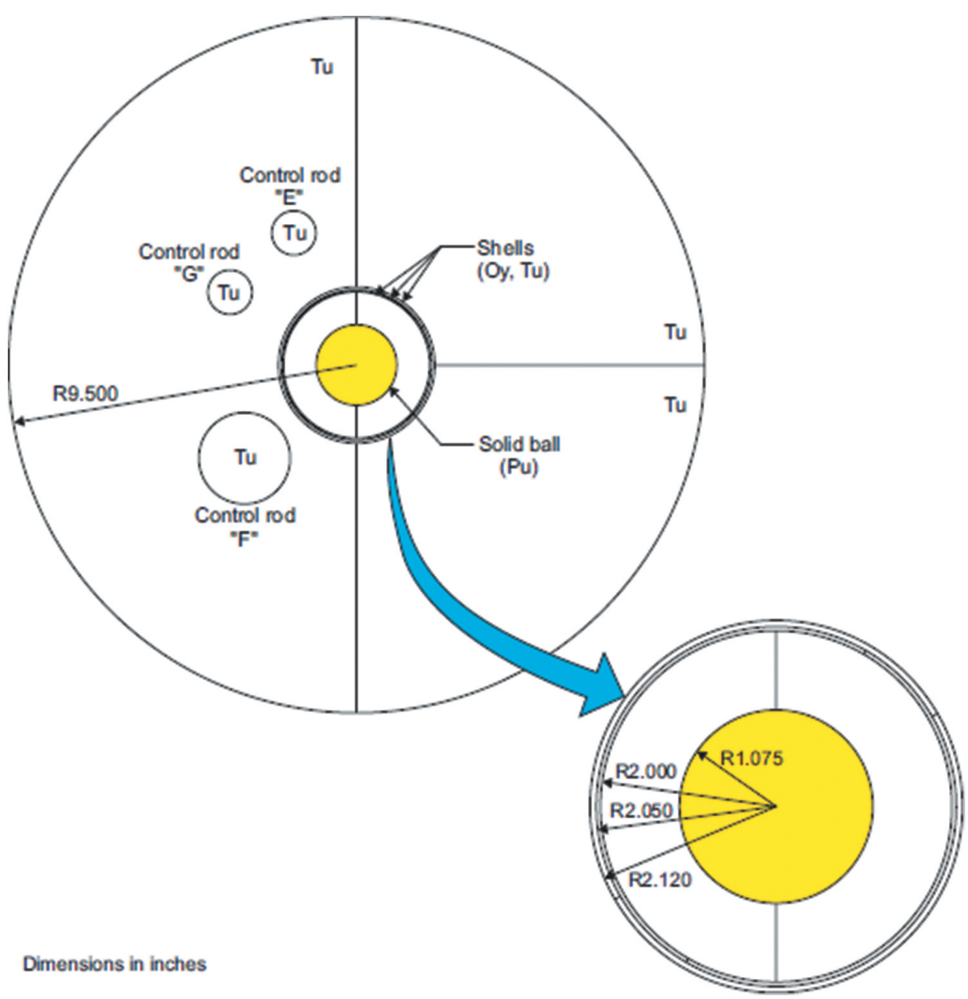


Fig. 8. Schematic of composite core benchmark.

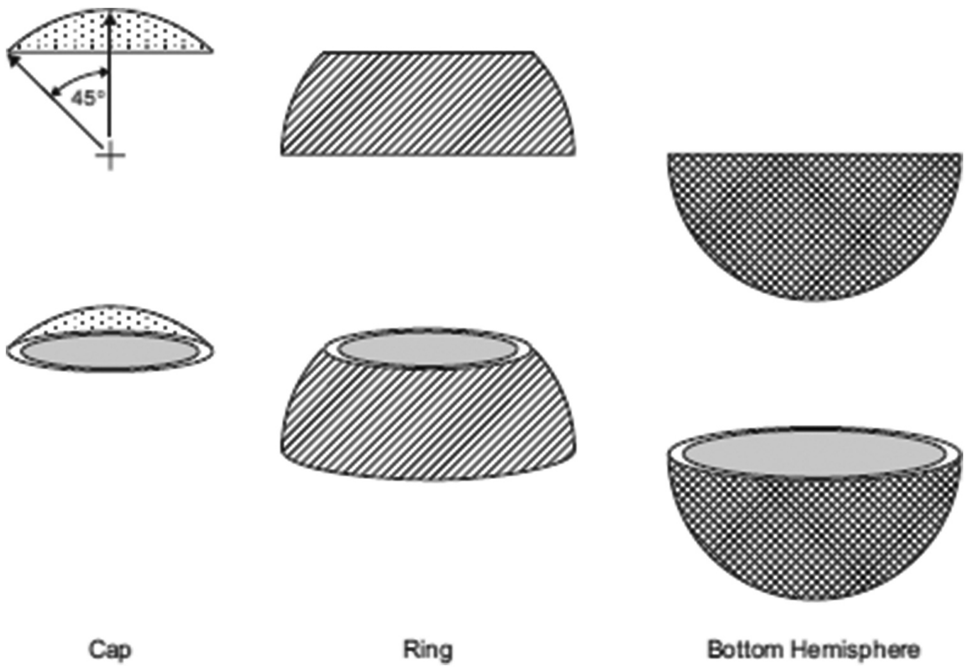


Fig. 9. Highly enriched uranium and NU shells used in composite core benchmark.

