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FEASIBILITY REPORT ON
FAST EXPONENTIAL EXPERIMENT

by

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J. J. Livingood, F. H. Martens, and B. I. Spinrad

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SUMMARY

The general program established at Argonne National Laboratory in connection with the Fast Power Breeder Reactor (PBR) includes performance of exponential experiments on assemblies having compositions which may exist in the reactor core. This report deals with that phase of the program known as the Fast Exponential Experiment which may be described very briefly as follows:

An assembly of fissile (U-235) and fertile material (too small to be self-critical) intermixed with poisons (such as are encountered in the mechanical structure and coolant system of a self-sustaining reactor) is fed with neutrons from an auxiliary source. By measurements of the neutron flux within the assembly, important parameters can be calculated which are necessary to the proper design of an actual critical reactor of the same composition.

SCOPE

Purpose of the Fast Exponential Experiment

The fast exponential experiment is planned to study the neutron physics of dilute fast reactors, with the aim of determining to greater precision than can be obtained theoretically the following properties of such reactors:

1. Bare critical masses, as a function of dilution of U-235 with U-238, and mixing of U with Fe and Na.
2. Reflector savings of U, Fe, and Pb on such systems.
3. Effect on the critical mass of local inhomogeneities, in particular, that of lumped fuel and Na channels.
4. Qualitative determinations of spectra.
5. Effect of various suggested control schemes on critical properties.

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Characteristics of Dilute Fast Breeders

Feasible engineering systems for dilute fast reactors are indicated as containing about 50 volume percent sodium as coolant, about 15 percent iron as structural and cladding materials and about 35 percent uranium, the U-238:U-235 ratio varying between 3:1 and 7:1 depending upon the size of core, fuel element design and effect of the reflector.

Since such systems contain no moderator, the neutron spectrum will be in the fast range. The peak in the neutron spectrum is expected to lie between 50 and 500 kev. The mean neutron energy is expected to be lower as the ratio of U-238:U-235 increases, due to increased inelastic scattering and decreased fission in U-238 as against U-235. Hence, the EBR has a faster spectrum than is expected for dilute systems.

The rate of conversion of U-235 to Pu-249 decreases as the neutron energy is lowered, owing to increased radiative capture in U-235. If the lowering of energy is accomplished by dilution, however, some gain is made because fissions in U-238 produce neutrons directly from fertile material. Which of these two effects predominates in dilute fast reactors is not known.

Control of fast reactors is more difficult than for thermal reactors. A much smaller variety of neutron absorbers is available for control rods in the fast range, and their absorbing power is not spectacular. Control and safety mechanisms usually take advantage of decrease in reactivity due to making gaps in the core or reflector systems. New ideas in control rods are required.

Kinetics are similar to those of thermal reactors, the delayed neutrons appearing to be the same. However, reactivities in excess of the delayed neutrons fraction are much more dangerous, since neutron generation times are 100 to 1000 times shorter than for the best moderated thermal reactors.

Types of Experiments to be Performed with the Fast Exponential Assembly

The basic problems of neutron physics of fast reactors are estimation of critical properties and conversion ratios, and evaluation of control schemes. The exponential experiments are designed to answer such questions by making the following specific measurements:

1. Buckling of systems as a function of concentration of core materials, and of core geometry (coolant channels, particularly).
2. Reflector savings, by determining the extrapolation distance of core fluxes into reflectors.
3. Effect on buckling of a lattice of control rods.

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4. Neutron spectra, by activation of threshold fission foils (U-238 and Np-237), $1/v$ foils (Au or In) and, if possible, by direct measurement on beams from the assembly. Determination of neutron spectra allows better prediction of the capture to fission ratio in U-235 and, hence, of conversion ratio.

The bucklings will be measured in the exponential array by activating foils of U-235 and fitting the observed activities to exponential curves in the axial dimension and to cosine curves in the transverse dimensions. The vertical transverse dimension will always be reflected on the bottom by uranium, iron or lead. The shift of the peak flux from the midheight of the assembly is then a measure of the reflector savings.

For control studies, a fraction of the elements of the assembly will be replaced by control materials, as yet unspecified. The observed changes in bucklings can be interpreted in terms of changed critical size.

Besides the spectrum measurements indicated, it will also be possible to estimate the deviation of the spectrum from its equilibrium value in natural uranium. This is obtained by measuring the intensity and duration of "multigroup harmonics" proceeding from the natural uranium pedestal into the assembly, as measured with various detectors.

Significance of the Experiments

It is expected that the experiment will enable materially improved prediction of the properties of the neutron physics of fast reactors. Intermediate design studies require knowledge of desirable fuel concentrations, shape effects, foreign material effects, and control possibility to a precision satisfiable by exponential measurements. In addition, studies on economics may be made with greater assurance.

By using the exponential technique, it is possible to get the results required for this stage in design and exploration with a significantly smaller quantity of enriched material than will be needed for final zero-power tests. Moreover, by using sub-critical assemblies, it is possible to undertake a flexible program of investigation without safety hazard.

Although the experiment is planned to cover a specific design range and obtain immediate information for design purposes, it is also hoped that the coupling of experimental results with reactor-theoretical interpretation will enable at least semi-quantitative results to be obtained for some of the significant reactor parameters: capture cross sections, transport cross sections, inelastic cross sections, and inelastic spectra.

