Final Report
U.S. Department of Energy

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

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Project Number: AL17SP22
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Project Duration: 3 years. 1996-1999

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3. Executive Summary:

We are addressing the need to measure nuclear wastes, residues, and spent fuel in order to process these for final disposition. 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. The objective of this project is to improve the capability of all active neutron system's 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 is an electrostatically confined (IEC plasma device. Previous experiments[1] have demonstrated a neutron yield of 2 x 10^{10} neutrons/second on a table-top device that can be powered from ordinary laboratory circuits (9 kilowatts). We have established theoretically the basis for scaling the output up to 1 x 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.

Most previous IECs have been single grid systems that operate at high density. These systems require high density for breakdown, but this results in a highly collisional plasma which seriously degrades the performance. The novel approach we have implemented at Los Alamos removes this limitation. The Los Alamos IEC uses a triple grid design which uses dispenser cathodes to initiate plasma ionization. We have successfully demonstrated this low density operating regime in the device.

We also have designed the machine with a capability to go to signicantly higher power levels than previous devices. We have a 75 kV 335 (25kW) milliampere power supply which will significantly push the operation envelope for IECs. This increased power level requires us to actively cool the device. The chamber is a double-jacketed design which is water cooled and the inner grid is made of surgical tubing which is cooled with compressed air.

Typical results to date have been 1.0e6 neutrons per second operating at 40kV and 30 milliamperes of current. We anticipate going to significantly higher currents when we install 6 new dispenser cathodes. Operating at higher voltages will require some modifications to the high voltage grid system. When these modifications are made, we will test operating at maximum power. We will also then have a large enough voltage/current/pressure operating window to test the empirical scaling laws in new plasma regimes.

When we have achieved these parameters in D-D we will then be ready for D-T operation. This will require a hermetically sealed system with a Tritium gettering system to handle the gas.

The major impact of a neutron source of the type we have developed is to cut the time and increase the throughput for nuclear assay of nuclear waste. Potential applications are both for TRU-waste and spent fuel. This technology will help make nuclear assay of waste faster and cheaper. This source potentially has a wide range of applications beyond waste assay that will benefit from real-time assay capability. Other potential applications include landmine detection, high explosive detection, drug detection, SNM detection (nonproliferation), and possibly (in a scaled up version) radioisotope production and neutron tomography. The neutron source we have built is the first actively cooled IEC source constructed. Our double-jacketed design has been incorporated by NASA into a device being constructed at the Marshall space center and it is being considered by groups the University of Illinois, the University of Wisconsin, and Kyoto University. This project has also been a catalyst for new ideas, including one to develop a similar device for fusion power applications. A project incorporating this idea is presently under construction at LANL and is being funded by the DOE Office of Fusion Energy Science. The primary remaining hurdle at present is simultaneous operation at high voltage and high current. Gas handling technologies also need to be included for D-T operation.

4. Research Objectives:

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.

The objective of this project is 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 is an electrostatically confined (IEC) plasma device. The IEC is a symmetric sphere that was originally developed in the 1960s as a possible fusion reactor. It operates as D-T neutron generator. Although it is not likely that this device will scale to fusion reactor levels, previous experiments[1] have demonstrated a neutron yield of 2 x 10^{10} neutrons/second on a table-top device that can be powered from ordinary laboratory circuits (9 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 x 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	25kW

5. Methods and Results:

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 D-T fusion cross section becomes large and the neutron production proceeds.

The IEC concept was initially developed in the 1950s and 1960s by R. L. Hirsch and collaborators. It was originally proposed as a possible plasma fusion energy device. The idea was initially presented to the DOE with a table-top experiment using ordinary office power. That system produced in excess of 10^6 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 2xl0^{10} neutrons per second (in D-T)in the mid 1960s.

The achievement of a total neutron yield of 2x 10^{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 linearly with grid current, and like the fusion cross-section with the voltage. Hirsch also ' found that neutron yield scaled inversely with the fill pressure, to the extent that it could be varied in a static device. This result was very surprising, because the classical reaction rate is proportional to the density squared. The primary reason for this behavior was the plasma collisionality. At high densities 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 Coulomb 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 ion 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 impart angular momentum to the particles that further increases the collision volume (although the plasma fluid must remain at zero total angular momentum).