TABLE III

Composite Core Critical Masses

Plutonium-240 (at. %)	Plutonium Mass (g)	HEU Mass (g)
2.43	1615.45	9521 ± 2
4.73	1610.30	9755 ± 2
16.1	1611.19	10 618 ± 3

experiments, the bare, spherical critical mass of ^{237}Np metal was derived to be 56 ± 10 kg at a density of 20.45 g/cm^3 (Ref. 10). These data contributed to the planning and successful casting in May 2001 of the neptunium sphere discussed in more detail within this publication.[11,12]

V. FLATTOP OPERATIONS AT NCERC

Many experiments and operations have been completed using Flattop as shown in Fig. 1, which plots the number of days of Flattop operation by experiment type over the last 10 years. The Flattop assembly is predominantly used for criticality safety training and nuclear irradiations. Sections V.A through V.F highlight selected operations that have occurred in the past 10 years.

V.A. Flattop Startup at NCERC

Flattop was assembled in the early days of NCERC and achieved first critical at NCERC on November 29, 2011. Startup included installation and certification of all safety and control systems. It also included careful positioning and alignment of the safety blocks and control rods. During startup of the HEU core, the rod worth of all three control rods was measured. Data on the control rods are listed in Table IV, and Fig. 10 shows the integral rod worth curves for each Flattop control rod with the HEU core. Rod worths compared favorably with data from the TA-18 operations. One difference from the TA-18 operations was evident in the safety block alignment. Better alignment (less neutron leakage) at NCERC was achieved as evidenced by increased excess reactivity relative to similar configurations at TA-18. The assembly is very sensitive to slight, even imperceptible, gaps, anywhere in the assembly. Figure 11 shows the Flattop HEU core separate from the pedestal.

Startup of the delta-phase plutonium core occurred later, in 2016, because of several delays related to interpretation of the safety basis and competing priorities for resources. For startup with the Pu core, a known configuration from the TA-18 operations was selected, with corresponding glory hole pieces and mass adjustment buttons. The HEU core was removed, and the Pu core

TABLE IV

Flattop Control Rod Data

Control Rod	Diameter	Length	Travel	HEU Core Worth	Plutonium Core Worth
F	2.487 in. + 0.000 − 0.003 in.	10.75 in. ± 0.005 in.	4.5 in.	108 ¢	165 ¢
E	1.237 in. + 0.000 − 0.003 in.	10.75 in. ± 0.005 in.	8 in.	27 ¢	41 ¢
G	1.237 in. + 0.000 − 0.003 in.	10.75 in. ± 0.005 in.	7 in.	26 ¢	40 ¢

was installed over the course of a single day. The Pu core is handled with great care given the very low likelihood of obtaining new Pu pieces coupled with the thin nickel coating (0.005 in.) on the existing pieces. This minimizes the potential for damaging the cladding and protects the integrity of the core. Subsequently, operations focused on approach to critical, verifying the excess reactivity, and measuring rod worths. Rod worths were measured over the course of 2 days, followed by removal of the Pu core and reinstallation of the HEU core. Rod worth curves for the Pu core at NCERC are plotted in Fig. 12.

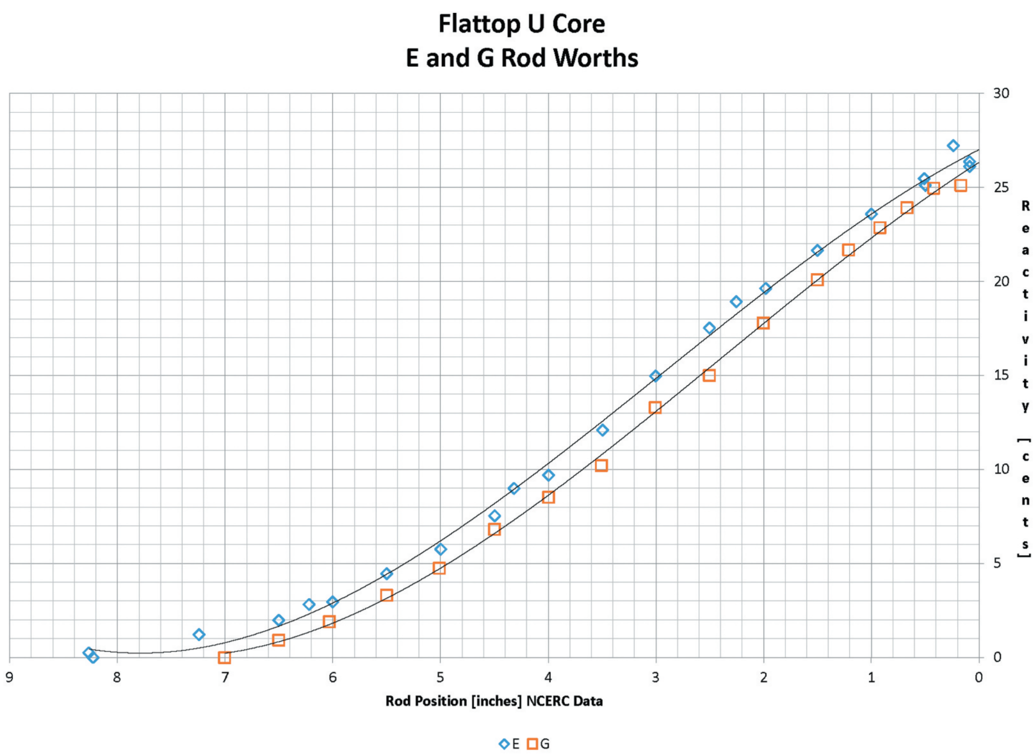
V.B. Demonstration Using Flattop Fissions Experiment

In 2012, Flattop was used as the fission heat source in the Demonstration Using Flattop Fissions (DUFF) experiment.[13] DUFF was conceived to demonstrate the use of a compact nuclear reactor–driven heat-pipe coupled to Stirling engines for electricity generation. Proof of concept was important because the technology had the potential of providing reliable, self-regulating power for space exploration missions. Beyond technology development and demonstration, the project had to demonstrate that an experiment could progress from concept to execution within a reasonable time frame (less than 1 year in this case) and reasonable budget. Flattop was the perfect option because it was already operational, had a proven record of long-duration operations at moderate power levels (equivalent to a few kilowatts that were sufficient to raise the temperature of the core) in support of irradiation campaigns, and could readily accept the heat pipe/Stirling engine test assembly.

