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Proposal for an Intense Steady-State Neutron Source

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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ABSTRACT

The Kinetic Intense Neutron Generator (KING) reactor is an advanced concept which promises to provide a substantial breakthrough in existing steady-state neutron fluxes.

The use of a rapidly moving aqueous liquid fuel core removes present steady-state reactor flux limitations since no internal heat exchanger is required. The wide range in uranium fuel concentrations which are permissible in such a system enables one for the first time to optimize both the annular fuel region and control flux trap to give the highest performance index or ratio of thermal flux to reactor power.

A conservative 25-MW power level is proposed for the reactor at Los Alamos. Such a power level does not strain the existing water supply and requires essentially no new technology. Thermal neutron flux levels are estimated to be second to none at this power level.

The full flux potential for this concept is not known and will require research and development. A 25-MW reactor can serve as a test bed for further studies in which fuel velocities and core transit temperature rise are increased for short times.

A description of the KING reactor concept and its dynamic test is presented.

The need for and importance of fully exploiting the unique diagnostic properties of neutrons by increasing existing flux intensities is well known. Only a few specific examples of LASL interest are therefore given in the Appendix.

I. INTRODUCTION

It is well known that neutrons possess unique qualities for studying the structure of matter, the motion of atoms, the production of new atomic species, and for the detection of minute traces of materials.

The need for more intense neutron sources for advances in various fields of science and technology has been well described.[1,2]

Substantial progress has been made in the past decade in the techniques for using neutrons to help satisfy these needs. During this time, however, little progress has been made in the design and construction of more intense steady-state neutron sources.

An optimization of existing technology was achieved by the Oak Ridge HFIR design[3] initiated in 1958. The 5×10^{15} thermal neutron flux achieved in 1966 in this reactor has received little challenge. Only slight improvements appear possible in this type of core design, and then by rather heroic methods.[4,5]

A new approach for producing a more intense steady-state neutron source was used by the Canadians in their proposed Intense Neutron Generator (ING).[2,6] This device was based on the spallation rather than fission process. Thermal fluxes of 10^{16} to 10^{17} neutrons/cm^2/sec were predicted. The high cost of building such a device which required very large currents of high-energy protons impinging on a heavy element target led to the abandonment of this proposal.

Further increase in the neutron flux from steady-state fission reactors using solid fuel elements is limited by the basic problem of heat extraction from the core. A limit has been reached in the power that can be extracted from such fuel elements because thermal and vibrational stresses have approached the strength of materials.

A new concept for a fission reactor core and mode of operation developed at Los Alamos Scientific Laboratory promises to remove not only the core heat extraction limitation but will also permit an optimization of the performance index which is a measure of the maximum thermal neutron flux to the total reactor power. This new design concept is known as the Kinetic Intense Neutron Generator (KING) reactor.

The use of a rapidly moving liquid fuel in the core eliminates the need for an internal heat exchanger because the heat capacity of the fuel itself can be sufficient to remove the fission energy released in the core. The use of an aqueous fuel such as uranyl sulfate which has a high solubility (> 3 M) for uranium provides an adequate range in reactivity so that the theoretically optimum peak flux geometry can be chosen for the first time.

Calculations[7,8] have shown that peak thermal fluxes can be achieved in a central water flux trap island only if the fuel concentration can be varied sufficiently so the thickness of the annular fuel region as well as the radius of the water island can be adjusted to optimum dimensions. These conditions as well as high total power requirements appear to be met by the KING reactor design, which has the potential for providing steady-state neutron fluxes one or two orders of magnitude above those presently available.

Testing of the neutronic and hydraulic properties of this moving core concept is now in progress at Los Alamos. These static and dynamic critical tests, called the Kinglet experiments, are described below.

II. KING REACTOR PROPOSAL FOR LOS ALAMOS

The highest flux potential of this type of reactor will require some research and development. Even when operating at the highest possible performance index, the ultimate attainable flux will require a large total power output.

It is therefore proposed that only a 25-MW KING reactor be constructed at Los Alamos. This modest power level is chosen for a number of reasons.

1. Cooling requirements do not strain existing Los Alamos water supplies.

2. No new technical problems appear to exist for steady-state operation at this power level. Operating temperatures < 100°C and fuel velocities < 60 ft/sec, adequate for this power dissipation, are known not to cause appreciable corrosion, erosion, or fuel stability problems.