As density is decreased, the plasma collisionality drops. Ions can accelerate more between collisions and achieve higher energies. 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 (particle-in-cell or PIC), plasma simulation code with atomic physics included. The code results, completed at Los Alamos, have confirmed the underlying dynamics of Hirsch's model.

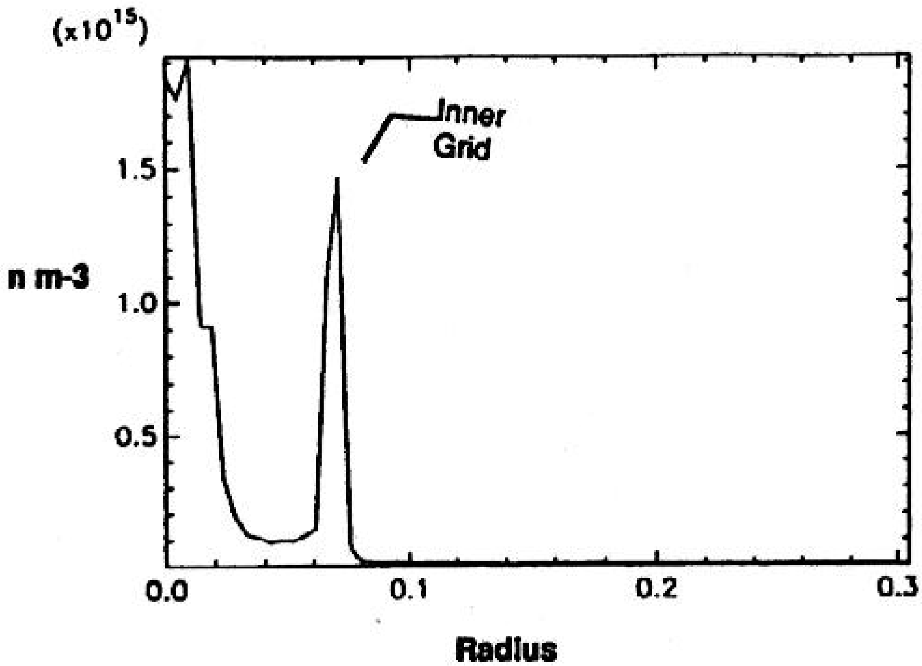

Figure 1: Plasma density profile for a high fill pressure discharge.

Figure 1 shows the steady-state density profile for a high fill density IEC discharge as calculated from a PIC simulation. Note that there is a significant peak in the density near the grid. The ions that are trapped in this region have energies that are less than 15% of the applied voltage. These trapped, low energy particles are a result of the high plasma collisionality. 90% of the total particle inventory is trapped in this region.

Figure 2 shows the steady-state density profile for the analogous low fill density IEC discharge. Note that the peak near the grid is significantly reduced. In this case, roughly 60% of the particles have energies exceeding 30% of the applied voltage. This results in a much more efficient production of fusion neutrons.