Specific Data to be Obtained

Critical mass predictions, which at the present date can be made to about 25%, are expected to be obtainable, as a result of the exponential

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experiment, to an accuracy of about 5%. To obtain this information, measurements of B^2 (good to $\pm 2 \times 10^{-5} \text{ cm}^{-2}$) will be made as a function of the concentration of U-235, U-238, Fe and Na. Rough measurements will be obtained as to the effect of channels and voids on B^2 .

Cross section data of a semi-quantitative nature will be obtained. It will be possible to demonstrate what materials have large reactivity effects and, for these, approximate cross sections will be obtained from multi-group analysis. For example, it will be possible to show whether Fe and Na affect the spectrum shape or produce absorption or moderation to an amount which is significant, compared to the effects produced by U. For this work, threshold detectors will be used at the center of the core, accurate to $\pm 10\%$, to indicate the fraction of the flux that lies above the threshold, and the low energy flux can be estimated by employing $1/v$ detectors. Similar data on spectrum distribution versus position relative to the reflector will be obtained, good to about $\pm 20\%$.

Reflector savings, accurate to $\pm 1 \text{ cm.}$, will be measured for U, Fe and Pb, if needed.

Productivity and reactivity bonus will be studied as a function of the U-238 to U-235 concentration ratio.

Control rod and foreign body effects on the flux can be evaluated roughly.

The spectrum shape possibly may be studied by methods of low precision but of high resolution. For this work, the possibility will be investigated of using photographic plates, loaded with small specks of Li-bearing glass; from the observed momenta of the disintegration products in the reaction $\text{Li}^6 (n, \alpha) \text{H}^3$, the value of the neutron energy may be computed. The question of the feasibility of this technique, for photographic plates embedded in the lattice, lies in the strong background of tracks due to gamma rays and recoil protons. The possibility also exists of employing a Wilson chamber or ordinary nuclear plates to determine neutron energy from the proton recoils, using a collimated beams of neutrons from the core of the experiment.

A Snell experiment will be performed; that is, an exponential experiment in natural uranium.

Range in Composition to be Covered

The range in volume percent of the constituents of the Power Breeder Reactor are expected to fall within these limits:

U	20 to 35 percent
Fe	12 to 20 percent
Na	65 to 45 percent
U-238/U-235	7:1 to 3:1.

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A program designed to study the behavior of a lattice with these variables would entail 27 different combinations if only the maximum, median and minimum values of each were considered. Even this would be a very formidable task. In the interest of economy of time and effort, it seems reasonable to plan to omit the median values, which reduces the number of combinations to 8. If experience suggests the desirability, a larger number can be investigated; an intermediate U-238/U-235 ratio of 5:1 appears to be a likely first candidate.

Three varieties of reflector material (natural U, Pb and Fe) will be used with at least one of the above combinations, and with more than one if experiment or theory dictates the desirability.

The following list gives (in round numbers) the 8 combinations which are planned for initial investigation.

<u>U-238</u> <u>U-235</u>	U	Volume Percent Fe	Na
3 and 7	21	12	67
3 and 7	21	20	59
3 and 7	35	10	55
3 and 7	35	20	45

Important Information Which Cannot Be Obtained

It is desirable to bring to notice the fact that certain significant data cannot be obtained by an exponential experiment. For example:

1. Direct values of microscopic cross sections will not be found; at best, only the effective average cross sections over rather wide energy groups will be determined.
2. High precision in estimates of conversion gain will not be given. The rather crude expected measurements of the spectrum can improve the conversion gain estimates only within the limits imposed by the accuracy of measurements on α and ν obtained from other types of experiments.
3. The effectiveness of control elements will not be obtained to great precision, nor will any estimates of statistical weights on an operating pile be possible.
4. Detailed flux behavior, adequate for heat transfer analysis, will not be determined.

Reason for Building the Exponential Assembly with a One-Sided Reflector

In designing the source pile mechanism, safety and convenience are obtained by inserting control mechanisms from the top of the source reactor.

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In order to maintain this arrangement, it is necessary to perform the exponential experiment, using a small pile such as ZPR-I as a source, in such a way as to utilize neutrons flowing out of either the bottom or sides of the source pile. The bottom not being again easily accessible, a horizontal exponential experiment is indicated.

In performing such a horizontal experiment, it is necessary to keep ceiling, walls, and floor remote from a bare assembly, so as to minimize the effect of the reflection of neutrons by room structure. This can be accomplished on the two sides of the assembly and on the end remote from the source pile by centering the assembly in a large room. The room is high enough so that the ceiling offers no difficulty. The height of the assembly above the floor is dictated by mechanical and experimental convenience; it is difficult to get a good design which allows the assembly and the source reactor to be supported midway between floor and ceiling.

We are, therefore, faced with the situation that no way exists to prevent floor scattering without much trouble and money. However, the contemplated assembly is high enough so that measurement of the vertical buckling, even with floor scattering, can be made, so long as the effect of the floor is geometrically simple and standard. This may be accomplished by reflecting the underside of the assembly with a quantity of reflector sufficient nearly to give to the assembly the reflector savings of an infinite reflector. This quantity is estimated as one foot of reflector. Buckling measurements in the vertical direction are thereby useful only for that part (crudely the top half of the assembly) where the flux distribution is part of a standard cosine curve. This measurement gives additional information about reflector savings of the reflector as well, inasmuch as the displacement of the maximum of the cosine curve from the center of the assembly is a measure of the reflector savings.

