ADVANCES IN DESIGN OF DRIVEN SUBCRITICAL FISSION REACTOR USING A PLASMA TARGET NEUTRON SOURCE

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Abstract-*A resurgence in use of nuclear power is now underway worldwide. However a number of university research reactors have been shut down. Thus student laboratories must rely more heavily on substitute experiments such as use of sub-critical assemblies. Here a novel driven sub-critical assembly for student laboratory use is proposed that uses a cylindrical Inertial Electrostatic Confinement (IEC) device to provide a fusion neutron source. The IEC allows a variable neutron source rate, greatly extending the range of student experiments possible with this assembly vs. the conventional radioisotope driven sub-critical. The small IEC neutron source would be inserted in a fuel element position, with its power input controlled externally at a control panel. This feature opens the way to use of the critical assembly for a number of transient experiments such as sub-critical pulsing and neutron wave propagation. That in turn adds important new insights and excitement for the student teaching laboratory. Such developments can be considered as a stepping stone towards eventual development of IEC driven subcritical power reactors. Like the accelerator- solid target driven power reactor concepts discussed in recent years, this approach would offer important safety advantages. It would differ from the accelerator version, however, by allowing smaller distributed IEC neutron sources to be inserted into select fuel element channels much as described for the student laboratory devices. This leads to an improved neutron flux distribution and lower system costs.*

I. THE NEED FOR A NEW GENERATION OF SUB-CRITICAL ASSEMBLIES

With the renaissance of nuclear power worldwide, there is a pressing need to revitalize Nuclear Engineering academic programs[1,2]. Laboratory experiments with a fission core represent one of the most basic elements in an effective Nuclear Engineering laboratory. This is true at all levels of experience. For example, Illinois Power Corporation used to send licensed operators to the University of Illinois Urbana-Champaign TRIGA reactor facility to obtain “hands on” experience with a reactor; i.e. to be able to see and move fuel elements, and to perform dynamic experiments like pulsing of the TRIGA. This experience was viewed as an important a supplement to their control room operation of the Clinton Power Plant where regulations greatly limited any non-normal operation. Even in this computerized age of sophisticated reactor simulators, there is no substitute for real “hands on” experiences. This program ceased with the closure of the UIUC TRIGA reactor some years ago. That also marked the end of a reactor laboratory for student experiments and operations training. Now, the main approach to “hands on” experience for Nuclear Engineering students in many universities is via sub-critical assemblies. Such units have been used in teaching labs for many years, but they are often viewed by students as “tedious and boring” experiments. Thus there is an urgent need to develop a next generation of stimulating sub-critical experiments to go along with the program towards Generation IV power reactors[3]. That is the intent of the proposed IEC-driven sub-critical discussed here.

II. THE IEC-DRIVEN SUB-CRITICAL ASSEMBLY CONCEPT

Sub-critical assemblies used in teaching laboratories typically employ a low intensity radioisotope neutron source. This source is usually left in the assembly during experiments and removed for storage in a shielded facility when shut down. Thus the experiments themselves are steady state, although changes in the core configuration, hence flux level, are often done by changing the number and location of fuel elements. Removal/storage of the source is tedious and time consuming as are core rearrangements. Here we propose to use an Inertial Electrostatic Confinement (IEC) neutron source. The IEC is driven electrically, so the source rate can be varied easily, or turned completely off, by simply adjusting the input power. This opens up the possibility of a wide variety of new transient type of experiments. A Radically Converging cylindrical type IEC (RC-IEC) would be inserted into one of the sub-critical element slots to drive the sub-critical assembly. The RC-IEC employs a fairly transparent (>95%) cylindrical grid mounted concentrically inside of a cylindrical vacuum vessel. The grid (cathode) is placed at a large negative potential (typically 20-100 kV) with respect to the vessel. When backfilled with a low-pressure of fusible gas such as deuterium (D) or a deuterium-tritium (D-T) mixture, the high electric field between the grid and wall creates a plasma discharge[4]. The ions formed in this plasma are extracted by the grid potential field and accelerated towards the center of the device. As these ions converge along the center axis, a dense plasma core region forms where a high fusion rate occurs. Thus a line-like neutron source is created extending over the length of the IEC, i.e. over the length of a fuel element.