3. Calculations indicate that, even at this relatively low power level, the world's highest steady-state fluxes should be obtained.

4. The former UHTREX reactor[9] facility is available. This building with its auxiliary equipment was designed for an experimental reactor and therefore offers numerous features ideally suited for a KING reactor, such as a complete secondary containment shell and remote handling equipment. It appears that with a few modifications following the removal of the UHTREX core a 25-MW KING reactor could be installed at a substantial saving over building such a reactor from scratch.

5. A 25-MW KING reactor at Los Alamos will not only supply very advanced neutron research capabilities to replace the existing Omega West facility but can also be used as the test bed to demonstrate that this type of reactor has the capability for a substantial additional increase in flux.

The Kinglet experiments now in progress at Los Alamos will demonstrate the nuclear properties of such a moving core system under realistic power and operating conditions.

III. KING REACTOR DESIGN CONCEPT

As indicated above, the breakthrough in steady-state thermal fluxes which appears possible with this new core design and mode of reactor operation is due to the elimination of the normal type of core heat exchanger.

The use of fuel elements in the core has not only limited specific power and hence neutron intensities but has also prevented designing the core to maximize the neutrons per unit of power. This latter consideration becomes very important when total power output may be the cost limiting consideration for the production of a very intense steady-state neutron source.

Most, if not all, previous designs for steady-state high flux reactors have been strongly influenced by core developments aimed at the production of useful power. The KING reactor design was developed solely for the production of neutrons and has ignored other design concepts and thus could bypass previous technical limitations.

The most intense neutron sources have in the past always been associated with fast burst reactors.[10] This is due to the fact that this type of reactor does not depend solely on the heat extraction by a conventional heat exchanger but has made use of the heat capacity of the core materials to absorb the almost instantaneous fission energy release.

The KING reactor design has made full use of this advantage of burst reactors. A rapidly moving liquid fuel has every element of fuel subjected to a burst during core transit but because of continuous core replacement results in a steady-state neutron flux.

Figure 1 illustrates schematically the basic and auxiliary KING reactor components exclusive of shielding and reactivity shim. The liquid fuel, such as uranyl sulfate, is pumped up and through the annular core fuel region (1A-1B) where it is heated by fission energy during its flow through the core. Fuel emerging from the top of the core impacts against a fuel deflector (2) which disperses the fuel radially outwards into a containment vessel (3). From here the fuel flows by momentum and gravity into an annular fuel plenum which leads to the external fuel circulation pumps and main heat exchangers (5). Solution leaving the heat exchangers is returned to the core region through pipes (6).

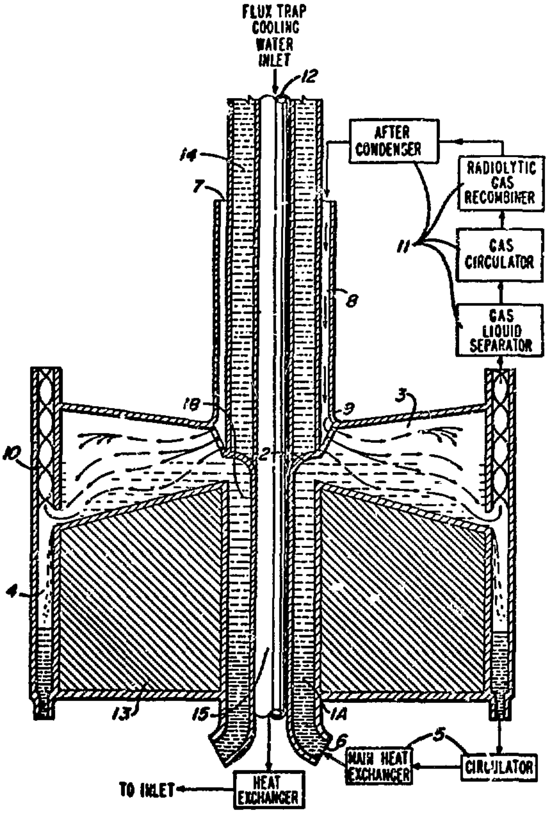

Fig. 1. Schematic KING reactor with some of the auxiliary equipment.