Required Size of the Exponential Assembly

For the concentrations of materials involved in the experiment, the spectrum appears to be appreciably different from the equilibrium spectrum in natural U. As a consequence, multigroup harmonics will appear in the neutron distribution function near the U pedestal, and also near the reflector. It is estimated that these harmonics will decay, relative to the fundamental mode on which buckling measurements will be made, in a distance of about 20 cm from pedestal or reflector. In order to get good buckling measurements, there should be at least one more relaxation length in each dimension; a typical value of κ is estimated as 0.05, indicating at least 20 cm more of experiment. In case it is necessary to back away further from the pedestal or reflector or in case room scattering is significant, it seems reasonable to specify an extra 20 cm of assembly.

Hence, in the two dimensions perpendicular to the U slabs (the reflector and pedestal), a core dimension of 60 cm is indicated. In the third dimension, 30 cm is barely adequate to obtain a flux traverse over a region

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unperturbed by source neutron shine or wall scattering, and 60 cm is certainly adequate. A variable third dimension, therefore, has been specified which will permit the proposed U-238:U-235 dilution range (3:1 to 7:1) to be covered by using a constant amount of U-235 and a constant U:Na:Fe ratio; the limits of this variation are 30 cm for the 3:1 ratio, and 60 cm for the 7:1 ratio.

If the volume of U runs around 35%, then in the latter case, the volume of U is $60 \times 60 \times 60 \times 0.35 = 75,600$ cc. of which $1/8$ or 9450 cc is U-235. The weight of this volume of U-235 runs to about 180 kg.

Duration of the Experiment

If fuel is made available during the early fall of 1953, some significant results will have been obtained by the winter of 1954-55.

Location of the Experiment

The fast exponential experiment will be performed in Building 316 of the Argonne National Laboratory's DuPage site. This is the same building which has been used for Zero Power Reactors I and II. The experiment will be performed in the same cell as was used for ZPR-I.

GENERAL DESCRIPTION OF THE EXPERIMENT

The experiment will consist of two weakly interacting nuclear systems: a source pile of U-235 moderated with H_2O to provide neutrons to the exponential assembly, and the assembly itself. Between the two systems is located a slab of uranium of such a thickness that thermal and resonance neutrons from the source pile are absorbed before reaching the assembly, and such that the most reactive assembly does not greatly affect the reactivity of the source pile. By analogy with previous vertical exponential assemblies, this insulating uranium slab will be referred to as the pedestal.

The experimental set-up is shown semi-schematically in Figures 1, 2 and 3. The plan and elevation show the location of the experiment in the ZPR-I (or East) assembly room of Building 316 and in some detail the components. The $12'' \times 18'' \times 24''$ thermal pile source is located against the face of a steel tank of square cross section. Outside the tank against the same face is the natural uranium converter-stabilizer (pedestal). In operating position, the $24''$ cube (maximum) exponential pile resting on a $24'' \times 24'' \times 12''$ natural uranium reflector is run against the pedestal by a lead screw arrangement or may be moved back 2 feet for loading. Along the centerline of the experiment and retained at maximum distance during operation is the iron personnel shield which can be run up remotely on tracks to surround the exponential pile on three sides, before approach. The entire system is skewed so that the experiment is aimed at the thin rear door of the cell. The control rod drives on their support structure are located above the source pile.

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Source Reactor

The ZPR-I reactor will be adapted to act as the source pile for the exponential experiment. A detailed description of this reactor may be found in ANL-4684. The alterations contemplated are the following:

1. Relocation of the supporting frame within the assembly room so that the exponential assembly will be at the center of the room with the "open" end pointing towards the large door. This will allow sufficient clearance so that scattering of neutrons from the walls will be insignificant. Such a move will involve minor alterations in the water lines from the reactor to the water pumping and storage system, which in other respects can be used in its present form.
2. Construction of a rectangular steel tank for the reactor vessel; this will supplant the cylindrical plastic tank now in use since this latter does not afford appropriate geometry. The new tank will be big enough to interpose a large mass of water between the source and the operating console (already behind a 3 feet thick concrete wall) and to contain, in addition, a new wall of lead bricks for gamma ray protection.
3. Construction of a new core, using MTR type metallic fuel plates with a content of about 3.3 kg of U-235. It has been determined by experiment that the original fuel elements (U-235 oxide embedded in plastic strips) will not withstand the embrittlement associated with damage due to fission fragments and gamma rays at the higher fluxes required for the proposed work.

The present control rod mechanisms, monitoring and scram circuits can be taken over as they stand, except for minor modifications to make them more adapted to the new source which it is desired to keep less flexible than ZPR-I. Once the new source has been brought to the necessary criticality, sleeves will be placed over the control rod cables so that the reactivity that can be introduced will be fixed, and the day by day operation of the pile can be performed by personnel less highly trained than are employed at present, when almost every run involves a new lattice structure.

Power of Source Reactor

It has been determined that a minimum flux of 10^7 will be required to obtain good measurements in the exponential assembly, using U-238 foils as detectors. A factor of 100 in activity will be expected over the experimental volume, hence, the hottest spot to be measured will require a flux of 10^9 neutrons/cm² sec. It is further assumed that the spectrum harmonics will have decayed to an insignificant amount relative to the fundamental spectrum, when the fundamental spectrum itself has decayed by a factor of 10. As a result, the flux at the interface between the exponential assembly and the uranium pedestal will be 10^{10} . It has been calculated that to obtain this flux the power in the core will be 2400 watts, and this calculation is believed to be correct to within a factor of 2.

