Detection of Highly Enriched Uranium Using a Pulsed D-D Fusion Source

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This paper overviews the work that has been done to date towards the development of a compact, reliable means to detect Highly Enriched Uranium (HEU) and other fissile materials utilizing a pulsed Inertial Electrostatic Confinement (IEC) D-D fusion device. To date, the UW IEC device has achieved 115 kV pulses in excess of 2 ampere, with pulsed neutron rates of 1.8x10^9 n/s during a 0.5 ms pulse at 10 Hz. MCNP modeling indicates that detection of samples of U-235 as small as 10 grams is achievable at current neutron production rates, and initial pulsed and steady-state HEU detection experiments have verified these results.

I. INTRODUCTION

The smuggling of illicit nuclear material has been an issue of serious concern for U.S. officials since the early 1990's, and has gained increased attention in the wake of September 11, 2001. In the past decade, there have been over 150 confirmed incidents of smuggling of nuclear material in the International Atomic Energy Agency's (IAEA) Illicit Trafficking Database.[1] Of these, nearly half involved enriched uranium or plutonium. In the wrong hands, these materials could represent a serious threat to national security in the U.S., and preventing this from occurring has become a high priority for the newly formed Department of Homeland Security.

The development of a cheap, reliable means to detect fissile and other nuclear materials will allow the U.S. and other countries to inspect cargo as it enters their borders. This work presents experimental results from one device designed to detect clandestine HEU material.

II. EXPERIMENTAL SETUP

The University of Wisconsin has been studying the performance of an Inertial Electrostatic Confinement (IEC) fusion device for more than a decade.[2] It has been recently used to develop an active detection system for fissile materials. As seen in Figure 1, one of the UW IEC devices is an aluminum chamber 65 cm tall and 90 cm in diameter.[5] A base pressure of ~10^{-7} torr is maintained in the device using a 1000 L/s turbo pump. Within this chamber are two highly transparent conducting grids. The outer stainless steel anode grid is 50 cm in diameter and is kept at ground potential. The inner tungsten-rhenium cathode grid is 10 cm in diameter and is connected to a 200 kV power supply with a high voltage feed thru.

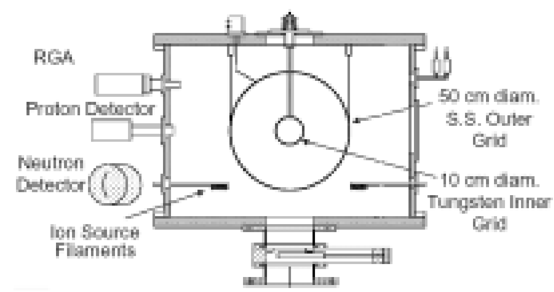

Fig. 1: IEC chamber

During normal operation, deuterium gas is fed into the chamber to produce a background pressure of 2 mtorr. This gas is then ionized using electron bombardment from standard light bulb filaments. Negative voltage is applied to the inner grid anode, and the positively charged ions are attracted to the center of the grid.

The UW-IEC device was modified to allow pulsed operation as shown in Figure 2. IEC current is nominally suppressed during pulsed operation by applying a positive bias to the electron filaments. Cathode current pulses are then generated by adding a large negative bias to the filaments. Cathode voltage is maintained during the pulse via a 100 nF parallel capacitor.

