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SUBMITTED BY:

Westinghouse Electric Corporation
Astronuclear Laboratory
Pittsburgh 36, Pennsylvania

PREPARED BY:

C.E. Barksdale
E.J. Ney

APPROVED BY:

F.D. Retallick
F.D. Retallick, Manager

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WANL
FLEXIBLE CRITICAL
EXPERIMENT (FCX)
DESIGN REPORT

(Title Unclassified)

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ABSTRACT

Presented herein are the conceptual considerations, both nuclear and mechanical, for the WANL Flexible Critical Experiment (FCX) that would provide an inventory of basic nuclear data required to establish and verify analytical design procedures for nuclear design of NERVA Program reactors.

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WANL FLEXIBLE CRITICAL EXPERIMENT (FCX) DESIGN REPORT

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I. Introduction

The successful development of a particular nuclear reactor requires that nuclear characteristics be well understood in order that design changes or design requirements can be properly assessed. This understanding of nuclear characteristics is best accomplished by performing a series of critical experiments and comparing the experimental results with predictions based upon various analytical models. The goal is the development of an analytical system which can be used with confidence in evaluating reactor nuclear properties.

Several practical problems, whose solutions are particularly important to NERVA nuclear technology, and which are amenable to study by a combined experimental analytical approach are:

1. Critical mass and reactivity worths.
2. Power and flux distributions (gross and intercell).
3. Effect of reflector and shielding materials on power distribution.
4. Neutron spectrum.
5. Kinetic parameters.

A series of carefully designed flexible critical experiments will provide more useful information in evaluating particular theoretical assumptions than would be obtained from other experiments which would be restricted to a particular materials inventory and geometry. Such a series of basic experiments is required in order to verify calculational models rather than rely solely on analytical interpretations.

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In this report are presented:

1. A discussion of nuclear and non-nuclear considerations for a clean flexible critical experiment.
2. A description of a flexible critical assembly.
3. A list of typical experiments that could be performed.

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II. Conclusion

A design description, experimental equipment and program considerations for a nuclear experimental facility that is proposed for the execution of clean, unperturbed critical reactor experiments have been evaluated by WANL. This experiment design is presented as a means of developing basic data that would permit verification of theoretical methods for reactor design. The general ideas of dual critical facility operation, control rod-fuel followers, control system, and operational philosophy have been established at other approved facilities.

III. Discussion

A. FCX Design Considerations

1. General

In order to arrive at a design for the FCX several factors must be considered to achieve the goals that are desired. These basic factors are: Fuel material, basic subassembly, cluster assembly, core assembly and control scheme. These areas must satisfy the following conditions in arriving at optimum design:

- a. Nuclear-wise, the experiment must represent approximately the fuel element matrix of interest in the reactor program to be studied. Specifically, the matrix must be capable of fabrication in the loading range of from 200 mg to 600 mg enriched uranium per centimeter cubed.
- b. The experiment must be subject to interpretation by analytical techniques, that is, structural materials, control techniques and fabrication methods must not introduce unknown factors into the experiment.
- c. The experimental materials and equipment must be purchased and assembled under sound economic considerations.
- d. The experiment must be sufficiently simple to assemble and disassemble, but be rigid enough to satisfy stringent requirements for safety.

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2. Fuel Material

The moderator and structural support of individual elements is set by condition a, above, to be either carbon powder or graphite. The fuel must, by the same criteria, be enriched uranium and preferably in a pyrolytic graphite coated uranium dicarbide form. However, present technology dictates the price of fuel of this type such that it is economically prohibitive. Alternate forms have been considered, such as pure uranium metal foil, metal wire, impregnated graphite or fuel solutions. These have been discarded because of unknown self-shielding characteristics, non-uniform uranium dispersion, due to variation in pore size and structure of graphite and complexity of handling.

Final selection of fuel is the oxide form (either UO_2 or U_3O_8). The question of reactivity perturbation caused by the presence of two atoms of oxygen for each atom of uranium has been evaluated by digital computer codes and the results displayed in Figure 1. It is noted that the reactivity change for UO_2 is of the order of 1% which can be adequately handled in the analysis. Spectral changes caused by the presence of oxygen have been studied, and the effect was found to be negligible.

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FIGURE 1 REACTIVITY CONTRIBUTION DUE TO OXYGEN

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Of importance is the process where fuel and graphite are joined. Copious literature is available on the process from the NERVA program, TREAT program, and commercial power reactor programs. It consists of mixing uranium oxide powder with graphite or carbon powder and thermo-setting resin. The mixture is then pressed or extruded to the desired shape and cured at elevated temperature (250°C) to set the binder. Continued baking at higher temperature (800°C) is required to remove the approximately 1.5 w/o hydrogen due to the thermo-setting binder. Further elevation of temperature is avoided to prevent the formation of UC or UC₂ which reacts with water as $UC + 3H_2O = UO_2 + 3H_2 + CO$ and $UC_2 + 4H_2O = UO_2 + 4H_2 + 2CO$.