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Consideration of reflector savings versus thickness of the U reflector (pedestal) and reflector savings of the water on the other five sides of the core, indicate that the critical mass will be 3.3 kg of U-235. It is believed that this is a reasonable estimate inasmuch as the critical masses of water-reflected piles of the same type have been measured and found to be around 3.3 kg. However, a somewhat greater mass may actually be needed, due to deviation of core shape from the optimum.

Although for most of the contemplated measurements the source power will be considerably less than 2400 watts, there is the possibility that some experiments may require operation at several times this power for short intervals. It is certain that a 10-kilowatt power level will not be exceeded.

Source Reactor Tank

The source reactor will be contained in a steel tank four feet square by 5 feet high, and will sit on the existing 1-1/8" thick base plate. The water dump and fill line will be a 6-inch pipe entering the tank at the bottom, through an existing hole in the base plate. An inverted well for the Po-Be neutron source will extend 6" into the tank from the bottom, through a 2" opening in the base plate. The cover will be a light plate which may be permanently secured after the source core is built. A hooded air vent will allow transfer of air on filling or dumping.

Fuel Elements for Source Reactor

The core will consist of MTR type plates in BORAX type assemblies. It is estimated that 210 plates will be required, plus 10 additional plates for adjusting criticality. Each assembly of 10 plates contains 157 grams and each plate 15.7 grams for a total requirement of about 3.5 kilograms of U-235. The meat is to be the same uranium-aluminum alloy currently in use in BORAX: 25 mils thick. The aluminum clad on each side is to be 17.5 mils. The extra plates are to be narrower than regulation plates to allow insertion in vacant slots. There will be 6 assemblies having 6 vacant slots in each. The assemblies will differ from the BORAX type in that the lower adapters will be omitted.

Burn-Up of Source Reactor Fuel

The burn-up of source fuel is estimated at a maximum of 0.07 grams of U-235 or 0.002 percent, based on 5 kw operation for 1 hour per day, 5 days a week for 15 months.

Location of Source Core

The source core will be adjacent to and centered on the side of the source tank. The core assemblies will be arranged in an array of 6 assemblies wide by 4 assemblies deep so that the nominal "active" dimensions

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will be 18 inches wide, 12 inches deep, and 24 inches high. The number of plates is nominally 10 per assembly but will be adjustable to attain the desired reactivity. After adjusting the core, it will be rendered inaccessible by a cover over the tank.

Within the source tank, a lead gamma-ray shield 6 inches thick will be stacked immediately around the core, on its sides and back, to serve also as a reflector. The pedestal will be built up next to the core outside the tank.

The core assemblies will be permanently fixed in the source tank, with an Al grid mounted below them, with the assemblies clamped at their upper ends to the sides of the tank.

Source Reactor Control and Safety Rods

There will be at least two safety rods and one control rod, providing more than 1.5% shutdown. It is planned to use ZPR-I blade control rods for safeties and one blade of adjusted strength as control. All drop in on scram. After the final core is assembled, the rod cables will be surrounded by aluminum ducts to make them inaccessible without disassembly, using the equipment now in use in ZPR-I for the same purpose.

The safety rods will be located in interstices between fuel elements, while the control rod will be located in an empty fuel position. The location of these rods will be chosen so that complete insertion of the control rod will remove about 0.5% reactivity from the system, and complete insertion of the safety rods will remove at least 1.5% reactivity. The safety rods are to be out of the pile, poised to drop, when the pile is operating. The motors and mechanisms for these rods will be those now in use in ZPR-I. They consist of drums powered by gear motors through an electromagnetic clutch. The drums are mounted on ball bearings and are free to rotate on the shaft when the clutch is de-energized, automatically at scram or power failure, or at will by the operator. The blades are mounted to the drum through flexible steel cables which unwind as the blades drop. When near the bottom of its travel, the rod is decelerated smoothly, and comes to rest fully inserted. The drive motors are 1/20 hp, operating from a 90-volt DC power supply. The gear drive allows a maximum withdrawal of 60 cm per minute; interlocks allow only one rod at a time to be withdrawn at this speed.

Primary Neutron Source

The present ZPR-I type of neutron source and drive will be used. The source will be Po-Be of 20 to 40 curies, producing about 10^8 neutrons per second. It is located below the source core near the southeast corner of the core, and may be driven up into the inverted source well to within about 1 cm of the bottom, or dropped into an oil-filled floor well to a depth

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of 100 cm. The source is mounted at the end of a rod set in an elevator which moves vertically on linear ball bearings along two parallel rods. The elevator is cable-operated by a gear motor.

Instrumentation for the Source Reactor

The instruments to be used on the source pile are all in present use on ZPR-I.

Three neutron detectors and two gamma ray detectors will be used as operating instruments.

One of the neutron-operated devices will be a pile period meter, driven by a $B^{10}F_3$ -filled neutron detector. This has a range of 6 decades and will operate from approximately 0.005 watt up to 5 kilowatts (the probable maximum planned operating level). A trip circuit will scram the pile whenever the period is less than a pre-determined value, say 5 seconds. No range changes are necessary and the period is given directly, so that this is an extremely useful instrument, even though it is not as sensitive as some of the other devices. (The trip circuit does not take hold until the pile is up to perhaps 0.1 watt.)

