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Development of a High Fluence Neutron Source for Nondestructive Characterization of Nuclear Waste

Annual Progress Report

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Goals of Project:
We are addressing the need to measure nuclear wastes, residues, and spent fuel in order to process these for final disposition. For example, TRU wastes destined for the WIPP must satisfy extensive characterization criteria outlined in the Waste Acceptance Criteria, the Quality Assurance Program Plan, and the Performance Demonstration Plan. Similar requirements exist for spent fuel and residues. At present, no nondestructive assay (NDA) instrumentation is capable of satisfying all of the PDP test cycles (particularly for Remote-Handled TRU waste). One of the primary methods for waste assay is by active neutron interrogation.
We plan to improve the capability of all active neutron systems by providing a higher intensity neutron source (by about a factor of 1,000) for essentially the same cost, power, and space requirements as existing systems.
This high intensity neutron source will be an electrostatically confined (IEC) plasma device. The IEC is a symmetric sphere that was originally developed in the 1950s as a possible fusion reactor. It operates as D-T neutron generator. Although it was not believed to scale to fusion reactor levels, these experiments demonstrated a neutron yield of 2 x 10^{10} neutrons/second on table-top experiments that could be powered from ordinary laboratory circuits (10 kilowatts). Subsequently, the IEC physics has been extensively studied at the University of Illinois and other locations. We have established theoretically the basis for scaling the output up to 1×10^{11} neutrons / second. In addition, IEC devices have run for cumulative times approaching 10,000 hours, which is essential for practical application to NDA. They have been operated in pulsed and continuous mode. The essential features of the IEC plasma neutron source, compared to existing sources ***of the same cost, size and power consumption, are:***

*Table 1: Present and Target Operating Parameters for **Small** Neutron Generators*

Parameter	Present	IEC Target or Already Proven
Neutron Yield (n/s)	10^8	10^{11}
Lifetime (hours)	500	10,000
Operation	Pulsed	Pulsed or steady state
Nominal cost $k	$100k	Same
Power	1kW	10kW

Technical Description of Work:
The design of a conventional IEC source is deceptively simple. The basic system is a spherical vacuum chamber containing a spherical grid. The grid is raised to a high

negative potential. A breakdown develops between the chamber wall and the grid, and this plasma becomes a source of positive deuterium and tritium ions. These ions are accelerated to the center of the vacuum chamber sphere where they may collide. The ion energy may achieve the full potential of the accelerating grid. If the grid is raised to a nominal 100 kv, the coulomb barrier for D-T fusion, then the fusion cross section becomes quite large and the neutron production proceeds.

The IEC concept was originally developed in the late 1950's and early 1960's by R. L. Hirsch and collaborators. Its incipient purpose was a possible plasma fusion experiment source for the fusion energy program. The idea was initially presented to the DOE with a table-top experiment using ordinary office power. That system produced in excess of 10^8 neutrons per second. Although the IEC was not favored for a future electric energy generator, the application as a potential neutron source was clearly established. Using nominal laboratory power and a modest sized sphere, Hirsch was able to achieve a maximum neutron yield of $2x10^{10}$ neutrons per second in the mid 1960's.

The achievement of a total neutron yield of $2x10^{10}$ n/s was a remarkable result, but the more important contribution of Hirsch was establishing the underlying plasma physics basis of IEC operations. Hirsch found that the IEC neutron yield scaled strongly with grid current, but not strongly with voltage. This result is surprising because ideally the accelerating ions collide with the grid potential energy, and the scaling of the fusion cross section with collision energy is very strong. Hirsch also found that neutron yield scaled inversely with density, to the extent that density could be varied in a static device. This result was very surprising, because the classical reaction rate is proportional to the density squared. Hirsch correctly surmised that the reason for this behavior was the plasma collisionality. The IEC plasma was operating in the collisional regime. In collisional operations, accelerated ions are likely to collide with fill gas neutrals in the accelerating grid interior. Thus the center of mass collision energy is derived from a single particle only, as the neutral is effectively stationary. In addition, each ion probably suffers multiple collisions with the neutral gas, because the Rutherford cross section is largest at low energies. Therefore, the ions never achieve the full accelerating potential of the grid. The fusion cross section drops rapidly with reduced collision energy and the neutron yield is small. In this mode the ions do not collide in a single, tiny point in the center of the chamber, but over a larger contained volume. The multiple collisions can also import angular momentum to the particles that further increases the collision volume (although the plasma fluid must remain at zero angular momentum).