Radiolytic gas is produced in the solution during core transit. To avoid possible ignition of the radiolytic gas formed, an inert gas is circulated through the containment vessel (3). This gas flows in a closed system down the annular duct (7-8) and through apertures (9) where it mixes with the ejecting fuel and entrained radiolytic gas. The containment vessel (3) serves as the first stage of a liquid-gas separation system which includes a liquid condensation region (10) followed by other components labeled (11) in the figure.

Water enters at (12) through the annular shield plug (14) to supply the neutron moderation and cooling for samples placed in the central flux trap region (15). Cooling channels, reactivity shim control, and structural details are not shown in the schematic beryllium reflector region (13).

Most of the basic components of this design need be only scaled up to make use of technology proved in more than 20 years of successful operation of the Los Alamos Water Boiler reactor.[11] There is one important new feature, however--the rapid motion of the fuel through the core. This basic change in mode of operation permits an astounding increase in the energy dissipation capabilities in the core. A new interesting nuclear feature also appears for this type of operation in that for rapid fuel motion the reactor will no longer operate with normal delayed neutrons because of the short core residence time. Reflector neutrons, however, will supply a constant large source of very short-term delay neutrons in direct proportion to the power level of operation.

Corrosion and high-temperature fuel instability problems which stopped the Oak Ridge Homogeneous Reactor Project[12] do not exist in the KING reactor concept for two principal reasons.

1. The purpose of the KING reactor is the production of neutrons and not the production of useful power so that fuel temperatures can be lowered from a 250 to 275°C range to less than 100°C. Zirconium, for example, which is an excellent core fabrication material, is very corrosion resistant at 100°C in sulfuric acid concentrations up to 75%.[13] The cause for the enhanced zirconium corrosion in the presence of radiation, which was observed in the Oak Ridge work, is now understood.[14]

2. Substantial advances have been made in materials technology in the past decade for containing uranyl sulfate fuel. Reactor components such as heat exchangers, for example, can now be fabricated as cheaply of titanium as of stainless steel.[15] New highly corrosion resistant zirconium-tantalum alloys have been developed in Russia.[16] Carpenter stainless steel #20Cb-3 with superior sulfuric acid corrosion resistant properties is now readily available and is well suited to other than core KING reactor components.

The simplicity of the KING reactor core region will permit not only optimizing thermal neutrons in the central island but also fast neutrons. By removing the water from the central island and inserting a thin annular neutron converter existing fast neutrons will be enhanced and thermals removed in the island cavity. The neutron converter would consist of HFIR type fuel sandwiches with the required annular coolant water channels.

The simplicity of the KING reactor core region will furthermore make it relatively easy to test and replace advanced core materials[17] that are subject to damage by fission products or by intense radiation. This capability will be useful in any program aimed at testing the full potential of the KING reactor concept. Oak Ridge, for example, has found it necessary to replace the inner beryllium reflector sleeve after a fast neutron nvt of about 10^{22} in the HFIR.

Steady-state fuel energy density limitations are avoided by adjusting the fuel exposure time during core transit and by the large total external fuel inventory. The uranyl sulfate fuel has been successfully exposed to very high intensities in a pulsed operation in the Kinetic Water Boiler Experiments (KEWB).[18]

The physical properties of aqueous sulfate fuels are well known from early LASL work and detailed studies for the Oak Ridge Homogeneous Reactor Project.[19]

Extensive work has been carried out on the radiation chemistry of aqueous reactor fuels.[20] Potential KING reactor fuel stability problems have been examined at Los Alamos.[21] This work indicates that at the proposed 25-MW operation no problems should be encountered.

A large effort at Oak Ridge also went into the high-temperature chemistry of uranyl sulfate fuels.[22] Although not directly applicable because of the much lower temperatures that will be used on the KING reactor, this work illustrates the large amount of knowledge available for this type of fuel.

Recent work at Los Alamos[23] has investigated the hydraulic effects in a KING reactor. This work is important since the actual fuel residence time is a function of the radial fuel velocity profile. The results of this work are now being included in a calculational study[24] of the overall hydraulic-neutronic operating behavior of a KING reactor.

Optimum core dimensions for the highest performance index require a flux trap diameter of about 10 cm and an annular fuel thickness of about 3 cm. This requires a fuel loading of about 200 g ^{235}U/liter which gives an H/U = 111.

The power equation for the KING reactor is

$$P \text{ watts} = HAv\Delta T,$$

where H = heat capacity of the fuel (watts-sec/°C-cm3),

A = cross-sectional area of the fuel annulus (cm^2),

v = fuel velocity through the core (cm/sec),

ΔT = fuel temperature rise during core transit (°C).