Such an IEC-driven assembly would mainly be used for the purpose of training. However, if desired, a somewhat higher power design is feasible which could also produce small quantities of radioisotopes for research use.

III. THE IEC CONCEPT

The IEC concept dates back to P. Farnsworth, the inventor of electronic television, and to R. Hirsch[4]. The concept lay dormant for many years, until the early 1990s, when a modified version device was developed at the UIUC. In this device, the ion guns used by Hirsch, were replaced with a grid-produced plasma discharge, operating in an unique "star" mode[5]. In addition to the spherical geometry used in the earlier devices, cylindrical versions were subsequently developed at the UIUC. The latter form the basis for the present line source concept.

In the spherical design, a transparent grid is biased at -60 to -90 kV. Operation is quite similar to that described earlier for the RC-IEC. However in this case, 3D ion focusing occurs. In the high current regime, an electric potential structure develops in the non-neutral in either spherical or an RC-IEC, creating virtual electrodes that further enhance ion containment and re-circulation[4] (Figure 1). Experimental measurements have demonstrated the existence of such potential structures, but at considerably lower currents than those required for higher yields. Potential structure stability could be an issue when high currents are used, although theoretical studies have not identified a problem to date.

Most experiments to date used spherical IEC units. They routinely produce ~10^8 2.54-MeV neutrons/s at steady state due to DD fusion. Pulsed operation has achieved up to 10^9 neutrons/s. This D-D yield is equivalent to 10^{11} n/s if a DT mixture is used under similar conditions, the scaling being proportional to the ratio of the respective fusion cross sections.

Studies of the IEC devices have greatly enhanced the understanding of the plasma discharge physics involved. They have been developed to the point where they offer an attractive low-level neutron source for applications such as a neutron activation analysis (NAA)[6,7]. Indeed, a version of the IEC has been produced commercially as a portable neutron source for industrial NAA applications[7].

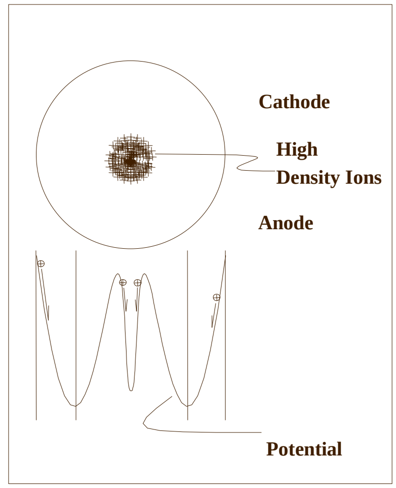

Figure 1. Illustration of the potential structure in the dense plasma core of a spherical IEC. The central "well" traps ions, providing efficient local ion re-circulation.

IV. CYLINDRICAL IEC's

While most IEC research to date has involved spherical devices, cylindrical IECs offer many advantages in a variety of practical applications, including the proposed sub-critical reactor system. Two possible versions of the cylindrical IEC are illustrated in Figure 2. These two cylindrical versions have been studied in the past[8,9]. The cylindrical device, in both of its versions, is advantageous for a wide range of applications that require coverage of a broad area with neutrons. The axial-convergent version is capable of more efficient heat rejection than the gridded spherical or cylindrical RC-IEC units, since rejected heat is carried by the larger area hollow electrodes vs. thin grid wires. However, the RC-IEC has the advantage of allowing uniformity of the neutron source over longer lengths such as desired here for sub-critical use. Since extremely high neutron yields are not required, grid-heating limits are not a problem.