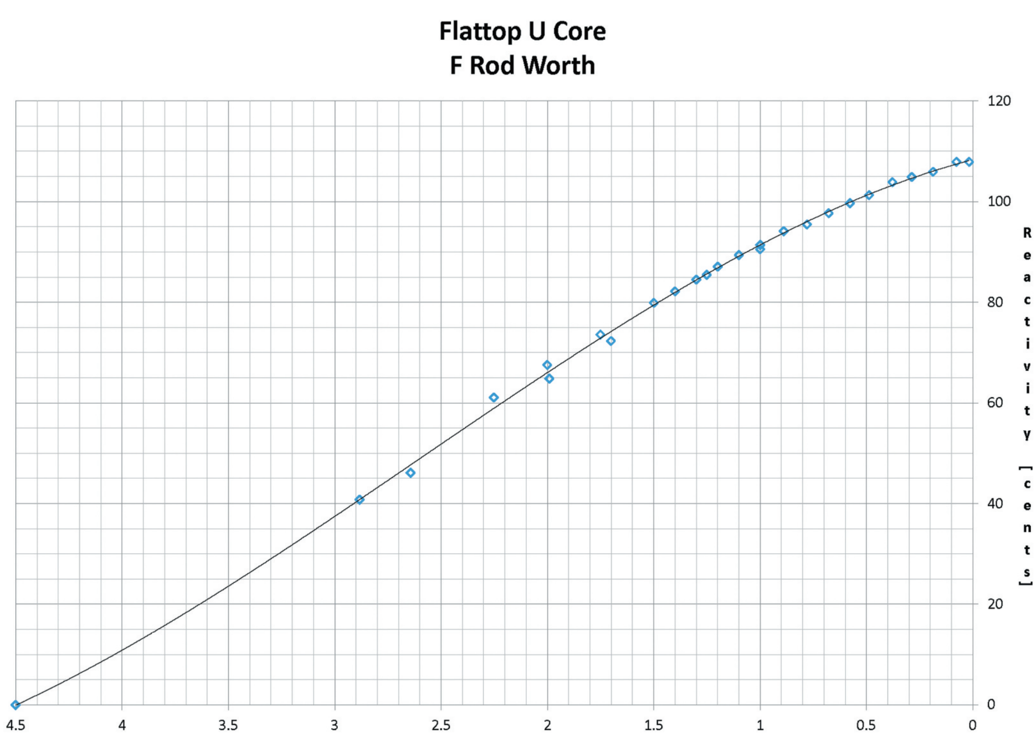
Scientists from Los Alamos National Laboratory (LANL) and the National Aeronautics and Space Administration (NASA) Glenn Research Center worked together to design a heat pipe and Stirling engine–based power conversion system that coupled to Flattop via the glory hole. Because of temperature limitations on Flattop, water (rather than sodium) was selected as the working fluid for the heat pipe. Figure 13 shows John Bounds from LANL installing the heat pipe into Flattop for the DUFF experiment. The initial setup occurred over a day and a half. The excess reactivity loaded on Flattop was 67 ¢ for the experiment, well within the 80 ¢ limit of the Technical Safety Requirements. Given a temperature feedback coefficient of −0.3 ¢/°C, the excess reactivity easily accommodated a core temperature of more than 200°C, which was sufficient to drive the water-based heat pipe.

Two operations at power were conducted over a 2-week period. The first operation was a shakedown to ensure system operability. Figure 14 depicts the power and temperature history of this first operation. Flattop was assembled, all control rods were fully inserted, and the excess reactivity was confirmed to be ~67 ¢. After achieving a power level sufficient to heat the assembly [nominally 2 kW(thermal)], delayed critical was established by withdrawing control rod F. After approximately 5 min, operators inserted ~30 ¢ of reactivity to increase power. Power peaked at nominally 10 kW(thermal), and operators inserted reactivity to maintain power for approximately 1 min. Power then began to decrease due to the negative temperature coefficient. At this time the temperature was sufficient to “turn on” the heat pipe, which began the heat soak of the Stirling engine hot end. Heat removal from the Flattop core resulted in a positive reactivity insertion and subsequent increase in power. When the hot end of the Stirling reached 225°C, the engine was started, producing 24 W(electric) and illuminating an LED panel. After approximately 1 min, a SCRAM was initiated, reducing fission power to zero. Operations with the heat pipe (on decay heat) and Stirling converter continued for 8 min longer until the engine stalled at a temperature of 120°C.

The second power operation focused on examining the system response to changes in the power conversion subsystem to confirm reactor self-regulation. Initiation of the run began as with the first run (see Fig. 15). However, after establishing delayed critical, power was incrementally increased from 2 to 3.5 kW(thermal) rather than a step insertion of reactivity as in the first run. Power



(a)



(b)

Fig. 10. Flattop uranium core integral rod worth curves: (a) E and G rod worths and (b) F rod worth.