This reaction can lead to entrapped hydrogen in the fuel elements in continuously varying amounts which would exhibit itself as an extremely strong reactivity drift. Even without the presence of uranium carbides, care must be taken to limit available moisture to the fuel elements so that absorption processes in the graphite are restricted. In addition, close tolerances on ash or impurities in the original carbon powder must be controlled to limit the amount of chemically bound water in the elements.

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3. Basic Geometry

Having selected the uniformly dispersed uranium oxide in graphite as the fuel material, the next step was to determine the element geometry. The final selection was an element whose geometry is a .750 inch from flat to flat hex with a .363 inch axial hole. This selection offers the following advantages:

- a. It can be made from easily acquired dyes, ovens, baking block molds, and by existing technological production methods.
- b. Void and graphite number densities can be easily varied by inserting rods in the relatively large hole.
- c. Fuel, poison and other worths can be measured by insertion into the hole.
- d. Wires, foils, solid state and chamber type neutron and gamma detectors may easily be inserted into the hole for axial, radial, and spectral distributions.
- e. It can easily be assembled into clusters and then into cylindrical core assemblies for testing.
- f. It contains approximately the desired void fraction, geometry and is interchangeable with program fuel elements.

4. Cluster Design

A cross sectional view of a cluster of seven subassemblies of the selected geometry is shown in Figure 2. An assembly view of the complete cluster is shown in Figure 3. It consists of top and bottom six-pinned aluminum plates with center hole. The center hole is penetrated by an aluminum bolt that screws into the threaded center subassembly. A flange around the center of the bolt holds the aluminum plate against the fuel elements with six pins on the plate penetrating the holes of the six outer elements, thus preventing radial movement of the subassemblies. The bottom bolt terminates as a tapered pin that fits into a drilled support plate of fixed hole pitch design. The top bolt terminates as a finger lifting ring for handling.

5. Core Designs

Core sizes expected to meet the experimental program of section III C of this report have been determined using twelve energy group calculations (Reference 1). The results are shown in Figure 4 along with other cases of interest. Additional core configurations are presently being calculated with consideration given to other core loadings such as 600 mg/cm^3 (smaller critical radii), other void fractions and different reflector materials and thicknesses.

FIGURE 2 FCX CLUSTER CROSS SECTION

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FIGURE 3 FCX CLUSTER ELEVATION

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FIGURE 4 - CORE DESIGNS

<u>Case No.</u>	<u>Fuel (U) Loading in Mg/cm³</u>	<u>Critical Radius in cm</u>	<u>Volume Fraction in % of Volume</u>	<u>Reflector Thickness in cm</u>	<u>Critical Mass in Kg(U)</u>
1.	400	56.6	21.2	0	417
2.	400	45.5	0	0	270
3.	400	45.0	21.2	9.7(C)	264
4.	400	40.0	21.2	14.1(C)	208
5.	400	30.0	21.2	24.9(C)	117
6.	400	40.0	21.2	7.6(Be)	208
7.	400	35.0	21.2	9.7(Be)	160
8.	400	45.0	21.2	5.5(Be)	264
9.	400	35.0	0	6.33(Be)	160
10.	400	40.0	0	3.46(Be)	204

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6. Reactivity Control

The design of the nuclear control schemes was considered in detail to assure that the standards of safety required in a critical operation were not in any way sacrificed for the expediency of time and experimental progress. The guidelines used in arriving at the recommended control scheme are as follows:

- a. Movement of large masses is not desirable. Systems with values above 10 - 15% mass movement would be undesirable since the cost of these systems is high and require an internal perturbing structure.
- b. There should be no more than 15 mechanisms in order to keep maintenance at a minimum.
- c. There should be at least 2% reactivity available in scrammable control to compensate for a 2% maximum credible step increase of reactivity. The rate of reactivity addition near delayed critical must be less than $.075\% \Delta k/k/\text{sec}$.
- d. There should be at least 12% total shutdown reactivity available in order to provide sufficient margin of safety for core and reflector changes, reactivity additions by uranium wires, human and mechanical reflector reactivities and for overnight standby.

- e. The system must be fail-safe and not be capable of inverted reactivity effects.
- f. At delayed critical, the assembly must be clean such that questionable analytical treatment is not required.
- g. The system must be mechanically sound and economical.
- h. Lastly, the system must be 100% dependable in that on signal from electronics, operators or loss of power, the intended shutdown is always achieved.