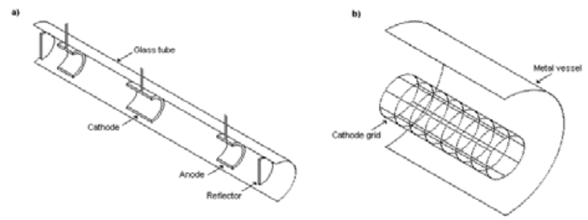

Figure 2: The two versions of the cylindrical IEC: a) axially-convergent ion beams, and b) radially-convergent ion beams (termed RC-IEC here).

The physics of the axially convergent cylindrical IEC version (Figure 2a), called a C-device, is closely related to that of the RC-IEC. The C-device has been studied experimentally more than the RC-IEC. It generates a deuterium (or DT) discharge, forming a beam-like ion flow along the axis in a hollow cathode configuration.

Fuel	UO_2
$^{235}U/^{238}U$ ratio on fuel	0.005
Fuel density (g/cm^3)	10
Moderator material	Graphite
Moderator density (g/cm^3)	1.6
Moderator volume fraction	95%
Multiplication factor	0.99
Diffusion coefficient (cm)	0.975
Absorption cross section (cm^{-1})	0.00265
Radius (cm)	30
Source strength (neutrons/s)	$1x10^9$
Power (W)	1.2

Table 1. Parameters for a graphite-moderated sub-critical assembly.

Then, fusion reactions occur along this beam volume, giving a line-type neutron source. The prototype c-device shown in Figure 3 uses two hollow cylindrical anodes (ground potential) at either end of the unit. A longer, hollow cylindrical cathode in the center of the device is biased to a high negative potential. Deuterium gas introduced at the end of the unit. In addition to experiments, the physics of this discharge has been studied in detail by numerical simulations.[9]

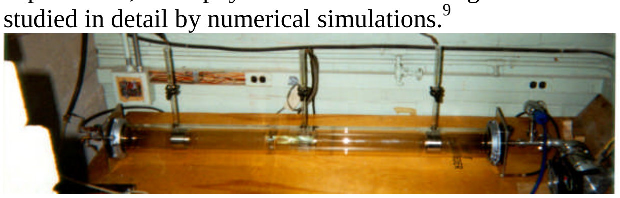

Figure 3: Photograph of the C-Device prototype.

To date, neutron yields of up to 10^8 DD neutrons/sec have been achieved in this device. Equivalent results have also been reported from experiments using a similar device at Kyoto University, Japan[10].

The RC-IEC[11] in Figure 2b forms ion beams in the volume between the grounded wall and the concentric cylindrical grid. Those beams converge in the center. Deuterium gas introduced at the end of the unit is ionized in the resulting discharge, and the ions are accelerated back and forth along the radius of the unit, and they collide and fuse. Thus, fusion occurs in and around the axis of the cylinder, producing a line-like neutron source. The RC-IEC configuration, however, has not been yet tested experimentally for neutron production. Early experiments by Dolan[12] using this design did not employ fusionable gases. While his measurements indicated the predicted performance, more studies of neutron production using a deuterium fill gas are needed to fully qualify the RC-IEC for driving a sub-critical as envisioned here.

The experimental RC-IEC's studied to date have normally had a vacuum station connected to them to permit study of pressure effects. That could be done for the sub-critical unit, or alternately a sealed-off unit, such as developed for commercial NAA applications[6], could be employed. The latter would simplify sub-critical installation, avoiding vacuum tube connections, but would reduce the flexibility of using the IEC in separate dual-use plasma experiments discussed later. The choice between these options will depend on the plans for a specific laboratory and the facilities available. For example, sealed units could be filled with deuterium elsewhere to save the expense of a dedicated vacuum unit. If funds are available, or a small turbo-pump is available in the lab, the vacuum station approach may be desired to increase flexibility.