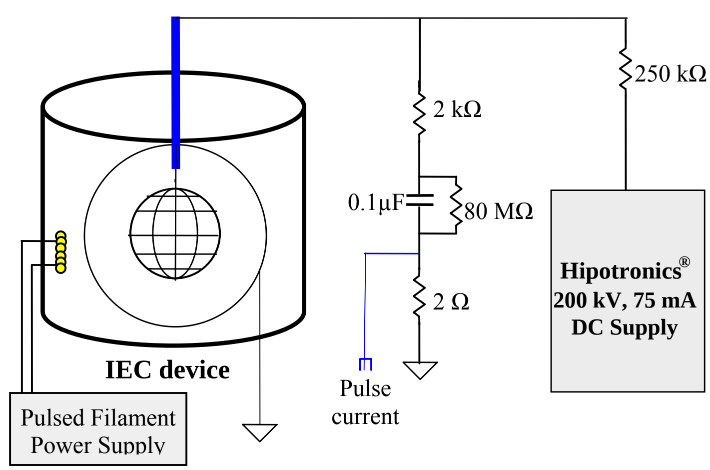

Fig. 2: Pulsed IEC schematic

III. MCNP RESULTS

In order to determine the feasibility of active HEU detection utilizing a pulsed IEC fusion device, the proposed concept was first modeled using MCNP5; a Monte Carlo based particle-tracking code[3]. First, a series of test modules were developed to test the validity of the code for this specific task. Once it was determined that MCNP5 was capable of properly modeling delayed neutrons with a pulsed neutron source in place, work was begun on a simple model of the IEC device. This model was used to test detector geometries in order to optimize neutron detection capabilities. Finally, the more detailed model of the IEC device and detection hardware, shown in Figure 3, was constructed to determine the neutron flux required to confidently detect a 10 gram sample of U-235.

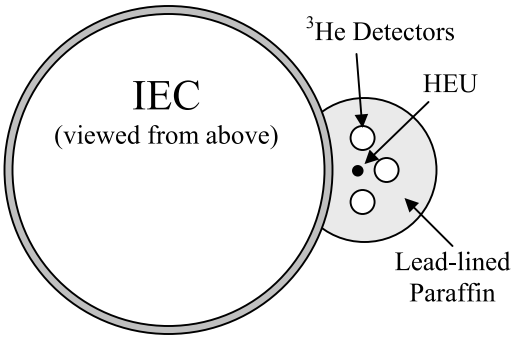

Fig. 3: MCNP model of the IEC experiment

Results were obtained that had sufficiently low levels of error present in the delayed neutron counts. Statistical error in the prompt neutrons is less than 0.1% and the delayed neutron error was kept below 10%.

This data was then used to determine the total number of reactions occurring in the detectors, and therefore the number of counts available for detection. A tally multiplier was added to the volume tallies corresponding to the detectors tubes that measured the reaction rate, R:

$$R = V\int \varphi(E) n\sigma(E) dE \qquad (1)$$

where φ(E) is the energy-dependent flux (particles/cm^{2}s), n is the number density of the ^{3}He, σ(E) is the energy-dependent absorption cross section and V is the volume of the detector assembly. The resultant number of reactions plotted as a function of irradiation time for the first second of irradiation is shown in Figure 4. The delayed neutron level after one second is approximately one-quarter of the maximum level.

Assuming the detector can resolve 80% of the delayed neutrons during the 90 ms between the pulses, this would correspond to ~32 counts/second for an 11 gram sample of 93% enriched uranium. This count rate is well above background and would be easily detectable with existing equipment.