Two other neutron detectors employ $B^{10}F_3$ detectors working into vibrating reed electrometers, with the outputs fed into Brown recorders. A pre-set trip is connected to one of these circuits, and a differential power level device to the other. The over-all time for the latter, from a step function input until the control rods start to fall, is approximately 0.32 second. Although this is not an extremely fast safety circuit, the pre-set level will not be more than ten times the operating level of the pile, and this level will be reached before the higher levels are attained at which some of the faster trip circuits will operate.

The first gamma ray detector will be a high pressure argon chamber working on a D.C. amplifier with a pre-set circuit, the over-all time for this to operate varying from 0.051 to approximately 0.026 second, depending on the value of the input resistor. This device has an extremely wide range and by proper choice of the position of the argon chamber and of the value of the input resistor, it will indicate the gamma flux level from the very lowest, (with the source up and the pile sub-critical) to the highest at which the pile will be operated.

The second gamma detector will be a scintillation detector with photo-multiplier tube and an extremely fast trip circuit; the delay between the input step function and the start of the fall of the control rods is 0.020 second. This instrument is used solely as a safety monitor and will be adjusted empirically to trip at the maximum permissible level of the pile, after preliminary settings at lower levels.

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These five instruments, incorporating four trip circuits, will be sufficient for operation. Any two of them should be adequate to indicate flux level for operation and three trip circuits should be available at all times.

For start up, there will be two proportional counters available for multiplication measurements. An audio pulse monitor or "popper" will be connected to one.

Source Reactor Water System

The present ZPR-I dump tank and pumping system is retained. The dump will operate on hand scram during initial testing (but not when the door to the control room is opened); after the reactor is buttoned up, the tank will be kept full so that advantage may be taken of the additional shielding. The reactor tank will contain about 600 gallons of water; at 5 kilowatts, the temperature rise will be about 2 degrees C per hour (neglecting heat losses), creating a density change of 0.005 percent; this will have a negligible (though negative) effect on the reactivity.

Pedestal

The thickness of the pedestal is determined by several factors. It must be great enough to allow conversion from slow to fast neutrons and yet not so great as to reduce the flux in the exponential assembly to an uncomfortably low level. It must also afford some buffering action, so that the reactivity of the source reactor is not too greatly affected by the size and composition of the exponential array.

It is felt that the latter should not exceed one half a critical mass, not only from safety considerations, but also to ensure that the flux show a reasonably exponential drop. It is also desired that the compound system of source, pedestal and assembly should not have a reactivity greater than 0.5%.

The pedestal will be built up of 2" x 3" x 6" bricks of natural uranium, with dimensions and surfaces precise enough to assure good stacking. It will be assembled on a sturdy iron table to a height of 3 feet and a width of 2 feet, so as to be flush with the source tank wall. The thickness will be adjusted by an initial loading experiment to a value such that the further addition of a semi-infinite slab of natural uranium would increase the pile activity by 0.15%.

It can be shown (as is demonstrated in the Safeguard Report) that the excess reactivity which can be added by a perfect reflector beyond the pedestal (such as an exponential assembly of one-half critical mass) will be about 3 times the amount added by an infinite mass of uranium. Hence, if this latter quantity is set at 0.15 percent, as chosen above, then a half

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critical assembly can add only 0.45%; this amount is controllable by the 0.5% control rod, or if the latter and the safety rods should fail, the runaway period would be large enough so that heat transfer from the source fuel rods to the water moderator would be sufficient to stop the reaction due to decreased moderator density.

It is expected that the exponential assemblies to be used will be of considerably less than a half critical mass.

After this loading experiment has been completed, and after an exponential experiment on a 2-foot cube of natural uranium (Snell experiment) has been run, the pedestal will be rebuilt to the nearest inch in excess of the required thickness and buttoned up. This buttoning up is accomplished by placing a 1/8" iron plate around the pedestal and bolting it to the source tank. The bricks of the pedestal are thereby restrained from shifting.

Exponential Assembly

The exponential assembly will be a group of 32 to 64 rectangular iron boxes ("fuel cans"), 3" x 3" x 24", into each of which may be placed a number of plates of fuel, plates of natural uranium and plates of iron, the voids to be filled with sodium. Alternate proportions of fissile, fertile, structural and cooling materials will be obtained by melting out the sodium and reassembling in the desired manner. Reasons for the choice of these dimensions are set forth in a later section of this report.

A maximum number of 64 fuel cans will be used, (for the 7:1 ratio of U-238 to U-235), forming a cubical assembly 2 feet on a side. There will then average 7.5 fuel plates in each box, containing at the most a total of 180 kg of U-235.

The minimum number of fuel cans used will be 32, arrayed to form a parallelepiped 2 feet by 2 feet by 1 foot (for the 3:1 ratio of U-238 to U-235). Each box will then contain, at most, 15 fuel plates, again totalling 180 kg of U-235.

For the intermediate dilution (5:1 ratio of U-238 to U-235), 48 fuel cans will be used in an array 2' x 2' x 18", each can holding, at most, 10 fuel plates, for a total of 180 kg of U-235.

The exponential assembly of loaded iron boxes will be mounted on a reflector 1 foot thick composed of either natural U, Fe or Pb, means being supplied to keep the array of boxes stable. This complex of reflector and assembly will ride on a truck which can be advanced (by remote control) until one side is in contact with the pedestal.

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Fuel Plates for Exponential Assembly

Since the minimum value of U-238 to U-235 ratio contemplated in the PBR is 3 to 1, there appears to be no need to use fuel plates in the exponential experiment containing a larger proportion of U-235, and there are very cogent safety arguments not to do so. It is proposed, therefore, that the fuel plates, which must necessarily be handled a large number of times, shall consist of 1 part U-235 and 3 parts U-238. Such plates may be fabricated from uranium metal enriched 25% in the U-235 isotope.