As density is decreased, (or as current is increased), the plasma collisionality drops. Ions can accelerate more between collisions and achieve higher collision energy. The fusion cross section increases. In addition, the rate of beam-background (or beam-neutral) collisions drops. Less angular momentum is imported and the ions are more tightly focused at the center of the IEC chamber. The beam-beam collision rate increases which effectively doubles the center of mass collision energy. The neutron yield increases with the larger fusion cross section. As the density is dropped, the plasma becomes collisionless, the ions focus in a tight spot at the chamber center, the dominant interaction is beam-beam, and the ions approach the full accelerating potential of the grid. In this mode, neutron production is highest.

These results were demonstrated experimentally by Hirsch 3 decades ago. They have subsequently been confirmed by a 1-1/2 dimensional, fully kinetic, plasma simulation code with complete atomic physics included. The code results, completed at Los Alamos, have confirmed the underlying dynamics of Hirsch's model.

However, there are practical and physics reasons why reduced-density IEC plasma experiments have not been deployed. Fundamental is that the plasma density is not a free variable but is constrained by the Paschen breakdown curve. The Paschen curve relates the applied electric field to the plasma density at breakdown, and constrains the density because without breakdown there is no plasma source of ions. Conventional, single grid, IEC experiments have been limited to high density operation by the Paschen limit. Typically fill gas pressures have been several millitorr.

A novel approach proposed at Los Alamos removes this limitation. The Los Alamos IEC uses a triple grid design. In the triple grid IEC device, the inner grid is the accelerating grid. It is raised to high negative potential and serves the same function as the single grid in conventional IEC systems. The central grid serves as electrical isolation, and is held at ground potential. The outer grid is raised to a modest positive potential, say 200 volts. Dispenser cathodes around the vacuum chamber wall inject electrons. The electrons are trapped and orbit around the outer grid, ionizing a local plasma. Because of the modest potential, the breakdown occurs at a different point on the Paschen curve, at a much lower density. The limit is further relaxed by the injected ionization from the dispenser cathodes. The result is a lower density plasma. Typical fill pressures for the triple grid IEC devices well over an order of magnitude below their single grid counterparts. The low density plasma diffuses across the second grid, and is rapidly accelerated by the inner grid. The result is a tight focus of fully accelerated ions that collide in a beam-beam mode. The collision energy and neutron yield are large. A schematic of the triple grid IEC design is shown in figure 1.

The triple-grid design enables extending Hirsch's results by mitigating the Paschen breakdown limit and operating in the collisionless, beam-beam mode. A schematic of the triple-grid device is shown in figure 1.