V. SUB-CRITCAL ASSEMBLY PARAMETERS

An important issue to be resolved for the CRIEC application to driving a sub-critical assembly is the source strength required to achieve a certain assembly neutron flux level. Initial estimates of the source strength required were presented in earlier papers, but there the concept then was to develop a low power reactor facilities as opposed to a teaching sub-critical assembly[11,13].

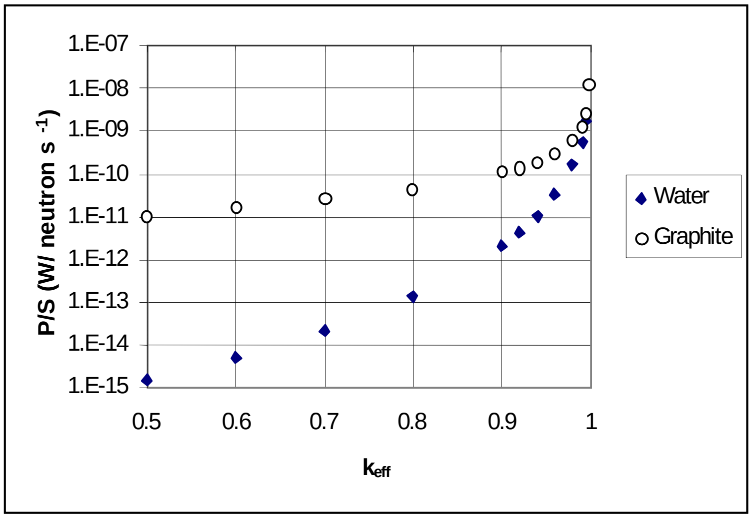

Figure 4: Power level per unit source (P/S) as a function as a function of k_∞ for two different moderators.

Such use would require a much higher neutron source rate IEC design and a radiation hardened system. Thus the present requirements are much easier to meet, and are compatible with existing IEC performance.

Nuclear Engineering laboratories have traditionally used either a graphite moderated sub-critical assembly or a light water moderated assembly. Both are considered here, and it is found that either could be adapted for use as an IEC-driven unit.

Figure 4 presents the power obtained per unit source as a function of the multiplication factor k_∞. The assembly is assumed to be a cylindrical homogeneous reactor, fueled by uranium dioxide. Results for the two different moderators, graphite and water, are presented. The fuel enrichment was adjusted to give the desired value of k_∞, maintaining the fraction of core volume occupied by the fuel fixed at 5%. It is observed from the figure that the graphite-moderated system runs at about 0.1 W of power with a source of 10^9 neutrons/sec when the sub-critical assembly k_{eff} is 0.99. Specifications for that system are summarized in Table 1.

Figure 5 shows the effect of the assembly size on the power per unit source for a value of k_∞=0.95. Observe that the power/neutron source ratio (P/S) remains on the same order of magnitude until a radius is reached. Once the radius increases above that critical value, the P/S begins to decrease dramatically. The graphite-moderated system is less sensitive to variations in size than the water-moderated system.

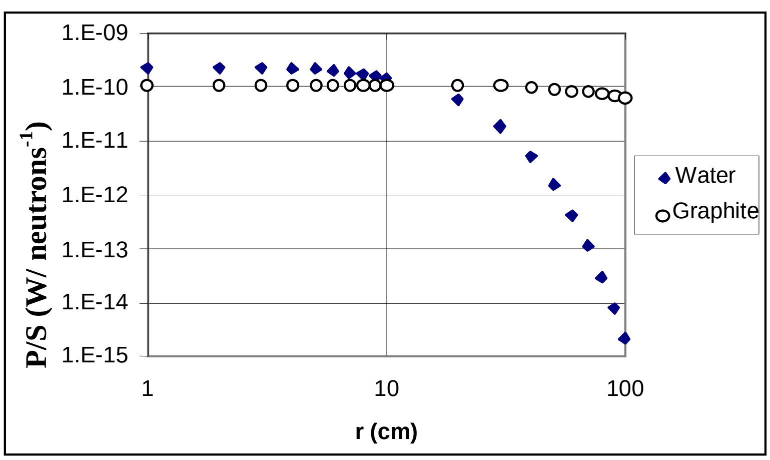

Figure 5. Power level per unit source as a function of the radius of the system for k_∞=0.95. Notice that in the graphite-moderated system, P/S remains fairly constant for systems up to 50 cm in radius.