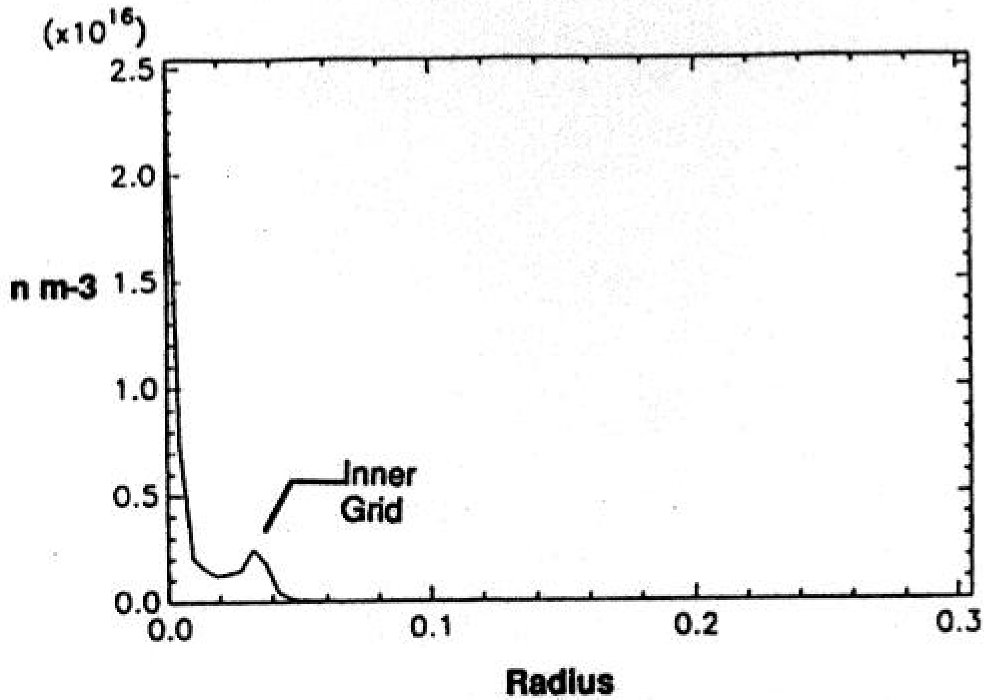

Figure2: Plasma density profile for a low fill pressure discharge.

However, there are practical and physics reasons why reduced fill pressure 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. Typical fill gas pressures have been several millitorr.

The novel approach we have implemented 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, typically 600 volts. Dispenser cathodes around the vacuum chamber wall inject electrons. The electrons are trapped and orbit around the outer grid, ionizing the 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, less collisional 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 3.