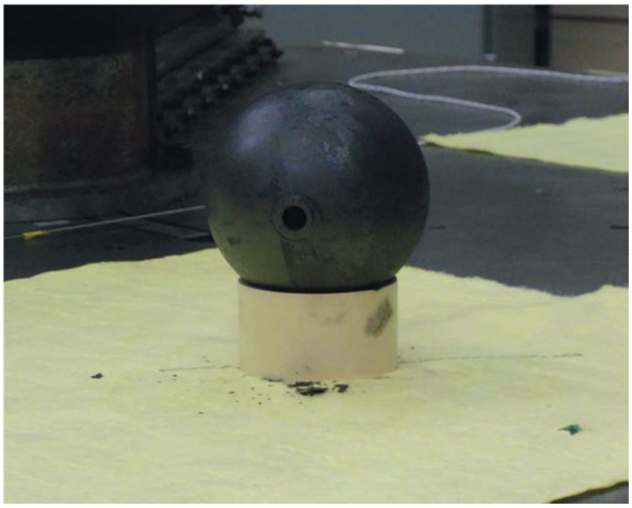


Fig. 11. Flattop HEU core.

from the Stirling engine was confirmed to follow Flattop power increases, and Flattop was confirmed to increase power in response to heat removal via the Stirling engine. Peak power output from the first operation [24 W(electric) at the 225°C hot end] was reproduced. Finally, Flattop was SCRAMed, and the Stirling converter continued operating on decay heat, with decreasing power until stalling at approximately 115°C some 9 min later.

DUFF successfully demonstrated the viability of a compact nuclear reactor–driven heat pipe/Stirling engine power conversion system, providing the data and confidence to proceed with the Kilopower Reactor Using Stirling Technology (KRUSTy) Experiment.[14,15]

V.C. Activation Foil Irradiations

Scientists have utilized Flattop for reaction rate measurements using fission and activation foil irradiations since the 1960s. Flattop provides a known standard neutron field for these irradiations. The central hole (the glory hole) that extends through the core and stationary reflector provides easy access for sample placement and retrieval. It also provides flexible options for loading samples and fuel pieces that allows for some customization of the neutron flux and energy spectrum to which the samples are exposed. Such foil irradiations support efforts to better understand nuclear reaction physics, fundamental nuclear data, and flux profiles in compact metal assemblies. These in turn are used to advance application tools in a number of civilian and national security fields and have influenced nuclear data evaluations for decades.

Campaigns on Flattop at NCERC have focused on fission and activation product yields utilizing both direct foil counting by gamma-ray spectroscopy as well as radiochemical separations and counting techniques that are the basis for our current understanding of cumulative fission product yields as contained in the ENDF nuclear data library.[16–18] In fission product yield measurements, the number of fissions occurring in an actinide sample can be correlated with the integrated current recorded on the linear channel neutron detectors, described in Sec. II. A. The typical goal for radiochemical analysis is to achieve 6×10^{13} fissions/g of the actinide of interest. This is sufficient to achieve adequate counting statistics for fission products in the valley and wings of the distribution. This corresponds to 2.90×10^{-2} ampere-seconds on linear channel 1 for uranium samples that are nominally enriched to 93% ^{235}U. Current efforts in this area are to couple fission chamber measurements with the relative cumulative yields as determined by radiochemical analysis to place all future data on a per fission basis. One of the goals of the new measurements is to support an international effort to generate a new fission product yield evaluation for the next major release of the ENDF nuclear data library.

In these modern measurement campaigns, the sample foils are encapsulated in aluminum cans that both contain the samples in a known geometry and prevent cross contamination from Flattop itself. They also make it easier to precisely locate the foils with respect to fuel pieces and other samples within the glory hole. Figure 16 shows a glory hole loading from an irradiation to measure reaction rates for activation products associated with elemental components of steel. The known neutron spectrum and ability to precisely place foils within the Flattop core provide scientists with data and uncertainties that may be applied to estimate neutron flux and fission yields based on activated samples from the field. In a 2016 irradiation on Flattop, activation products from several stainless steel and constituent element foils were analyzed to determine if their gamma signatures could be used to determine the grade of an unknown alloy.[19,20]

The measurements discussed here represent a collaborative project by LANL, Lawrence Livermore National Laboratory (LLNL), and Pacific Northwest National Laboratory (PNNL) that is funded by the Office of Defense Nuclear Nonproliferation Research and Development within the U.S. Department of Energy's (DOE's) National Nuclear Security Administration. Initially, only the HEU core was used for these irradiations, but recently, the first irradiation to measure activation products from components of steel using the Pu core was conducted in April 2021.