The 25% enrichment will provide a system in which dilutions of 3:1, 5:1, and 7:1 can be studied by interchanging partially enriched and natural plates. The arrangement of plates for these three dilutions is shown in Figure 4. The partially enriched plates are distinguished from the natural plates by an aluminum rivet located 1/4 inch above the center of the plate and projecting 0.10 inches from it on one side. This rivet also restricts inadvertent packing without spacers of U-235-containing plates to a maximum of 22 plates in a back-to-back arrangement. For further check identification after loading, the natural plates have 1/8 inch deep saw-cuts at the center of each end.

The Na range calls for percentage of Na between 45 and 65. If the basic design has something slightly less than 45, higher Na content can be realized by removing uranium plates. To keep the Na in range for the 3:1 dilution with minimum iron content, the 180 kg of U-235 will allow only 1/2 the pile to be loaded so that an assembly 12" wide, 24" long, and 24" high can be made by a 4 x 8 array of boxes. Fifteen plates per box are chosen, since for the 5:1 enrichment, increase of Na requires removal of U plates in groups of 3. A smaller number of plates (say 12 or 9) per box makes the percent change in Na too great on removal of 3 plates. A larger number of plates makes the plate thickness uncomfortably thin. The resulting arrangement has the disadvantage of requiring a loading of 7 and 8 enriched plates in adjacent boxes for the 7:1 dilution. Clearance between plate edge and box has been set at a minimum of 12 mils each edge. For the 15 plate arrangement then, and a uranium density of 18.5, the plate sizes and numbers are:

	Number Required	Thickness Inches	Length Inches	Width Inches	Est. U ²³⁵ Content, Grams/Plate	U ²³⁸ Content, Grams/Plate	Total U ²³⁵ kg	Total U ²³⁸ kg
Enriched 25%	480	0.076	24.00	2.72	375	1125	180.0	540
Natural	480	0.076	24.00	2.72	11	1489	5.3	715
							185.3	1255

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These plates may be given a nickel flash of a half mil after fabrication to reduce oxidation, bulk dusting, spread of activity, background, and isotopic mixing. Alternate schemes include the use of rust-inhibiting chemicals ("Dichan"), a thin oil film, or dehumidification of storage areas.

If the procurement of 25% enriched metal is not possible, a less desirable and more restrictive alternative is suggested using combinations of fully enriched and natural metal.

One might construct a "sandwich" of fully enriched (~~93.5%~~) and natural U plates, riveted together, but this suffers from the disadvantage that it would be extremely difficult to remove, from the narrow space between the plates, the NaOH which will form during the cleansing procedure following a redistribution of fuel and diluents. To bolt the plates together, so that they can be separated for cleaning, reintroduces the hazard of fully enriched plates lying about. Hence, the "picket fence" fuel plate is suggested: three strips of uranium, side by side, two of natural uranium and one of fully enriched uranium, riveted at top and bottom to cross strips of Fe, the rivet head projecting 0.10 inch from the plate surfaces (Figure 5). The length and thickness of all the strips will be the same, but the width of the enriched strip will be less than that of the natural U strips, both to obtain a 3:1 ratio of U-238 to U-235 in each unit and as a means of identification. 160 of the units will be built with the enriched strip lying between the natural pieces, and 320 units will have a natural strip in the center, so that the units may be disposed in a box with the U-235 positioned at the left, center, right, etc., to obtain greater homogeneity.

Gaps will be left between the pickets to facilitate removal of Na and NaOH; the amount of these materials trapped between the plates and the cross arms will be negligible.

The plate line up for this arrangement is as following (assuming a density of 18):

	Number Required	Thickness Inches	Length Inches	Width Inches	Est. U ²³⁵ Content Grams/Plate	U ²³⁸ Content Grams/Plate	Total U ²³⁵ kg	Total U ²³⁸ kg
Enriched 93.5%	480	.081	24.00	0.68	365	25	175.2	12
Natural	960	.081	24.00	0.96	5	545	4.8	524
Natural	480	.075	24.00	2.82	11	1489	5.3	715
							185.3	1251

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This alternate scheme of fabricating the fuel plates from fully enriched and natural uranium strips has a number of tangible disadvantages in comparison to the use of 25% enriched plates:

1. The batch size which can be handled during casting and rolling will be limited to 2 kg; as a result, the ratio of intermediate scrap to finished material will be high and the production rate will be low.
2. The drilling and riveting is increased by a factor of 8.
3. Three times as many plates must be made.
4. The procedures for handling, cleaning and assembling in the fuel cans become more difficult.
5. The minimum iron content of the exponential assembly is increased about 1 percent.
6. The homogeneity of the structure will be about one-half that obtained with the 25% enriched fuel. The effect of this inhomogeneity on the accuracy of the results cannot be stated with precision. An additional inhomogeneity arising from the accumulation of iron (the cross straps) near the top and bottom of each assembly adds a further uncertainty.
7. There is a substantial increase in the criticality hazard during the assembly process, before the 480 U-235 and 960 natural uranium strips are riveted together into 480 groups of three.