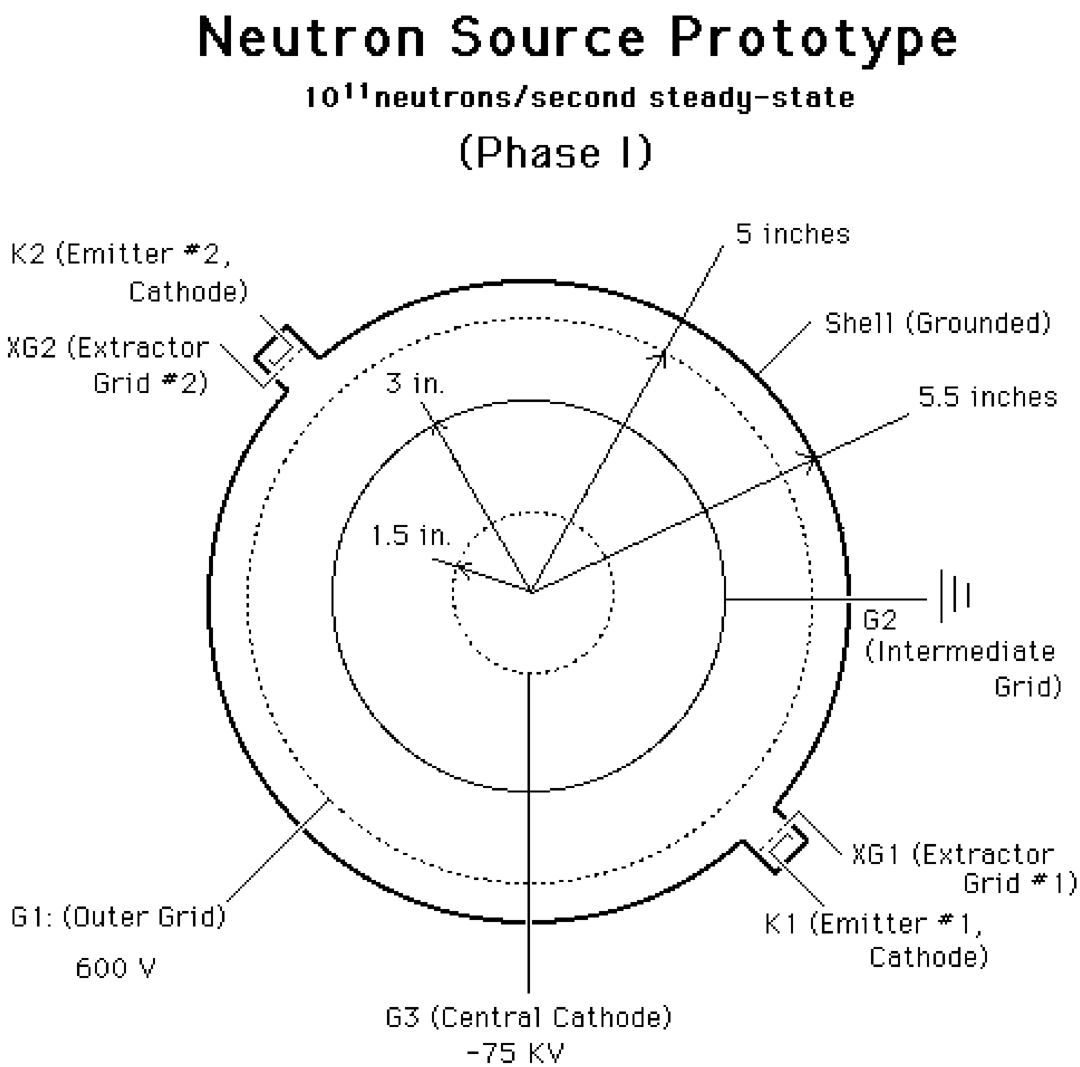

Figure 3: A triple grid IEC schematic.

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. 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 specifications of the kinetic code simulations.

Empirical scaling laws suggest 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 project. 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	6" Diameter	12" 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 25kW.). We believe that the low density, triple grid design affords this opportunity.

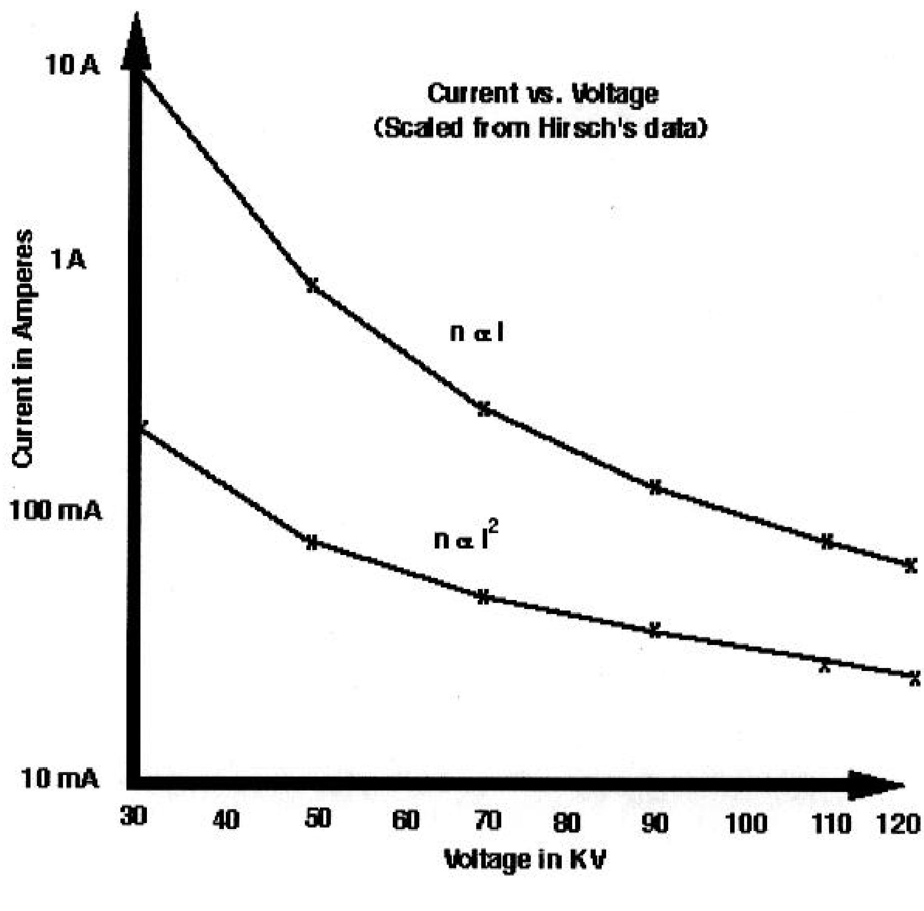

Figure 4: Plasma current and voltage required for neutron yields of 1.0e11

The scientific justification for this extrapolation is predicated on the basic plasma physics established by Hirsch, and subsequently verified. Figure 4 shows the empirical scaling from Hirsch's data for beam-background fusion (linear with current) and beam-beam. fusion (quadratic with current). Note that the desired yields should be achievable even with the pessimistic scaling assumptions.