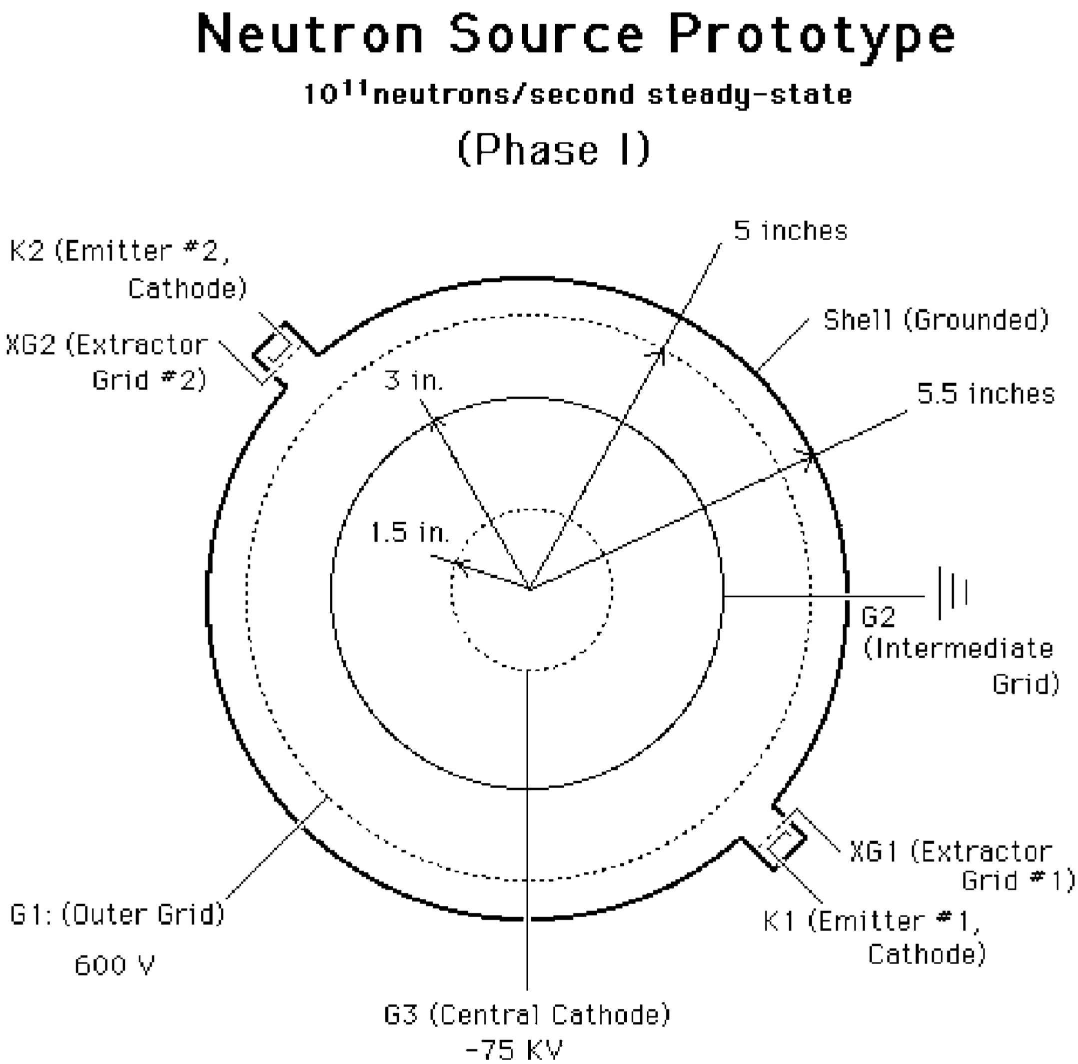

Figure 1: A triple grid IEC schematic.

This approach has been examined at Los Alamos using the fully kinetic simulation code. The code confirms low density breakdown, a collisionless plasma, a tight beam focus, negligible particle angular momentum, and high energy, beam-beam collisions. Low power experiments with triple grid systems have also confirmed the basic scaling relationships. These efforts involved very modest funding level from Los Alamos internal funds. A full, high-power experiment is the next step and is the basis for this project.

The approach for this research project is to construct and test a high-power, triple-grid, IEC experiment according to the specification of the kinetic code simulation.

We believe that a triple grid system can extend Hirsch's 1960's results a factor of 5 to achieve the 10^{11} n/s target for this proposal. Table 2 summarizes presently achieved IEC performance and our target values. The extrapolations are reasonable given the significant advances in plasma physics, power electronics, and instrumentation in the last 3 decades.