Having selected the fuel material, subassembly, cluster, core designs and control criteria, consideration was given to the conventional control schemes for thermal, epithermal and fast reactors. The methods studied were: (1) Geometric separation by splitting the core either axially or radially, (2) Geometric separation by removing the reflector or by removing a large central segment of the core, (3) Poison gas or poison solution control, (4) Poison rods, wires, or blades into the central hole or between clusters, and finally, (5) Control rod-fuel followers, enhanced by providing a highly moderated flux trap region inside a poisoned annular region. The latter scheme was selected as the method that most suited items a through h, above.

Control rod studies were made to evaluate the effect of control rod size and position. The selected scheme is shown in Figure 5. The results of rod worth studies for several of the cases are shown in Figure 6.

B. Physical Description of FCX

1. General

The existing scope for the FCX program allows the use of the test cell area described in Reference 2. The area would encompass one quarter of the test cell at the Westinghouse Astronuclear Experimental Facility (WANEF) leaving one quarter for the Pre-assembly Experiment (PAX) for the NERVA Program and one half for preparation, assembly, storage and auxiliary equipment for both activities. (Figure 7.) No modifications to the WANEF are required to initiate the FCX program. Use of existing fuel storage facilities and methods of handling are anticipated. They are described in Reference 2.

The overall site, WANEF facilities, test cell and auxiliary services have been described in detail in Reference 2. The design of electronics, test stand, core and reflector support structure and a mechanical control rod design that satisfied the nuclear requirements of Section III A.6 are discussed below.

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FIGURE 5 CONTROL ROD STUDY MODEL

FIGURE 6 - CONTROL ROD WORTHS

<u>Case Number</u> <u>from Figure 4</u>	<u>Single Central</u> <u>7 Fuel Element Rod</u>	<u>Approx. Total Shutdown</u> <u>for 7 Rods</u> <u>(17.94 cm spacing)</u>
1.	2.59%	14.3%
5.	3.30%	20.0%
2.	3.54%	17.7%

FIGURE 7 WANEF PLAN VIEW

2. Electrical

The console and instrumentation will be the same as that employed in the PAX reactor operations. There is electronics for the safe operation of the reactor, electronics for taking data prior to, during, and after reactor operation, electrical interlock systems for safe operations and maintenance duties, and control panel and position indicating panel for operation of the control rod drives. The main feature will be the ability to operate either of the two reactors (PAX or FCX) in the test cell area from a single console by using a patch board. See Figure 8.

The safety instrumentation required is given in Reference 2, and is considered to be an adequate operational system. Backup or alternate channels are provided to reduce maintenance time and malfunction allowance.

The data collection system will be comprised of recorders, connected to nuclear instrumentation and scalars and associated electronics, used for inverse multiplication plots and to monitor the test cell during assembly and disassembly of a core or an experiment.

FIGURE 8 CRITICAL FACILITY CONTROL DIAGRAM

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Other data collection equipment such as a Packard-Bell 250 Computer for automatic data reduction, nuclear noise measuring equipment, and pulse neutron electronics will be available at WANEF. Special attention will be given to personnel protection from the high radiation leakage cores to be tested. High quality dosimetry along with dependable closed circuit television is provided. Further specialized test equipment will be required, but is not discussed here since it will be a function of the test program which develops as a result of initial experiments and analytical requirements.

3. Test Stand

The test stand for the flexible critical would be designed to give maximum flexibility for accommodation of the reactor assembly. This would incorporate features allowing:

- a. Ease in core assembly.
- b. A simple and safe shutdown method.
- c. Convenience for core maintenance. Ladders and railings would be installed in areas of constant activity.
- d. Servicing of rod drive mechanisms.

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- e. Use of crane for movement of heavy or bulky components in assembly and disassembly.
- f. Convenient access to catwalks.
- g. Major support beams be held to a minimum in the vicinity of the core, thus alleviating the problem of extraneous matter perturbing the reactor experiment.
- h. The test stand will be capable of supporting at least twice the load that is anticipated.
- i. Economic considerations and use of existing facilities and equipment at WANEF.

To meet these criteria, it is felt that a design following that of Figure 9 would be satisfactory. It consists of a 1-1/2 inch aluminum base plate, six feet in diameter and penetrated by numerous holes of spacing such to accommodate the single pins of the closely packed array of seven element clusters. The plate would be beam reinforced for load purposes. It would be placed over an existing 10 foot diameter tank in the test cell. Four vertical 6 inch steel pipes with a 1 inch wall thickness placed just outside the circumference of the 10 foot diameter tank would support the work platform. It is located 4 feet-11 inches above the floor. The top deck, 16 feet-7 inches above the floor,

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FIGURE 9 FCX TEST STAND ELEVATION

supports the rod drive mechanisms. The vertical pipes would also serve as a mounting means for the core radial arms maintaining lateral support. The top of the core support structure will extend through the work platform and will provide additional lateral support for the core.