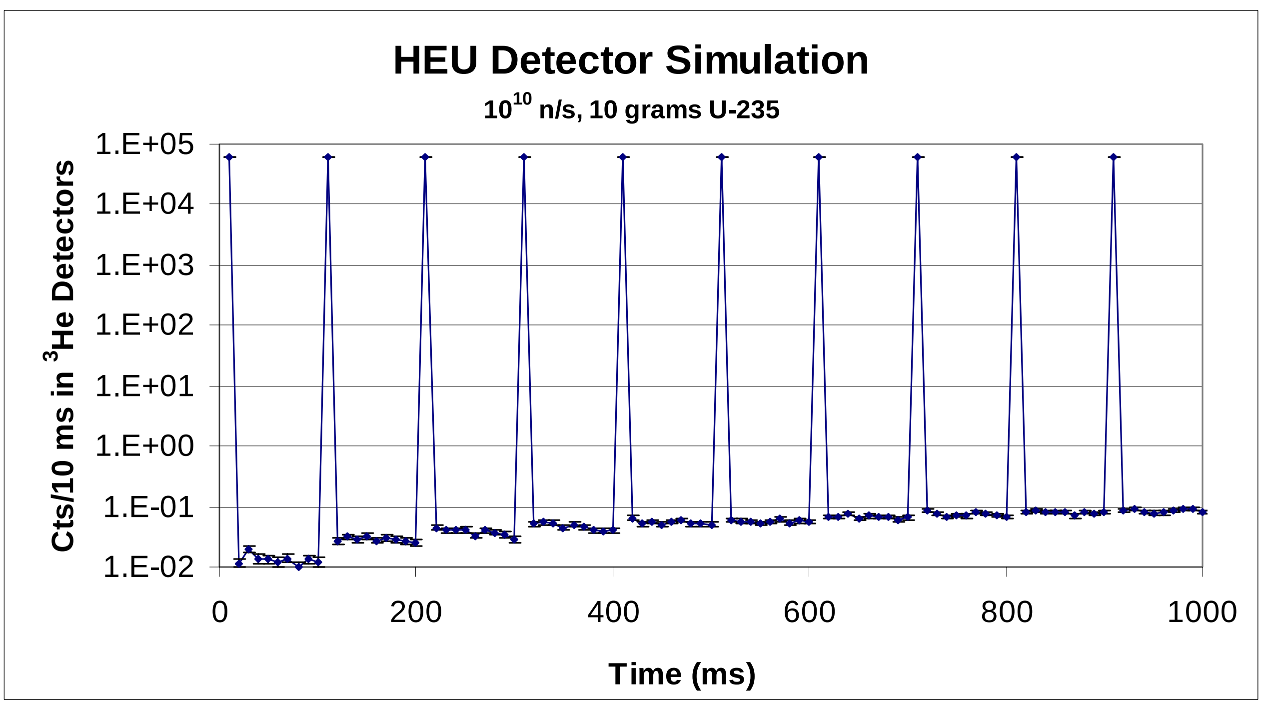

Fig. 4: Predicted counts in ^{3}He detectors for an HEU detection experiment

IV. EXPERIMENTAL RESULTS

IV.A. Pulsed IEC Results

Significant progress has been made in the past year towards the development of a pulsed IEC at the University of Wisconsin. Figure 5 shows the maximum pulsed neutron production rate achieved over the past year. Two events that led to increased neutron production are noted. The first is an upgrade to the power supply that generates the pulsed source plasma from a home-built model to a Cober Electronics, Inc Model 606P High Pwer Pulse Generator. The second is the modification of the cathode/anode geometry. These and other improvements have led to pulsed neutron rates reaching 1.8×10^9n/s during 500 μs pulses.

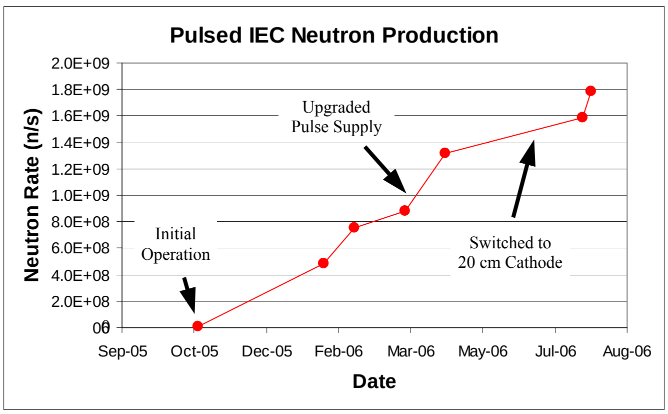

Fig. 5: Pulsed IEC Neutron Production

Standard and modified cathode/anode geometries are shown in Figure 6. Two benefits to the modified configuration were observed. The first was an increase in the pulsed current. It is believed that this increase was due to the increased Child-Langmuir current limit with the conducting spheres closer together in the Modified configuration.[4]

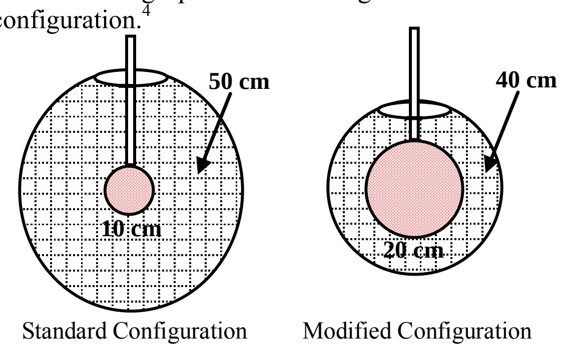

Fig. 6: Standard and Modified Cathode/Anode Configurations

The second benefit was an increase of up to 80% in neutron production during both pulsed and steady-state operation at 100 kV, 2 mtorr D_2 pressure. Figure 7 compares neutron production in standard and modified grid configurations for the UW IEC. Both of these runs were performed at identical current, pressure, and vacuum conditioning.