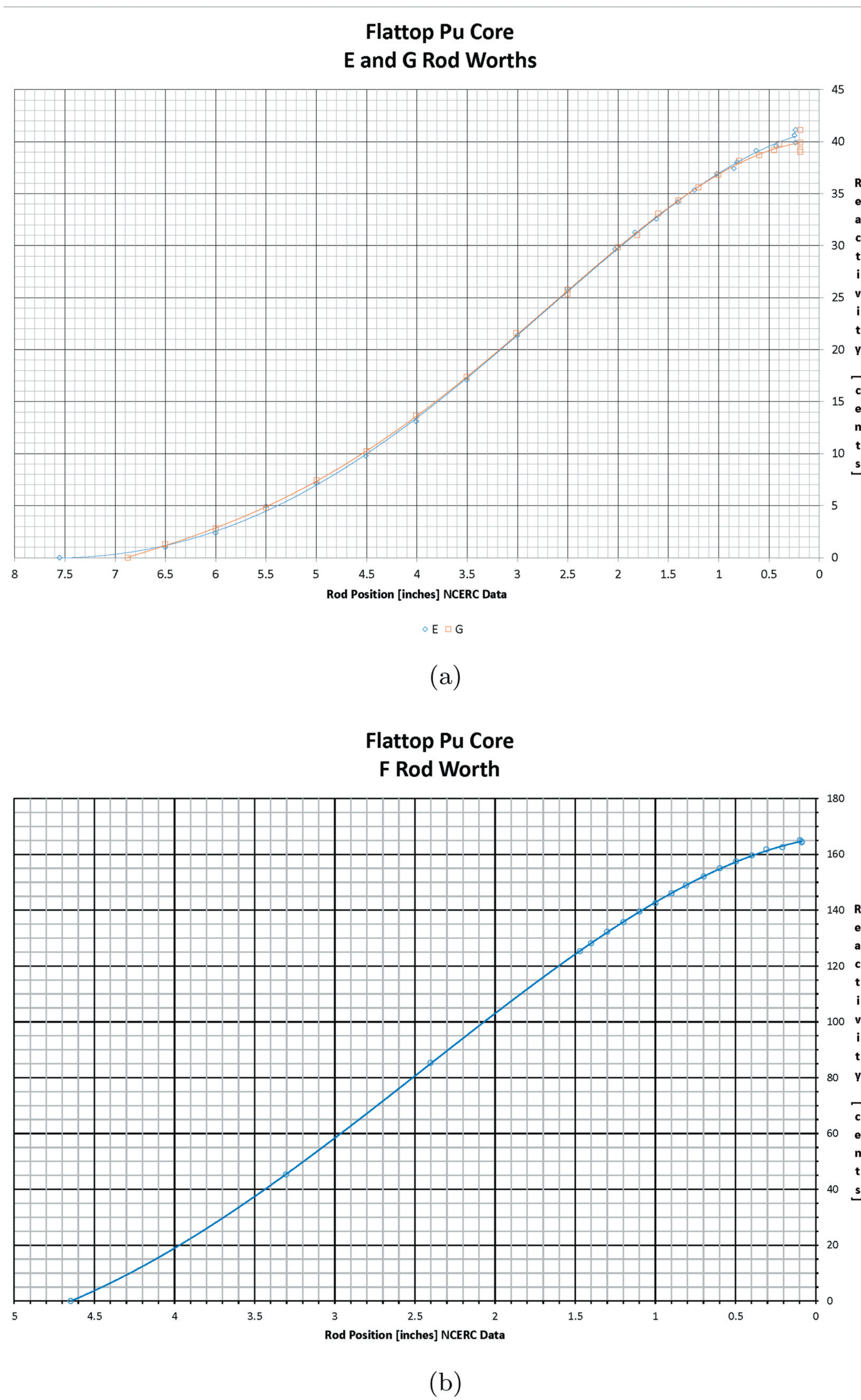


Fig. 12. Flattop plutonium core integral rod worth curves: (a) E and G rod worths and (b) F rod worth.

Fig. 13. John Bounds (LANL) adjusting the heat pipe on the DUFF experiment.

V.D. Joint Neutron Noise Measurements

In July 2013, LANL and the Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA) Valduc met at NCERC to resume a collaboration begun on the critical assembly machines at Valduc.[21] Neutron noise measurements were conducted on Flattop, Godiva IV, and Planet at NCERC. Five Flattop configurations were measured including four subcritical and one at delayed critical.[22] The purpose of the measurements was to compare the detection and data analysis techniques to known benchmarked systems. The multiplication factor and reactivity were estimated based on the measured data and compared to the known reactivity of the configuration. While Flattop benchmarks have been evaluated in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) handbook, none contain detailed models. Consequently, a detailed model was developed based on the specific measured configurations. Results of the five measurements and MCNP models compared favorably with the rod worth curves. However, the measurements pointed to the need for an updated, detailed ICSBEP evaluation of Flattop.

V.E. Radiation Field Characterization and Dosimetry Intercomparison

U.S.-based International Nuclear Accident Dosimetry (NAD) Intercomparison Experiments, last performed in 1995 at LACEF (Ref. 23), resumed in 2014 at NCERC with Godiva. In 2018 an intercomparison experiment was conducted using the different and somewhat more challenging spectrum provided by Flattop.

Characterization of the radiation field around Flattop was the first task.[24] Fission foils [U(93)] were irradiated to

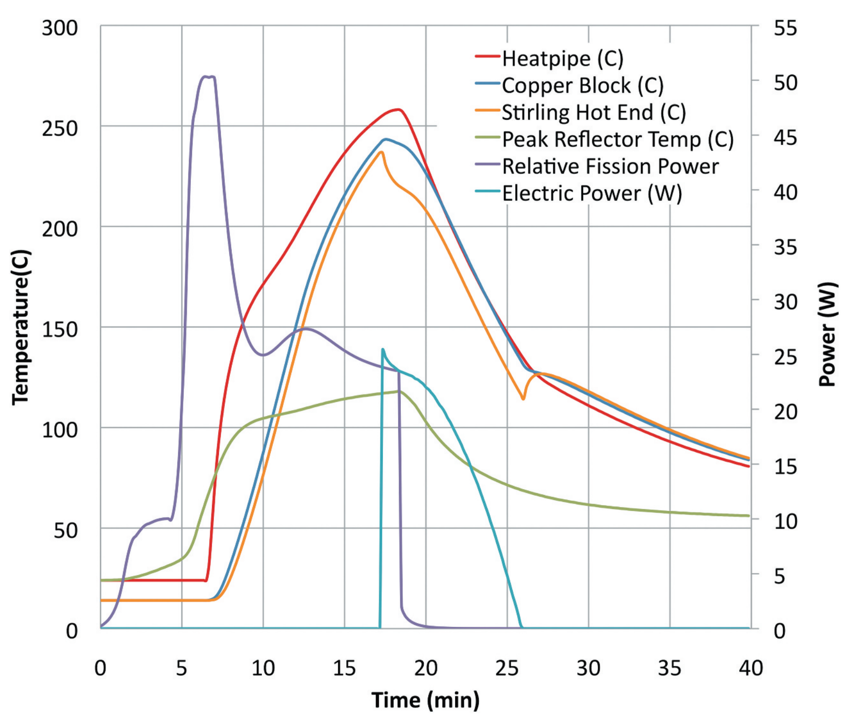


Fig. 14. Data from DUFF experiment on September 13, 2012.