VI. SUB-CRITICAL EXPERIMENTS

The IEC-driven type sub-critical enables a whole new class of transient experiments and also simplifies some "traditional" steady-state type sub-critical experiments. Some illustrative transient experiments are listed in Table 2. These range from start-up experiments and programmed transients to neutron wave propagation studies.

Since the IEC can be turned off without removing it from the assembly, experiments that require core or fuel rod movements are more easily carried out than with an isotope neutron source. These types of experiments include studies of core reactivity via buckling measurements, approach to criticality by fuel element additions, and foil activation measurements of the flux importance function.

Investment in a second D-T filled RC-IEC (in additions to the "standard" deuterium-filled unit envisioned for most experiments described here), would open the way to a number of advanced physics experiments based on differences between a 14 MeV (D-T) vs. a 2.5 MeV (D-D) neutron source. Such experiments would delve into differences in core leakage, flux profiles, flux importance function, and neutron lifetimes due to the difference in neutron energy.

VII. DUAL USE FACILITY

The main objective of this concept is the development of a versatile sub-critical assembly to provide the student with exciting "hands on" experience with fission reactor dynamics. However, the IEC used in the device is a unique and important example of fusion confinement and fusion dynamics. Thus the IEC could be removed from the sub-critical when it was not in use and studied independently. Such experiments are already employed in various student fusion plasma teaching laboratories.[14] Students can study neutron production as a function of key parameters (voltage, current, and pressure) to gain experience with fusion reaction physics and confinement. They can also do studies of plasma breakdown phenomena, e.g. the Paschen curve, to gain insight into plasma discharge physics. This dual use capability is an added benefit of the IEC driven sub-critical concept, and it makes the added investment in developing an IEC for the teaching laboratory even more attractive.

VIII. CONCLUSIONS

An RC-IEC-driven sub-critical reactor has many attractive features for eventual use in ultra-safe power reactors. However, this application requires significant improvements in IEC neutron rates. An IEC driven-subcritical assembly is proposed here as an alternative to the standard student laboratory type sub-critical assembly. This represents an important near-term application which can capitalize on existing IEC capabilities, This type of assembly opens the way to a variety of transient experiments, which would significantly enhance the student experience in the laboratory. In addition, the RC-IEC source itself can be used in student plasmas experiments, offering a dual use facility.

The basic physics for the RC-IEC neutron source has been demonstrated in various laboratory experiments, and the present units operate at neutron levels needed for sub-critical use. However, some more study would be useful to demonstrate the operation of the RC-IEC design with design specifications (e.g. diameter, length, etc.) corresponding to those needed for use in a sub-critical assembly. Another crucial issue for study involves developing a radiation hardened high voltage system for the power supply.

In addition to the near term enhancement of student laboratories, the experience gained from using these driven sub-critical units can also be viewed as a vital first step towards eventual development of an IEC-driven low power research reactor such as described in Refs. 11 and 13. Such a research reactor has many advantages, especially related to safety, which could help later when the revitalization of university research reactor facilities that are hoped for occurs.

Table 2. Examples of Transient Experiments for use with IEC-Driven Sub-critical Assembly

Experiment	IEC mode of operation	Objective
Sub-critical pulsing	Msec pulse mode	Fast transient physics
Die-away	With power off	Fast scram and delayed neutrons.
Step start up	Programmed steps in power	Start-up and load following
Neutron wave propagation	Sinesodial wave form, 1 – 1000 ms FWHM	Neutron diffusion physics

IX. ACKNOWLEDGMENT

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