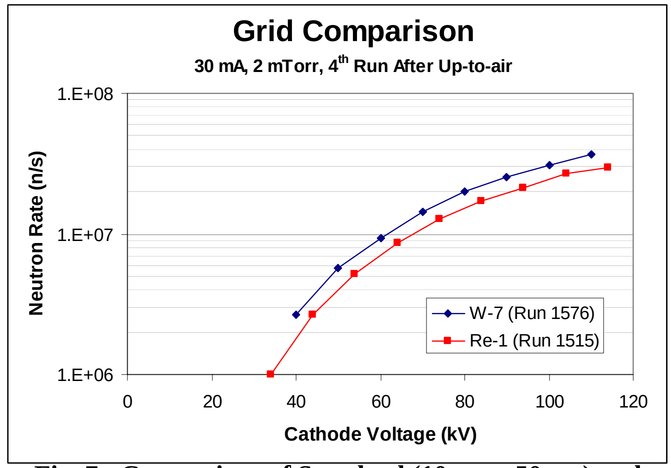

Fig. 7: Comparison of Standard (10 cm – 50 cm) and Modified (20 cm – 40 cm) Configurations

Switching to the modified cathode/anode configuration not only increased the neutron production at 2 mtorr D_2, but allowed stable operation up to 3 mtorr D_2. At this pressure, a steady-state neutron production record of 2.16×10^8 n/s was achieved at 165 kV, 65 mA.

Initial pulsed IEC work at Wisconsin has focused on characterizing pulsed neutron production. To date, pulsed neutron production has been measured as a function of cathode voltage, cathode pulse current, D^2 pressure, duty cycle, and as a number of ion source conditions. Figure 8 shows pulsed and steady-state neutron production as a function of cathode voltage. Both traces follow similar trends, as would be expected.

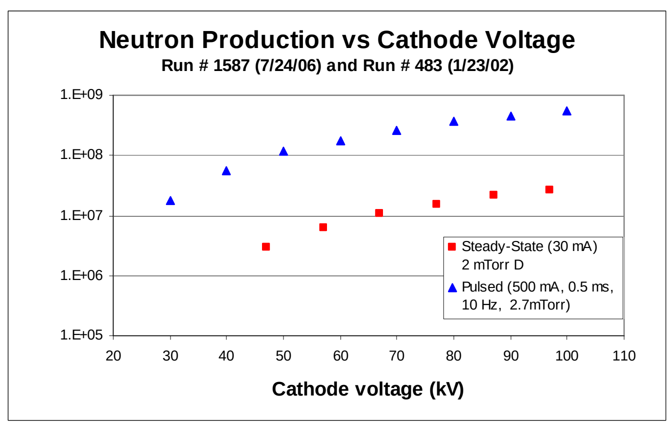

Fig. 8: Neutron Production vs. IEC Cathode Voltage

Figure 9 shows pulsed neutron production as a function of pulsed cathode current during 0.5 ms pulses at 10 Hz for both 80 kV and 100 kV cathode voltages. Both sets of data exhibit linear increases in neutron production as a function of pulsed current, which is consistent with beam-background fusion production theory.

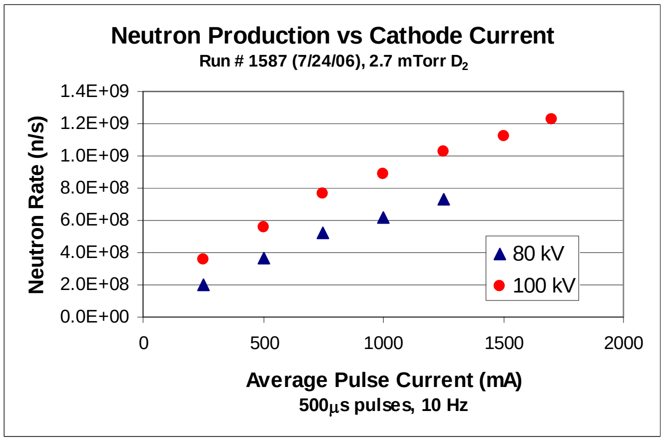

Fig. 9: Pulsed Neutron Production vs. Cathode Pulse Current (0.5 ms, 10 Hz)

IV.B. Pulsed IEC Diagnostics

In order to understand what is happening during pulsed IEC operation, faster diagnostics were required that operated on pulse timescales. Filament bias voltage, cathode voltage, and cathode current were all fed into a LabVIEW™ data collection program. An example of a pulse captured in LabVIEW™ is shown in Figure 10. In this Figure, a 2 ms pulse is generated using the filament bias voltage. The resulting cathode current pulse exhibits typical characteristics, including a gradually decreasing current during the pulse and a ~100µs decay time.