ANS

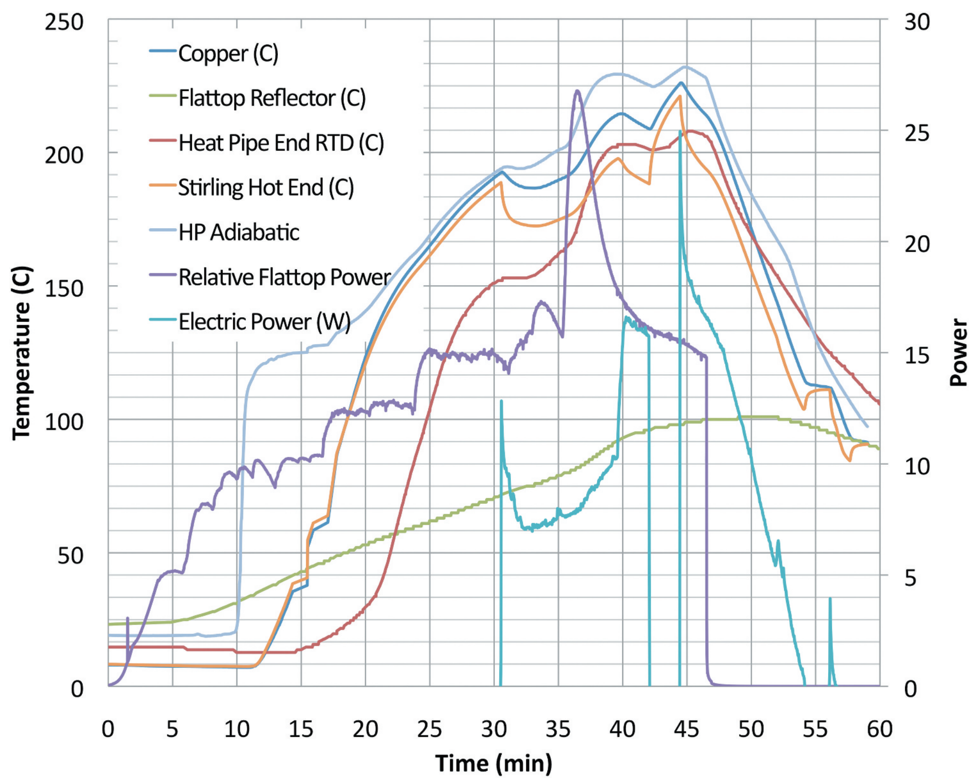


Fig. 15. Data from DUFF experiment on September 18, 2012.

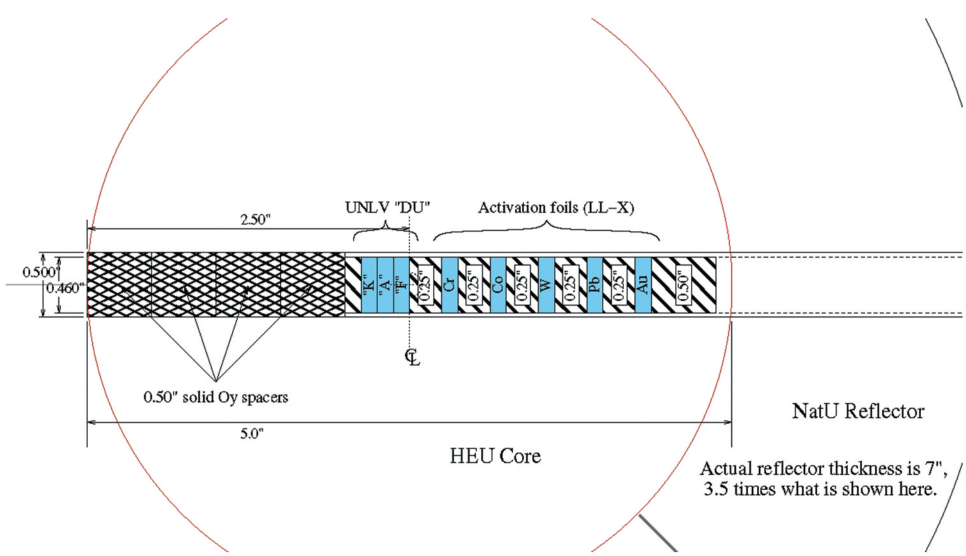
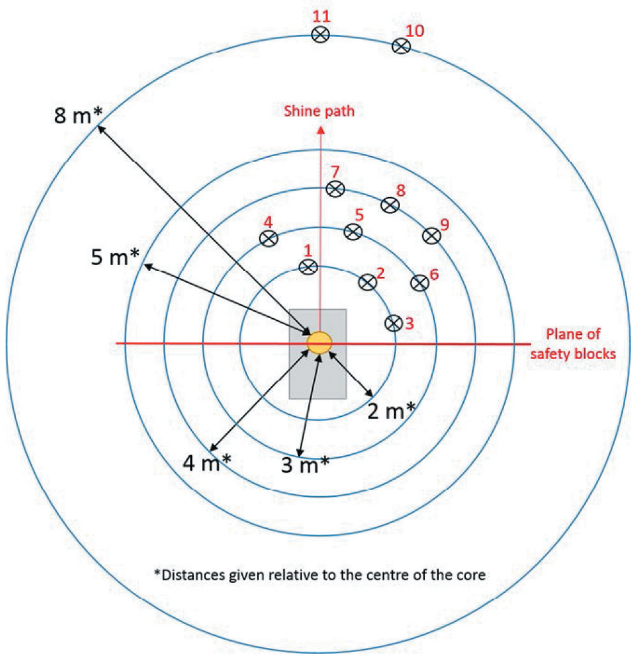
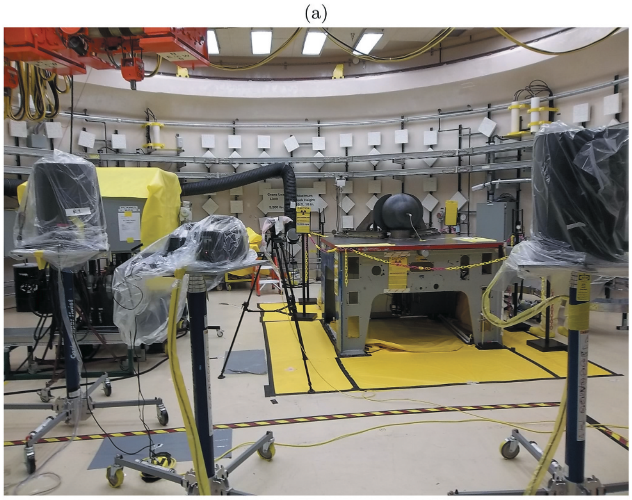