Fuel Cans

The fuel cans will have nominal external dimensions of 3" x 3" by 2". The exact size is determined by the width of the fuel plates (somewhat less than 3"), the clearance between fuel plates and can wall (.012"), and the wall thickness. It is desired to have the minimum quantity of Fe in the box walls so that studies with increased iron content can be made by adding thin sheet iron pieces in the sodium gaps. Fourteen gauge is chosen for the can walls, which will be of Armco iron.

The can will be made of one piece construction for bottom and sides. The top, which will be open, will have two sides extended into ears about 1" long. These ears will have holes drilled into them to allow attachment of a loop of picture frame wire by which the can may be grappled on a hook or bar. A top plate is provided for each can, such that when the assembly is filled with fuel plates and sodium, the top plate may be fitted snugly into the end and cemented into place; the bottom is 1/8" thick with a 1/8" thick boss to allow tapping for the insertion of a handling eye during the process of removing sodium. The bosses will fit into oversized holes drilled in an iron plate forming the top surface of the reflector.

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Some of the cans will have two $1/8$ " square vertical ribs welded onto one side at the corners of the can; these will act as spacers, providing slots for foil holders at strategic positions in the assembly.

Assembly of Plates in Fuel Cans

The layout and order of assembly of fuel plates, natural uranium plates and iron plates will be determined for a given experiment, and the plates will be slid into the cans one by one. Spacing is accomplished by iron wire of suitable diameter bent in a zig-zag pattern and laid between plates. (Figure 6). Slack is taken up by the last wire which may be bent out of the zig-zag plane. The fuel can then will be lowered into a steel oven, equipped with internal electric heating elements; the oven is then evacuated, and liquid Na introduced through a pipe connected to a supply tank. When the fuel can is full, as seen through a glass window, He or N_2 will be introduced as a cooling agent and the lid of the fuel can will be cemented into place.

The same general technique will be used to drain the fuel cans. After removing the lid, a zig-zag of wires is strung, through holes in the ears of the can, across the opening, to retain the plates; the can is inverted and lowered into the oven by means of an eye-bolt screwed into the boss on the bottom. After evacuation, the heaters are turned on and the sodium allowed to drain out into the bottom of the oven, from whence it is forced by helium pressure into a collection barrel.

After cooling, the can is removed from the oven and the fuel plates are withdrawn one at a time and given three consecutive alcohol baths with final air drying; the first bath is cooled by a refrigerating coil. The alcohol containers are built with baffles so that only one fuel plate may be introduced at a time.

Since no molten sodium will be exposed to air, there is little chance of spillage or fire; nevertheless, barrels of dry sand and of dry sodium carbonate will be kept on hand.

The hazard of criticality, due to the moderating influence of the alcohol, is discussed at length in the Safety Report. In brief, the technique outlined above is shown to be entirely safe; even a fuel can inadvertently overloaded to full capacity of 22 fuel plates (instead of the normal maximum complement of 15) appears to constitute only half of a critical mass when wholly immersed in alcohol or water, largely due to the unfavorable geometry of the assemblage.

Burn-Up of Exponential Fuel

Burn-up of U-235 will be negligible; during the contemplated operation, even at the highest flux densities proposed, the total number of fissions will not exceed 10^{18} , i.e., a fraction of about 10^{-8} of the total number of U-235 atoms initially present in the exponential assembly.

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Foil Holders

The space between the external ribs welded to certain fuel cans allows the insertion of poison or diluent strips, or of foil or pin-holding strips into the assembly. These detector holders will be made out of iron, aluminum or natural uranium. They are split into two parts, each $1/16$ " thick, which are pinned together when the foils are in the assembly, and separated to allow foil removal. Appropriate recesses or grooves are machined into the holders to clamp the pins or foils in place.

In order to accomplish the removal of these holders without requiring the approach of personnel to the experiment, the foil holders are mounted on long spears, which may be grappled from behind the personnel shield.

The orientation of the fuel cans may be rotated to allow insertion of the foil holders parallel or perpendicular to the axis of the experiment.

Reflector and Assembly Table

The assembly plus reflector will be supported on a sturdy 2' square steel table whose top is $1/8$ " below the bottom of the pedestal. The reflector is built up to a 1' height on the 2' square. The 1' depth of reflector will be surrounded by $1/8$ " iron or steel sheet to insure against shifting of the reflector material. The section of sheeting at the pedestal end of the assembly will be the full pedestal height (3') so as to provide lateral support for initial stacking of fuel cans.

The reflector will be stacked with one of at least three materials: 2" x 3" x 6" natural U bricks, 4" x 4" x 8" Pb bricks, or 6" x 6" x 24" Fe bars. Other materials may be used as indicated. A $1/8$ " thick Fe plate is placed in position on top of the reflector; this plate will have appropriate oversized holes drilled into it to receive the bosses on the bottoms of the fuel cans.

To perform experiments with the 12" and 18" wide assemblies, the reflector is built up to these widths. The Fe cover plates for these assemblies will be three-sided, so as to fit over and around the reflector, and bolt to the table.

Assembly Cage

In place, the bottoms of the fuel cans will be located 1' from the bottom of the pedestal. They will be approximately located by means of the studs on their bottoms, and by the orientation of their foil holding sides. Lateral support is obtained from the pedestal side by the $1/8$ " plate coming up from the reflector. Fully loaded, the assembly has further lateral support in the form of a 1" x $1/8$ " iron strap cage which is supported from the table on angle iron corners. The back of this cage is hinged to swing out of the way during loading and unloading of the assembly.