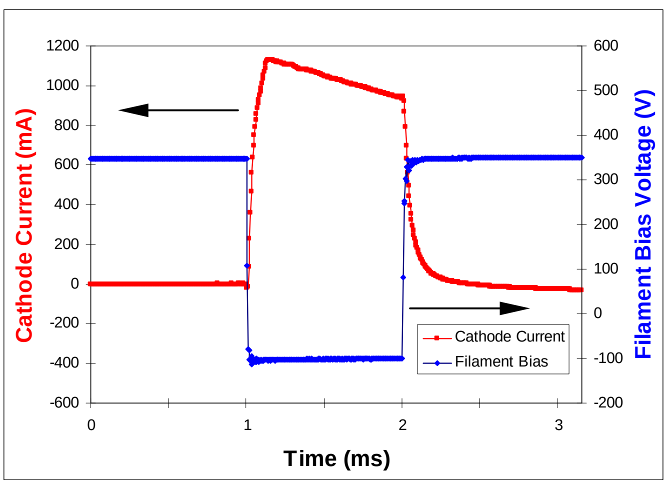

Fig. 10: IEC pulse captured with LabVIEW™

In addition to the LabVIEW™ diagnostics, high-speed neutron SCA software was used to evaluate pulsed neutron production. A screen capture of 1 ms pulses being recorded with the detection software is shown in Figure 11. This system allows the neutron pulse width and shape to be characterized during operation. More importantly, it can be used to determine the neutron flux produced between pulses. The experiment shown in Figure 10 has a few neutrons being produced between pulses. This mode of operation is unacceptable for HEU detection, as it would lead to elevated background counts in the HEU detection system described in the next section.

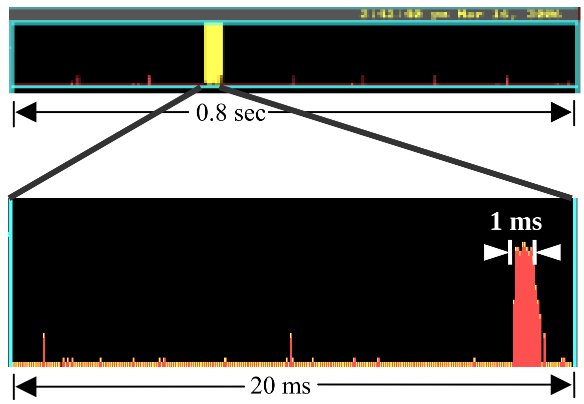

Fig. 11: High-Speed Neutron Detector

IV.C. HEU Detection Results

HEU detection experiments were performed using the apparatus shown in Figure 12. Pulsed or steady-state neutrons interact with a 10 gram U-235 sample surrounded by paraffin, producing prompt and delayed neutrons. These neutrons interact with one of three ^{3}He tubes, producing electronic signals that travel through pre-amplifiers and are combined to one signal that is amplified and sent to an MCA. During pulsed operation, a gate generator is used to block neutrons that are detected during the pulse and for an additional 10 ms after the pulse.

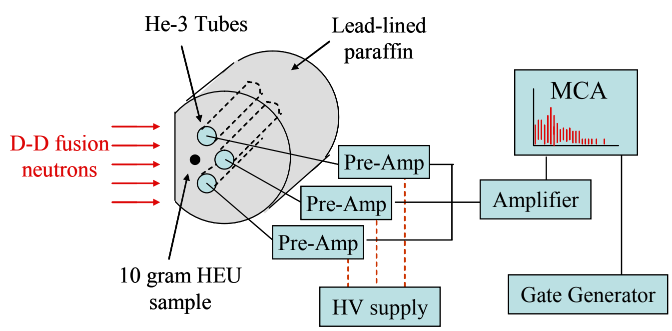

Fig. 12: HEU Detection System

Initial experiments were performed by irradiating the HEU sample with a steady-state neutron flux. Figure 13 shows neutron counts after shutdown for four cases. In each case, the IEC was run at 130 kV, 60 mA and 2.6 mtorr D_2, producing neutrons at ~1.5×10^8 n/s. As noted in the plot, the IEC was run for 2 minutes, 1 minute, and 30 seconds with HEU present, and for 2 minutes with no HEU present in the system.