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 75 kV and 335 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 have pursued the physics experimental program for the IEC. There are four central 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. This has been demonstrated and is routinely achieved.

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 57 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 57kV at present. These experiments continue.

The third challenge is to operate the plasma simultaneously at high voltage and high current. At present we are routinely operating at 40 kV with currents of about 30 milliamperes. Neutron yields of 1.0e6 neutrons/second steady-state have been achieved in D-D at this level. The major challenge presently is to try to increase the current to the 335 milliampere level. In order to achieve this goal, we are upgrading our dispenser cathodes to significantly increase the ionization rates in the plasma. Work is proceeding in this area. High power operation will then be possible which will enable us to test the components under their maximum design conditions. This will also increase our operating window so we can adequately study the scaling of the neutron yield with the current, voltage, and the fill pressure. This will give us sufficient scientific information to proceed with D-T operation.

The final challenge is to operate the plasma with D-T. We have postponed this activity since we feel it is more important to first resolve the electrical/plasma issues before we deal with radioactive gas handling issues.

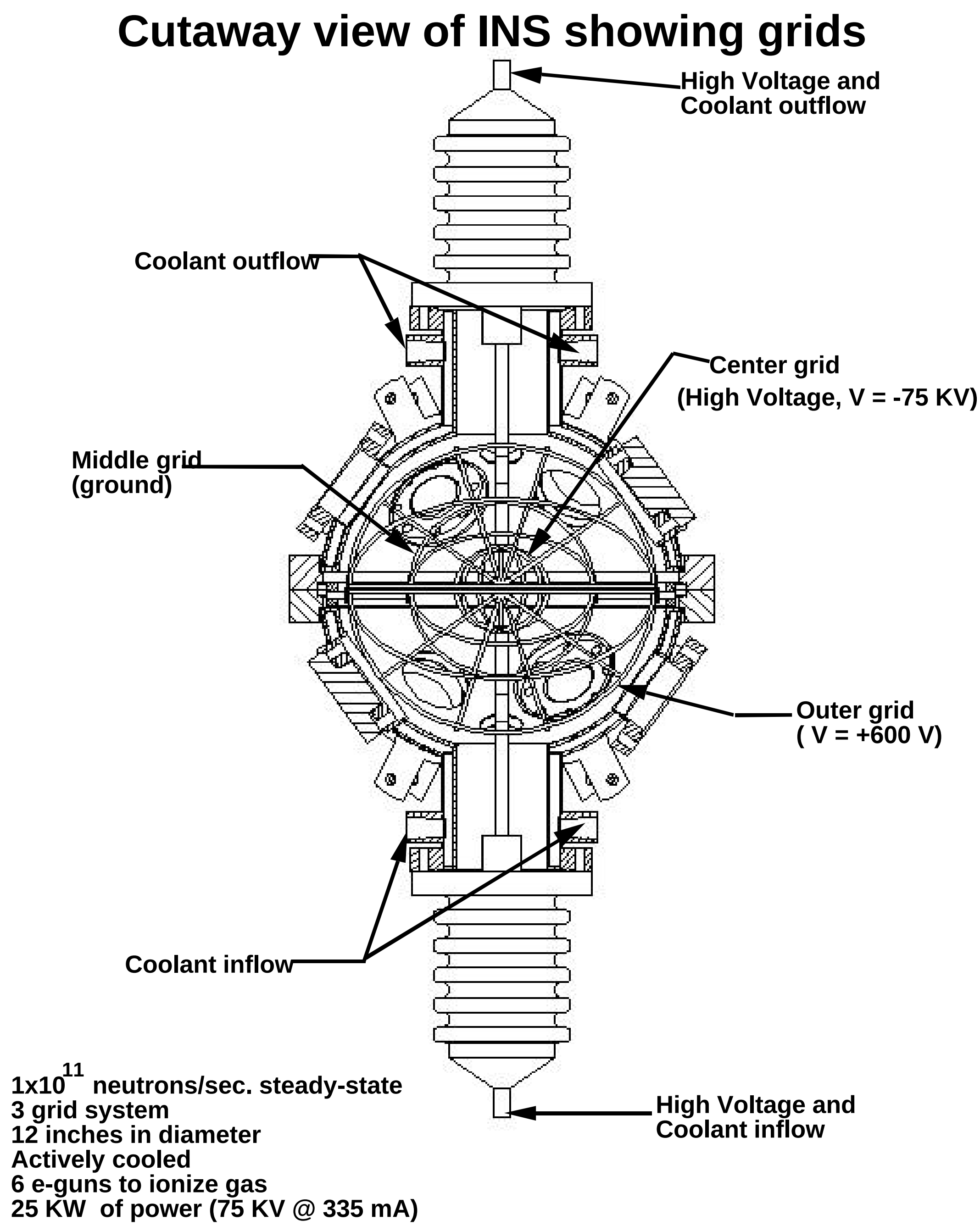

Figure 5: Cutaway view of the IEC vacuum chamber.

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 can 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, 480 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 less than $1x10^{-8}$ tore. 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, 75 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.

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, 480 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 6 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 is easily visible through the viewport.

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 l5kV 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.

Figure 7 is a picture of the fully complete experimental chamber inside the vacuum chamber.

Figure 6.- Picture of the electrical power equipment outside of the shield cell at the location of the IEC experiment.

Figure 7. A picture of the entire system in the hot cell. Power supplies are located outside the hot cell.

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.	To be 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. At present, typical operating conditions are at 40 kV and 30 milliamperes on the central grid. Neutron yields in D-D are about 1.0e6 neutrons per second steady-state. Our upgraded e-gun system should improve these numbers dramatically.

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.