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Sheets of cadmium, approximately 0.04 inch thick, may be attached to the sides of this cage, as a precaution against re-entry into the fuel cans of neutrons reflected from a man during handling of foil holders or cans. Experiments on neutron multiplication with a synthetic man may be carried out to determine if this is desirable.

To insure against toppling of fuel cans when loading or unloading is incomplete, a clamped bar is provided which may be set across the upper side bars of the cage to hold the fuel cans in place against front to back displacement. Sideways toppling of uncompleted rows (during partial assembly experiments) can be restrained by the use of dummy cans.

Assembly Table Drive

Since the reflector savings to the exponential assembly caused by the close presence of the pedestal are considerable, safe loading of the assembly is assured by backing the assembly away from the pedestal, then adding to its loading, and driving it slowly toward the pedestal for a reactivity check. To this end, the assembly table is mounted on rails, and may be moved backwards two feet by the use of a lead screw. The speed of the lead screw when the assembly is being moved forward towards the pedestal is limited to 6" per minute. At scram or at the will of the operator, forward motion of the assembly is stopped and the drive mechanism reversed.

Neutron Beams

It will be necessary to obtain collimated beams of high intensity from the assembly in order to utilize some of the spectrum measuring techniques which have been proposed (cloud chambers, for example). To do this, fuel cans will be removed from the assembly to the required depth, starting at the rear of the assembly, and a beam will be taken out back from the interior of the assembly. Collimation shields will be required to be some distance behind the assembly, and provision for remote removal of film, plates, etc. will be made, if necessary.

Special Instrumentation for the Assembly

Direct reading health physics monitors will be placed near the assembly at those distances representing the closest allowed approach of personnel to the assembly.

The detecting component of a period meter of the same sort as is used in the source pile may be permanently mounted on the assembly table. This meter would be operative during the process of moving the assembly toward the pedestal. The sensitivity would be nil unless the multiplication of the assembly became appreciable, at which time, it would provide a check, at the assembly side, of the period of the compound system which is also measured in the source pile.

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It is believed that this extra check is unnecessary, but it may be of psychological value.

SHIELDING

Shielding the Assembly from the Source Reactor

The exponential pile must be adequately shielded from source neutrons except at the pedestal face. This is accomplished by means of thermal absorber solution tanks on either side and above the pedestal. If too many thermal neutrons are scattered in, the exponential pile can be covered with cadmium sheet on the four exposed faces.

Interaction of ZPR-II and the Fast Exponential Experiment

ZPR-II (the Savannah River critical experiment), which is separated from ZPR-I by a 3-foot thick concrete wall, will have been shutdown and the D_2O and uranium removed by the time power runs in the Fast Exponential Experiment are started. The ZPR-II tank and instruments are being retained in situ since there exists the possibility of eventual operation for experiments built around these components, although no such schemes exist at present. If such a proposal is made, the question of interaction of the two reactors will be examined. The shield wall between the two systems is thick enough so that there is no hazard in entering one cell immediately after shutdown in the other, but truly simultaneous operation may be precluded by the high power (for a ZPR assembly) of the Fast Exponential Source Reactor.

Shielding in the Assembly Room

Shielding must be provided for personnel after shutdown on entry to the assembly room because of the increased power levels. The shielding design criteria used are 5 kw operation for one day. This operating time was chosen to be long so as to account for the cumulative effects of many short operations. It is hoped that the assembly room may be entered within a few minutes after shutdown without intolerable exposure. Experiments on ZPR-I indicate, by extrapolation, an unshielded shutdown gamma intensity of about 1000 R/hr., 2 minutes after shutdown from a 5 kw run for 45 minutes, measured 2 meters from the core centerline.

Six inches of lead brick will be provided directly around the core to reduce the decay gamma intensity by a factor of 5×10^4 for 1 Mev gammas, including build-up factor. 200 bricks, 2" x 4" x 8", weighing 5400 lbs. will be needed. Further protection against gamma rays from the core and from the exposed face of the pedestal (when the assembly is drawn back) will be supplied by a remotely operated personnel shield of steel and lead which is arranged to move on tracks so as to shield two sides and the end of the

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exponential assembly, after shutdown and prior to removing foils. The space between the assembly and the shield will be sufficient so that no appreciable reactivity will be introduced by reflection of neutrons from the shield itself. When not in use, it will be withdrawn by means of a motor drive and located far from the assembly.

Shielding of the Control Room

The water in the tank provides 30 inches of neutron shielding on the North (control room) side. This provides a factor of 100 over the attenuation now existing in ZPR-I, so that the fast neutron intensity at the controls should not be higher than for current operation at 50 watts. If the neutron flux should, nevertheless, turn out to be too high, there is sufficient space between the reactor tank and the control room wall to add a further barrier of precast concrete blocks (18" x 18" x 30") such as forms the present wall between the cells of ZPR-I and ZPR-II. The adequacy of the shielding will be determined by low level experimentation on the source reactor when it is brought to criticality.

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PROPOSED FAST EXPONENTIAL
EXPERIMENT

PLAN

FIG.1

PROPOSED FAST EXPONENTIAL
EXPERIMENT
ELEVATION

FIG.2

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FIG. 3

ANL-WHZ-10986

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FIG. 4
RE-5-10980-B

ANL-WHZ-10980

PLATES AND ARRANGEMENT

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FIG. 5
ALTERNATE PLATES

RE-5-10978-B

ANL-WH2-10978

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SUB-ASSEMBLY AND PILE

FIG. 6
RE-5-10979-A
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