Fig. 16. Example core loading used for an irradiation to measure activation products in elemental components of steel. The sample foils are placed in aluminum cans (blue rectangles). Fuel pieces and hollow aluminum spacers are used to precisely position the sample foils within the core.

confirm the aforementioned correlation between integrated linear channel current and fissions within Flattop. The correlation was determined using a 1-mg U(93) fission foil irradiated to 2.0×10^{-2} ampere-seconds. Based on gamma counting and analysis of six fission products, 3.8×10^{13} fissions occurred in the foil. Thus, the correlation is nominally 3×10^{19} total fissions/ampere-second. Radiation field characteristics were measured by deploying a spectrum of neutron and photon detectors followed by nuclear accident dosimeters. Figure 17 shows the layout of the detectors.



(a)



(b)

Fig. 17. Flattop radiation field characterization: (a) detector location map and (b) detectors configured around Flattop.

Detectors were chosen to assess both low- and high-power operations enabling the analysis of the linearity of fluence and dose as a function of Flattop power. Low-power measurements utilized two ROtating Neutron SPECtrometer (ROSPEC) detectors, a Simple Scintillation Spectrometer (SSS-PROBE), and Bismuth Germanate (BGO) gamma-ray spectrometers. Passive neutron spectrometers were used during high-power measurements. Fluence variations as a function of distance from Flattop, radial contour, and height off the floor were measured using 129 nuclear accident dosimeters. Data and analysis from these measurements were used as the reference for the NAD intercomparison.

Approximately 1 yr after the characterization experiments, a "blind" intercomparison exercise was conducted involving ten laboratories.[25] Participants were LANL, LLNL, PNNL, Sandia National Laboratories, Savannah River Site, Y-12 National Security Complex, Atomic Weapons Establishment, Institute for Radiological Protection and Nuclear Safety, Mission Support and Test Services (MSTS), and the Naval Dosimetry Center. Details of the dosimetry elements and their positions relative to Flattop were unknown to the participants in order to simulate the need for dosimetry analysis in response to a criticality accident.

Nuclear accident dosimeters were dispersed on aluminum plates and BOttle MAnnikin ABsorber (BOMAB) phantoms placed at varying locations around Flattop. Figure 18 shows one such arrangement. The phantoms were used as "reference men" to simulate personnel present during a criticality accident. The aluminum plates were used to obtain "free-in-air" dose measurements. Postirradiation, 220 dosimeters were analyzed independently by each participating organization. Results indicated that improvements in dosimetry and methodologies are required to improve performance under blind conditions.

V.F. Experiments Supporting Nuclear Criticality Safety Training

Flattop is regularly used to conduct nuclear criticality safety training. While the objective of criticality safety is to ensure systems remain subcritical, there is no better means to demonstrate how varying parameters can affect criticality than to operate a critical assembly. Flattop is one element of a week-long training at NCERC intended to satisfy the hands-on experiment requirements of the Criticality Safety Engineer Training and Qualification Program.[26]

Neutron leakage is very important in operations involving fissionable materials, and the effects of changing leakage are readily demonstrated by Flattop. Imperceptible gaps in fissionable material systems have large impacts on neutron leakage and therefore criticality. To demonstrate this, students operate Flattop under the supervision of certified crew members. Withdrawing a Flattop safety block by less than 0.1 in. while at critical will immediately result in a subcritical system, which will be evident from the displays of the startup and linear counters. Several lessons are observed and learned as a result:

1. Small gaps in fissionable material systems have large reactivity effects.

Fig. 18. Dosimetry arranged around flattop for international NAD intercomparison.

2. Spacing of fissionable materials, even modestly, is of great benefit to criticality safety.

3. Conversely, closure of small gaps due to inadvertent movement by an operator can have serious consequences; fissionable material systems in unknown states should never be approached or handled without specific guidance from Criticality Safety.