6. Relevance, Impact and Technology Transfer

a. How does this new scientific knowledge focus on critical DOE environmental management problems?

The major impact of a neutron source of the type we have developed is to cut the time and increase the throughput for nuclear assay of nuclear waste. Potential applications are both for TRU-waste and spent fuel.

b. How will the new scientific knowledge that is generated by this project improve technologies and cleanup approaches to significantly reduce future costs, schedules, and risks and meet DOE compliance requirements?

This technology will help make nuclear assay of waste faster and cheaper.

c. To what extent does the new scientific knowledge bridge the gap between broad fundamental research that has wide ranging applications and the timeliness to meet needs-driven applied technology development?

This source potentially has a wide range of applications beyond waste assay that will benefit from real-time assay capability. Other potential applications include landmine detection, high explosive detection, drug detection, SNM detection (nonproliferation), and possibly (in a scaled up version) radioisotope production and neutron tomography.

d. What is the project's impact on individuals, laboratories, departments and institutions? If so, how will they be used, by whom, and when?

The neutron source we have built is the first actively cooled IEC source constructed. Our double-jacketed design has been incorporated by NASA into a device being constructed at the Marshall space center and it is being considered by groups the University of Illinois, the University of Wisconsin, and Kyoto University.

This project has also been a catalyst for new ideas, including one to develop a similar device for fusion power applications. A project incorporating this idea is presently under construction at LANL and is being funded by the DOE Office of Fusion Energy Science.

e. Are larger scale trials warranted? What difference has the project made? Now that the project is complete, what new capacity, equipment or expertise has been developed?

Larger scale trials will be warranted if the neutron yield specifications of the present device can be met. As noted above, work is still continuing in this area. The project has produced an operating neutron source system for NIS-5. Its utility will depend on achieving the high neutron yield goals.

f. How have the scientific capabilities of collaborating scientists been improved?

The principal collaborator in this endeavor was largely a theorist prior to this project, He has now designed, built and operated a fusion device. Plasma experiments are not easy, and he has acquired invaluable practical experience in this area. Also, we have had two Undergraduate Research Assistants who have had the experience of building and operating an experiment. This was also their first exposure to cutting edge scientific research.

g. How has this research advanced our understanding in the area?