Table 2: Target and Present IEC Parameters

Parameter	Presently Achieved	Target Value
Neutron Yield	2×10^{10} n/s	10^{11}n/s
# Grids	1	3
Size	24” Diameter	6” diameter

In addition, our objective is to achieve the modest cost, size, weight and power consumption listed in table 1, and the long operating lifetime also listed in table 1. These values have already been achieved in low power IEC devices at INEEL and the University of Illinois. The scientific challenge will be to maintain these parameters in a high-yield IEC device (except for power which will increase from 1kW to 10kW.). We believe that the low density, triple grid design affords this opportunity.

The scientific justification for this extrapolation is predicated on the basic plasma physics established by Hirsch, and subsequently verified. The collisionality scaling argument is compelling that the target values can be achieved. In addition, the plasma physics computational capability available today for exceeds that 3 decades ago. The fully kinetic code is a highly accurate simulation that will be used to optimize the IEC design for maximum yield and lowest possible power consumption. These analytical tools have only been recently developed.

In the first year of this project we designed and mostly completed construction of the IEC device. The principal components were the spherical vacuum chamber containing 3 grids and dispenser cathodes, the main high voltage accelerating power supply (rated at 100 kv and 350 milliamperes), the intermediate voltage breakdown supply, and control electronics. All of the IEC components were designed and fabricated in the first year. Much of the system assembly was also completed. The remaining assembly of the IEC was completed during the second year. In addition, during the second year we established approved safe operating procedures for the operation of this system within the facility safety envelope. We completed preparation of the hot cell and control areas for the IEC operation. Finally, we operated and tested the entire experiment and achieved full operation of all systems. Plasma breakdown was achieved during this operational testing.

In the final year we are pursuing the physics experimental program for the IEC. There are two central physics issues that must be resolved successfully. First, we must establish that we can operate a low-density, collisionless discharge. The premise of the triple-grid IEC design is that we can lower the density below typical operating values of conventional (single grid) IEC systems.

Second, we must demonstrate operation at high accelerating voltages without arcing. Plasma arcs are a pernicious problem for high-voltage, high-vacuum systems. However, in order to achieve the projected 10^{11} n/s output we need to achieve an accelerating potential at the fusion threshold for D-D and D-T fusion reactions. The nominal value is 75kV. To date, we have achieved 53 kV.

The plasma arcing typically occurs between the high voltage electrodes or between the high voltage electrodes and the vacuum chamber. This problem was predicted to be the most challenging in our initial proposal, which has turned out to be true. We had originally planned for an initial experimental operation followed by extensive redesign and rebuilding of the experimental chamber. In fact, we have had several (rather than a single) redesigns and modifications, but all were more modest in scope. In this way we have explored several design changes incrementally and improved the high voltage stand off capability in a step-by-step fashion. This approach has proved quite effective. We have consistently raised the maximum allowable accelerating voltage from 15kV initially to 52kV at present. These experiments continue.

Accomplishments to Date:
In the first two years we completed the design, fabrication, and assembly of the IEC experiment. This construction consisted of:

1. Design, construction, and assembly of the mechanical systems. These are primarily the vacuum chamber, vacuum pump system, gas flow handling system, and the support structure.
2. Design and construction of the electrical systems. The electrical systems consist of the power supplies that power the IEC grids and also the power supply control systems. The main high voltage is run steady state, but the ionizing grid and the electron injectors operate in a pulsed mode. The control electronics also contains the pulse mode and current feedback controllers.
3. Preparation of the shield-cell experimental area. Because we anticipate the production of large number of neutrons, an appropriately shielded experimental area must be used. An uncontaminated "hot cell" was available, but it had to be prepared for the IEC experiment, including the installation of 100 kW, 3 phase, 280 volt electrical power.
4. Preparation of approved, safe operating procedures for operation of the IEC within the facility safety envelope.