For a given fuel solution, the core geometry $H \cdot A$ is a constant. The power output is then solely dependent on the product of fuel velocity and temperature rise during core transit.

Since the heat capacity of the uranyl sulfate fuel for the concentrations of interest (< 0.9 M) is essentially that of water and the fuel area in an optimum flux core is about 123 cm^2, the product $v \cdot \Delta T \approx 4.85 \times 10^4$ for a power of 25 MW.

One obviously has a broad range of choices of velocity or temperature rise. If the ΔT is chosen as 30°C, for example, the velocity will be 1615 cm/sec or 53 ft/sec.

The most desirable KING reactor startup and operating procedures will be established in the Kinglet experiments. It now appears that the use of an annular shim for reactivity control simplifies operating procedures because the hydraulic parameters can then be established for startup prior to the appearance of any nuclear effects.

Similarly, the Kinglet experiments will be used to study fuel deflection geometries at the core exit.

Work on the KING reactor concept has been summarized in laboratory reports[25] since its inception in 1967 as well as in the literature.[26]

IV. KINGLET EXPERIMENTS

A new and interesting feature of the KING reactor concept mentioned above is the precise nuclear behavior to be expected in a small liquid core when operating only on reflector neutrons rather than the normal delayed neutrons.

It therefore seemed advisable to carry out a series of static and dynamic critical experiments to test the basic neutron properties of a rapidly moving liquid fuel core under conditions that would be realistic for a high-flux facility.

The Kinglet Dynamic Critical Experiments are now being carried out at Pajarito Site in Los Alamos as the basic feasibility test of the concept. Because the purpose of these experiments is to test the nuclear properties of the core, much of the auxiliary equipment required for an actual reactor can be eliminated or modified. Figure 2, a vertical section through the Kinglet device, therefore does not resemble in a number of ways a KING high-flux neutron device.

The basic components of the Kinglet assembly shown in Fig. 2 are an overall containment shell, an annular fuel reservoir, a fuel circulation pump, a zirconium core tube, a fuel deflector above the core region, a beryllium reflector, and a shim poison sleeve with actuator. Auxiliary components also shown are a means for venting the main containment vessel, a fuel sampling and liquid addition pipe, a fuel level indicator, and a pipe leading to an outside fuel storage tank.

Numerous costly and large components required in a full-scale reactor which could be eliminated in the Kinglet experiments are gas-liquid entrainment separator, radiolytic gas diluent and recombination system, reflector coolant system, heat exchanger, experimental irradiation facility and flux trap, and radiation shielding.

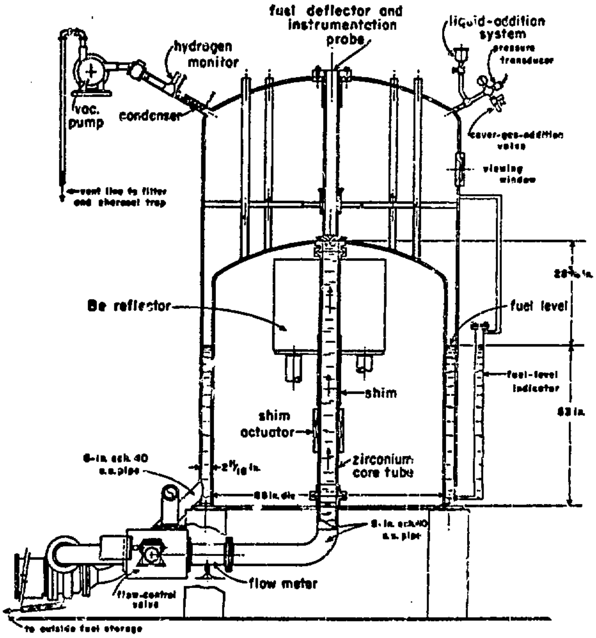

Fig. 2. Dynamic Test Facility--"Kinglet".