To date, this project has served as a springboard for new ideas for high power plasma/fusion-based neutron sources. One of these is mentioned in section 6d.

We also anticipate that we will learn a great deal about the scaling of the device with voltage, current and pressure once we have achieved our higher power operation and the operating parameters window increases significantly.

h. What additional scientific or other hurdles must be overcome before the results of this project can be successfully applied to DOE Environmental Management problems?

The primary remaining hurdle is simultaneous operation at high voltage and high current. Gas handling technologies also need to be included for D-T operation.

i. Have any other government agencies or private enterprises expressed interest in the project?

As mentioned above, OFES has already incorporated some results of this research into their ongoing programs. We anticipate that other parts of DOE will express an interest now that we have an operating facility.

Also, a US-Japan workshop was held in Los Alamos relating to this idea in September 1998. Representatives from Daimler-Chrysler, GammaMetrics and Manfred Frey Physics were in attendance and expressed varying degrees of interest in the concept.

7. Project Productivity:

Funding has been entirely within budget. Each year the funding used has been just what was authorized. There have been no over runs and we do not expect an over run this year as well. The project will be accomplished within budget. The table below summarizes the budget status:

Table 4: Funding Status

Fiscal Year	Requested (k$)	Authorized (k$)	Spent (k$)
97	500	400	400
98	175	175	175
99	175	175	175

There have been significant difficulties with this project, but we believe we have addressed them properly. The authorized funding was below what we requested, which slowed the construction phase somewhat. More significantly, there was a flood in the facility that housed the experiment, that caused a 5 month delay. However, we had been ahead of schedule before the flood so that the total delay was about 3 months.

Another difficulty that was anticipated was the optimization of the high voltages inside the vacuum chamber. It is always a technical challenge to achieve high voltages in a vacuum environment, the voltages typically cause arcing between the electrodes or between the electrodes and the vacuum chamber. We have also experienced these problems. In the original experimental plan we allocated considerable time to the development of the IEC design to minimize arcing. The necessary criterion was that the main accelerating voltage of 75kV could be reached. The process toward achieving full 75kV accelerating voltage has been rather constant. During each reporting period the operating voltage has been raised.

However, it is still not at the full 75kV level. Full output of neutrons will not be achieved until we can operate at the full accelerating voltage.

We were somewhat ahead of schedule when the flood occurred, so that the schedule delay was mitigated. Also, we were able to design and build the IEC device in a very cost effective manner, so that these schedule delays were minimal. The effort required, however, to achieve full operating voltage has taken longer than planned. We have implemented two strategies to deal with this issue:

1. We insured that all other aspects of the IEC operation were fully functional and within the design specifications. For example, we did low voltage tests to insure that we could produce the low density plasma needed for collisionless operation. We were able to successfully achieve the low density operation. Also, we fully checked out and demonstrated the engineering aspects of the system, so that all power and vacuum systems have become fully operational. Therefore, the only remaining challenge to achieving the high neutron output is the accelerating voltage. The other experimental issues were less of a problem, and therefore we insured that they were all fully resolved. Our experimental program is now tightly focussed on the voltage stand off problem.

2. We curtailed the commercialization and engineering design aspects of the project. These did not contribute to the scientific development at all, but were intended to facilitate the follow on activities. Therefore, we reduced unnecessary efforts in order to focus resources on the central scientific problem. In this way we can achieve the fundamental goal of the project without delay and without cost increases.

8. Personnel Supported:

All personnel listed below worked part time on the program:

Richard Nebel, TSM, T- 15, Los Alamos National Laboratory
John Montoya, Machinist, NIS-4, Los Alamos National Laboratory
Guy Eden, Technician, NIS-4, Los Alamos National Laboratory
Robert Bollman, Technician, NIS-4, Los Alamos National Laboratory
Lee Morrison, Designer, NIS-4, Los Alamos National Laboratory
Raymond Jermance, Technician, NIS-DO, Los Alamos National Laboratory

9. Publications

a. Reviewed publications

1. R. A. Nebel, D. C. Barnes, "The Periodically Oscillating Plasma Sphere", Fusion Technology 38, 28 (1998).

2. D. C. Barnes, R. A. Nebel, "Stable, Thermal Equilibrium. Large-Amplitude, Spherical Plasma Oscillations In Electrostatic Confinement Devices", Physics of Plasmas 5, 2498 (1998).