The entire IEC experiment has been completed build and is fully operational. We have designed, built, and tested all systems. The vacuum system has been assembled and we have achieved a base vacuum pressure of 3×10^{-8} torr. The electronics system is complete and consists of two electronics racks and a high voltage unit. Figure 2 is a pictorial of the vacuum system. The high voltage unit and one of the racks are the high voltage, 100 kilovolt, 25 kilowatt, accelerating supply for the interior, accelerating grid. The remaining electronics rack contains the power supplies and feedback controllers for the ionizing grid and electron injectors. The IEC operates essentially as a vacuum tube, so that the ionizing grid must be energized using a current source. There are also feedback-controlled power supplies for each of the electron injectors. The drive current for each of the injectors is individually regulated and controlled. Again, each injector is operated as a current source. Most of the scaling studies with the IEC scale either the ionizing grid or electron injector currents.

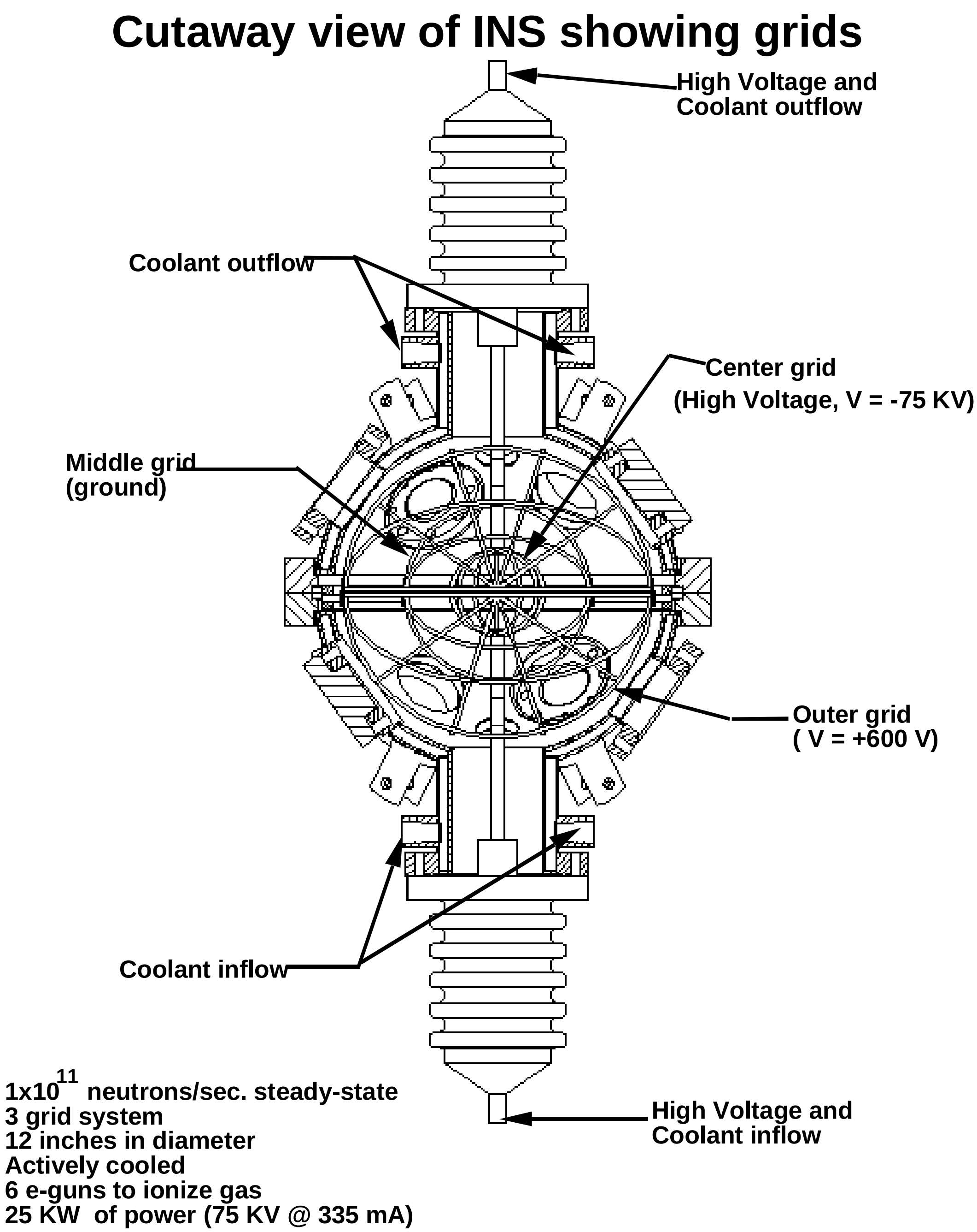

Figure 2: Picture of the two halves of the IEC vacuum chamber.

The preparation of the "hot-cell" experimental area is complete. The hot cell is necessary to provide adequate shielding from the intense neutron flux that we anticipate. A hot cell was available, but it had to be cleared of radioactive sources and prepared for the operation of the IEC source. In addition, the main shield door was not operating and had to be repaired. (This repair was ***not*** funded from this project but from internal, infrastructure development funds.) Finally, we installed a 3 phase, 100 kilowatt, 280 volt line to provide the required power for the main accelerating power supply. (The

remaining supplies and control systems operate from ordinary 115 volt, single phase service.)
Figure 3 is a picture of the electrical power systems outside the hot cell. One of the main viewports of the hot cell, which is an oil-filled window 4 feet thick, is visible. Remote manipulators are also available. The electronics and control systems are placed just outside the hot cell for convenient and safe operator access. They are connected to the IEC vacuum chamber with cables that snake through the access ports in the hot cell, where the IEC chamber itself is placed. We have already tested neutron leakage through the access ports using sensitive neutron detectors and isotopic sources. No detectable radiation was found. The IEC will be easily visible through the viewport.