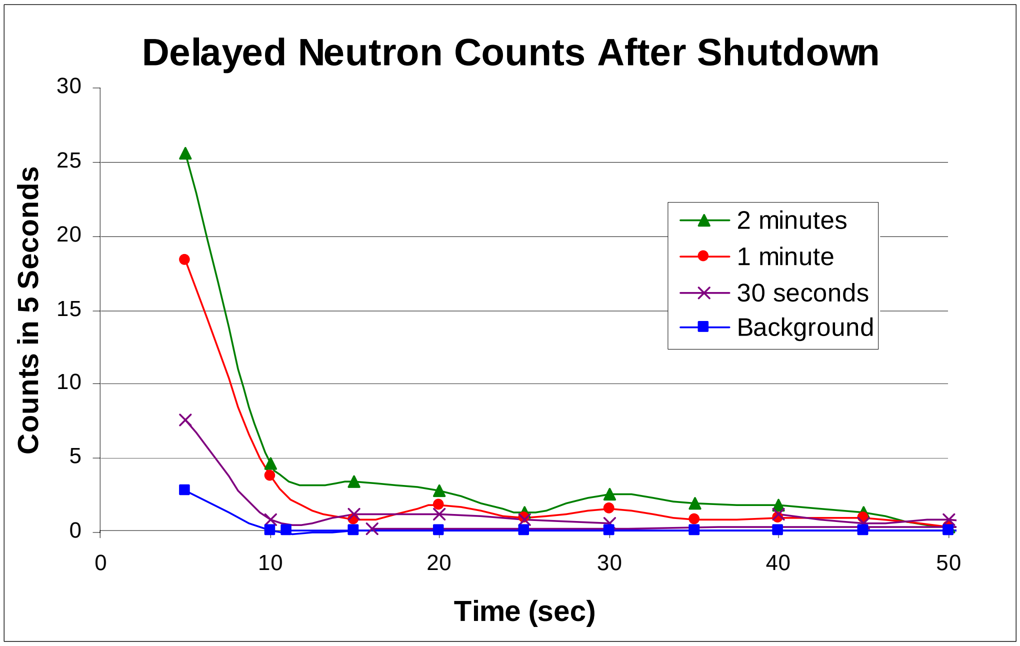

Fig. 13: Steady-State HEU Detection Results

Preliminary HEU detection experiments were also performed during pulsed IEC operation. For these experiments, a gate was added to the detection system that prevented neutron counts from being collected during pulses and for 20 ms following the pulses. Using this technique, experiments were performed at IEC cathode voltages as high as 75 kV, with ~1 ampere pulse current. During the experiment, pulsed neutron rates of ~$5x10^8$ n/s were achieved during 500 µs pulses. Delayed neutron counts were collected at a rate of 0.8 counts/second, with a background rate of 0.4 counts/second.

V. CONCLUSIONS

A pulsed Inertial Electrostatic Confinement (IEC) fusion device has been constructed at the University of Wisconsin. This device is capable of generating 500 µs, 115 kV deuterium ion pulses of up to 3 amperes at 10 Hz. Pulsed D-D fusion neutrons have been generated at fluxes as high as $1.8x10^9$ n/s during these pulses.

Improvements in high-speed diagnostics at the Wisconsin facility have allowed the closer study of both machine characteristics and neutron production during pulsed mode. These diagnostics will allow improved pulse shaping and will be used to lower background counts between pulses.

MCNP modeling has been performed to predict the levels of delayed neutrons that will be generated during Highly Enriched Uranium (HEU) detection experiments and the fraction that will be seen by the ^{3}He detectors. These models indicate that detection experiments will be achievable using the Wisconsin IEC device.

Preliminary HEU detection experiments have been performed using both steady-state and pulsed D-D neutrons. Both neutron sources were successful in generating delayed neutron levels significantly higher than background rates.

ACKNOWLEDGMENTS

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