Unreviewed publications

3. R. A. Nebel, D. C. Barnes, R. Bollman, G. Eden, L. Morrison, M. M. Pickrell, W. Reass, "The Los Alamos Intense Neutron Source", Proceedings of 2nd Symposium on CURRENT TRENDS IN INTERNATIONAL FUSION RESEARCH: REVIEW AND ASSESSMENT, Washington, DC March 1997.

4. R. A. Nebel, D. C. Barnes, "The Periodically Oscillating Plasma Sphere", paper 1B-3 presented at 1997 Sherwood Theory Meeting, Madison, WI April 1997.

5. D. C. Barnes, R. A. Nebel, M. M. Schauer, and M. M. Pickrell, "Inertial Electro-Magnetostatic Plasma Neutron Sources", Paper 7EO4, 1997 IEEE International Conference on Plasma Science, May 19-22, 1997, San Diego, CA, p. 319.

6. R. A. Nebel, et. al., "The Los Alamos Intense Neutron Source", Winter ANS meeting, Albuquerque, NM (1997).

7. R. A. Nebel, R. Bollman, G. Eden, J. Montoya, M. M. Pickrell, K. R. Umstadter, "Innovative Energy Sources and Advanced Applications: The Los Alamos Intense Neutron Source", presented at ECOMAP98, Kyoto, Japan, (1998).

8. R. A. Nebel, A. J. Cole, K. R. Umstadter, "The Intense Neutron Source", presented at the 18th IEEE Symposium on Fusion Engineering, Albuquerque, October (1999).

c. Accepted/submitted publications

9. R A. Nebel, J. M. Finn, "Kinetic and Fluid Calculations for the Periodically Oscillating Plasma Sphere", accepted for publication in Physics of Plasmas.

10. Interactions:

Papers have been presented at the following meetings:

1. 1997 Innovative Confinement Concepts Workshop, Monterrey, CA February 1997.
2. 2nd Symposium on CURRENT TRENDS IN INTERNATIONAL FUSION RESEARCH: REVIEW AND ASSESSMENT, Washington, DC March 1997.
3. 1997 Sherwood Theory Meeting, Madison, WI April 1997.
4. 1997 APS-DPP Meeting, Pittsburg, PA November 1997.
5. 1997 Winter ANS meeting, Albuquerque, NM November 1997.
6. 1998 Sherwood Theory Meeting, Atlanta, GA March 1998.

7. 1998 Innovative Confinement Concepts Workshop, Princeton, NJ April 1998.
8. IEC Workshop on Neutron Sources, Los Alamos, NM September 1998.
9. ECOMAP-98, Kyoto, Japan October 1998.
10. 1998 APS-DPP Meeting, New Orleans, LA November 1998.
11. 1998 Sherwood Theory Meeting, Atlanta, GA March 1999.
12. l8th IEEE Symposium on Fusion Engineering, Albuquerque, NM October 1999.
13. 1999 APS-DPP Meeting, Seattle, WA November 1998.

11. Transitions:

So far two government organizations have made use of technologies we have developed:

1. NASA-Marshall has incorporated our double-jacketed shell design into their new IEC
   Contact: Jon Nadler

2. LANL is using our oscillating plasma concept in an Innovative Concept device funded by DOE-OFES.
   Contact: Martin Schauer

12. Patents

none filed for at present.

13. Future Work

As discussed above, there are two major chores remaining. The first is to operate the device at maximum power (voltage and current simultaneously) in order to significantly increase the neutron yield. This should greatly expand the operating parameters window which will allow us to determine scaling with current and voltage, which is the second remaining task. Thirdly, we need to install a sealed gas handling system so we can operate the device with D-T.

We also are formulating plans for an upgraded system that will utilize an oscillating plasma. Theoretical projections indicate that we may be able to achieve yields of 1.e12 neutrons per second with a D-D system. This system would enable us to do neutron tomography.

14. Literature cited:

1. R. L. Hirsch, *J. Appl. Physics* **38**, 4522 (1967).