Figure 3: Picture of the electrical power equipment outside of the shield cell at the location of the IEC experiment.

Figure 4 is a picture of the fully complete experimental chamber inside the vacuum chamber.
We anticipated and indeed executed re-design and development of the accelerating grid feed-throughs because these must withstand the high accelerating voltages without arcing inside the vacuum chamber. The feed-throughs are designed with ceramic insulators. Several design and test iterations have been conducted and we have raised the maximum stand-off voltage from 15kV initially to 52kV at present.
We have achieved a plasma discharge using the low voltage systems. The initial experimental phase to explore breakdown physics has been completed. The breakdown physics issue is essential to achieve a low-density plasma. Therefore, without using the high voltage power supplies, we have explored the plasma breakdown physics to achieve a low density plasma. These experiments have been completed successfully; we have achieved routine low density operation.

Fig. 4. A picture of the entire system inside the hot cell. Power supplies are located outside the hot cell.

Projections:

We will not complete the scope outlined in 1997. However, we will accomplish the essential scientific components. A summary is given below, which lists all of the project milestones established in the original proposal:

Table 3: Milestone Summary

Milestone	Date	Accomplishment	Status
1	4 mos	Procure all power supplies and vacuum equipment.	Done
2	8 mos	Execute CRADA agreement	Not completed.
3	8 mos	Complete construction of electrical systems.	Done
4	10 mos	Build vacuum chamber	Done
5	11 mos	Initiate experimental program	Done

6	16 mos	Complete initial experimental program.	Done
7	20 mos	Build second vacuum chamber.	Done.
8	26 mos	Complete second experimental program.	Not completed
9	30 mos	Complete industrial engineering design.	Not completed

We fully expect to complete milestone 8, the second experimental program before the end of this fiscal year. Therefore, the only aspect of this project that will not be completed will be the engineering design and the commercialization. However, all of the scientific components will have been completed, according to our projections. Once the underlying science is demonstrated, then the follow on engineering and commercialization are a natural step.