4. Critical Assemblies

Section III A has described in detail the physical aspects of the subassembly and clusters and Section III C describes the typical core configurations. The adjustment of the void fraction of the core will be carried out by inserting .343 inch carbon rods into the hole of each fuel sub-assembly. The design of the reflectors will follow exactly the core design in that solid .750 inch from flat to flat beryllium and/or graphite hexes will be utilized. They will be 52 inches long and held in clusters of seven in a fashion similar to the fuel cluster. All presently envisioned core assemblies will be of right circular cylinder geometry controlled by the gravity scrambled, flux trap control rods.

5. Control System

The nuclear description of the control rods was discussed previously. The support scheme for a typical rod is

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shown in Figures 9 and 10. It consists of a rod drive motor connected to a pinion gear through a gear reduction system and position indicating selsyn motor. The pinion gear drives a rack onto which the armature of a magnetic clutch is attached. The control rods are withdrawn by lowering the rack and coupling onto the rod by an electromagnet. Scrams are accomplished by de-energizing the magnet and allowing the control rods to fall, by gravity, into the core where they are stopped by a pneumatic shock absorber below the core. The control rod is made of seven subassemblies held to the rack by a transition quick disconnect piece which mates with a steel vertical tie rod that travels the entire length of the fueled region and the poisoned region of the rod. The entire fueled region and polyethylene cadmium region are surrounded by a .053 inch thick stainless steel skin. This assembly is guided in its vertical travel by a stationary .108 inch thick wall aluminum guide tube commencing at the top of the critical assembly, penetrating the core and extending approximately 4.5 feet beneath the core into the steel tank below. Figure 11 and Figure 12 show cross sections through the control rod assemblies at the fueled region and the poisoned region, respectively.

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FIGURE 10 FCX CONTROL ROD - FUEL FOLLOWER ASSEMBLY

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FIGURE 11 FCX CONTROL ROD CROSS SECTION THROUGH FUEL SECTION

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FIGURE 12 FCX CONTROL ROD CROSS SECTION THROUGH FLUX TRAP SECTION

C. FCX Experimental Program

1. Critical Assemblies

A series of measurements will be made on several critical assemblies. The specific geometry for the initial assemblies will be dictated by the programmatic requirements and by the end use as discussed in Reference 3. Typical assemblies that could be studied are:

FCX-1 - This assembly will be a critical unreflected cylindrical configuration of the elements having 400 mg of uranium (enr.)/cc of fueled graphite. The void fraction will be reduced to nearly zero by inserting graphite rods into holes in the hex.

FCX-2 - This will be a cylindrical graphite reflected assembly made up of fuel elements in the central region. The fuel will have a concentration of about 400 mg of uranium (enr.)/cc of fueled graphite and a void fraction of about 21.2%.

FCX-3 - This is a cylindrical unreflected assembly of fuel elements having 600 mg of uranium (enr.)/cc of fueled graphite. Void fraction will be essentially zero.

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FCX-4 - This will be a cylindrical graphite reflected assembly of fuel elements having 600 mg of uranium (enr.)/cc of fueled graphite. Void fraction will be about 21.2%.

FCX-5 - This is a cylindrical graphite reflected assembly which has two zones of different uranium density concentrations. The central region would consist of 600 mg of uranium (enr.)/cc fueled graphite and the outer fueled region would consist of 400 mg of uranium (enr.)/cc fueled graphite.

FCX-6 - This will be a cylindrical graphite reflected assembly in which the inner zone consists of 200 mg of uranium (enr.)/cc of fueled graphite (obtained by alternating 400 mg of uranium (enr.)/cc fuel elements and pure graphite elements) and the outer zone 600 mg of uranium (enr.)/cc fueled graphite.

FCX-7 - This assembly is the same as FCX-5 except that a poison vane would be placed either in the region between the outer fuel zone and the beryllium reflector or inside the beryllium reflector.

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2. Measurements

The nuclear parameters of specific interest have been discussed in detail in Reference 3 and are summarized here. Typical measurements that may be made on each assembly are:

- a. Critical mass.
- b. Measure and calibrate worth of control system.
- c. Power distribution - gross and fine.
- d. Power distribution as a function of hydrogen content.
- e. Bucklings and detailed activation distributions will be measured with several detectors, such as:
 - (1) enriched, (2) depleted uranium, (3) a thermal detector, (4) fission counters, (5) lutetium.
- f. Reactivity coefficients of various core materials.
- g. The prompt neutron lifetime will be measured.
- h. Critical mass as a function of void fraction.
- i. Critical mass as a function of reflector materials.
- j. Critical mass as a function of fuel zoning and core configuration.

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- k. Power distribution as a function of flux suppressor.
- l. Reactivity coefficients of materials in presence of hydrogen.
- m. Kinetic parameters.
- n. Beryllium photoneutron effect on transfer function and inhour equation.
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