Finally, Flattop is used to demonstrate a criticality accident in slow motion. A typical criticality accident occurs above prompt critical and relies upon prompt neutron generation to drive the system. This Flattop exercise occurs below prompt critical and relies on the delayed neutron generation to drive the system. As in a true criticality accident, reactivity is inserted as a step function followed by an exponential rise in power until negative feedback terminates the pulse. However, in this demonstration the timescale is minutes rather than milliseconds because the excursion is controlled by delayed neutrons rather than prompt neutrons.

To start the demonstration from a delayed critical configuration, control rods are positioned for an excess reactivity between 15 and 30 ¢. Safety block B is withdrawn to allow delayed neutron precursors to decay away. Safety block B is reinserted, placing Flattop in a supercritical configuration, and the assembly is allowed to "free-run" with no operator intervention (see Fig. 19). Students

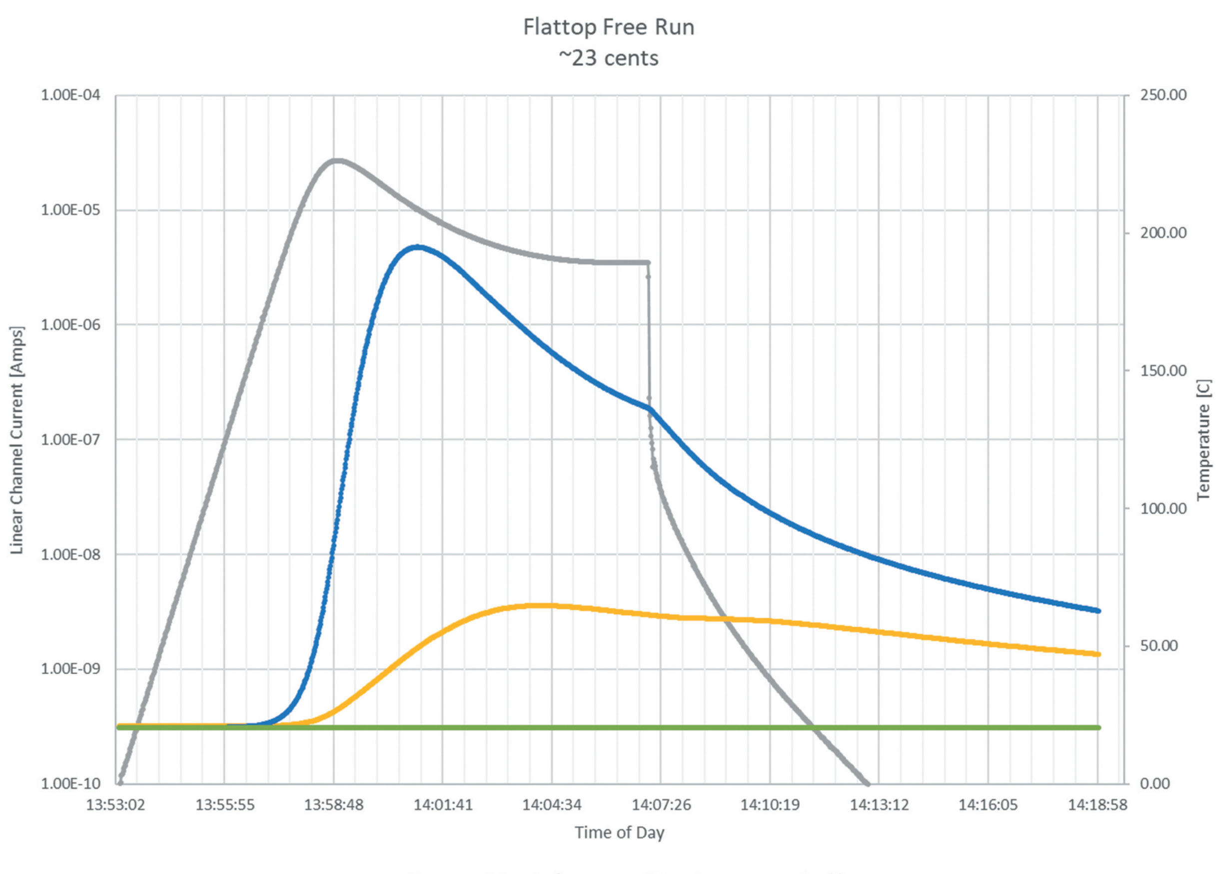


Fig. 19. Flattop 23 ¢ free run.

observe the rise in power accompanied by negative reactivity feedback as the core heats and expands. The density of the core decreases as it expands, increasing the leakage of neutrons. Peak power is achieved, and power decreases as the negative temperature feedback overcomes the initial excess reactivity. Power continues to oscillate as the core expands and contracts until an equilibrium of heat generation and rejection is reached. The students have now observed a criticality accident on the timescale of delayed neutrons versus prompt neutrons.

VI. CONCLUSIONS AND FUTURE WORK

Flattop is a fast benchmark criticality assembly relocated to NCERC for operations in 2008. Since then, Flattop has been used for numerous experiments including dosimetry intercomparisons, the DUFF experiment, irradiations for nuclear forensics, and nuclear criticality safety classes.

Clearly, Flattop will continue to be used in nuclear criticality safety training. In addition, Flattop has contributions to make with regard to nuclear data. Experiment planning is underway to study the reactivity effects of plutonium aging, critical mass estimation of ^{241}Am, and irradiations with the plutonium core. Finally, revisions to the uranium and plutonium core benchmarks will incorporate modern density and dimensional measurements.

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