These components could be eliminated in the Kinglet assembly due to the planned mode of operation which could test nuclear properties without long periods of steady-state operation. Each run is initially limited to about 40 MW-sec energy release to fall within present operating procedures for critical assemblies at Pajarito Site. This type of energy limitation permits each run to be carried out remotely without a shield or heat exchanger if sufficient time is allowed between runs. Radiolytic gases released during such a run have adequate dilution in the large containment shell volume above the fuel deflector. For high-power test runs, a flat-topped pulse operation will be used rather than steady-state operation, i.e., power is brought up rapidly, leveled off, and stopped rapidly so as not to exceed the 40 MW-sec energy release limitation per run. During the flat-top period, the nuclear stability will be determined. Radiolytic gas is vented between runs following decay.

The simplicity of the core and elimination of much of the auxiliary equipment has permitted realistic testing of the concept in a relatively simple setup.

Hydraulic properties of the system can be studied independently of neutronic effects since with the shim in the "in" position the system is held substantially subcritical. A precalibration of the worth of the shim as a function of position permits a choice of the ΔT that the fuel will be subjected to during core transit and is independent of the fuel velocity. An increase in velocity for any chosen ΔT increases the power output in direct proportion as indicated in the power equation mentioned in Section III above. Some nonlinearity will appear in these simple relations when specific power levels are such as to form appreciable amounts of radiolytic gas.

Internal memoranda and progress reports[27] on the Kinglet experiments and other related work have been summarized in the quarterly status reports.[25]

A safety evaluation report[28] has been prepared and the following table lists the proposed operating conditions for the Kinglet experiments.

TABLE

Maximum power	4000 kW
Specific power (max)	700 kW/liter
Operating time per test at full power	10 sec
Total fissions per test	1.24×10^{18}
N-2 fission limitations/10-sec burst	1.36×10^{18} (41 MW-sec)
Core volume (cold critical)	~ 8.0 liters
Core operating volume	9.0 liters
Operating core height (max)	71.1 cm
Core cross-sectional area	126.6 cm^2
Fuel inlet temperature	20 to 50°C
Fuel outlet temperature	20 to 50°C
Fuel ΔT (at max fuel velocity)	~ 10°C
Core velocity (max)	688 cm/sec (~ 22.5 ft/sec)
Fuel pumping rate (max)	87 liters/sec (1150 gal/min)
Fuel inventory (max)	600 liters
Uranium inventory (max)	51.6 kg ^{235}U
Fuel storage	100 ft of 6-in.-diam pipe
Radiolytic gas production (max) STP	17 liters H_2-O_2/sec
Core residence time	100 msec
Energy deposition per pass	44 kW-sec/liter

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APPENDIX

SPECIFIC LASL NEEDS FOR A MORE INTENSE STEADY-STATE NEUTRON SOURCE

As pointed out in the proposal, neutrons have a unique analytic and diagnostic quality for studying the properties of matter not accessible with probes like x rays, infrared, or microwaves.

The full potential of these unique properties of thermal neutrons in particular can be determined only by more intense sources than those presently available.

A KING reactor at a steady-state power level of 25 MW is expected to provide central unperturbed thermal fluxes of 6 to 7 x 10^{15} neutrons/cm^2/sec. Short-term operation with fluxes as much as a factor of 10 higher than this should be attainable during the exploration of the full flux potential of this type of reactor.

Such fluxes would provide LASL with a facility substantially better than the best in the world and some two orders of magnitude higher than most research reactors including the LASL OWR.

Such intense neutron beams and irradiation facilities would be important to the LASL weapons supporting research effort in chemistry, metallurgy, and physics. Higher neutron fluxes are also of direct interest to the LASL weapons program in a number of ways.

The radiochemical methods of quantitative analysis of nuclear weapons debris are basic to both the development and diagnostics of such devices. The sensitivity of these methods is in direct proportion to the intensity of an available neutron source. There are several instances, for example, where second and higher order neutron capture cross sections are of importance and can be measured only in higher neutron fluxes than are presently available. An example of cross sections of interest are ^{153}Eu → ^{154}Eu → ^{155}Eu → ^{156}Eu → ^{157}Eu.

Higher intensity neutron beams can be used to assist in the study of weapons vulnerability problems.

The capability for producing numerous transuranic elements is of interest to the long range weapons program. An increase in flux is particularly valuable for the production of nuclides where short-lived intermediaries are involved in the capture chain such as in the production of ^{250}Cm and ^{257}Fm. Both ^{250}Cm and ^{257}Fm would be extremely valuable for use as targets for making new neutron-rich isotopes of the very heavy elements by heavy ion bombardment. Studies of ^{257}Fm itself are also of prime importance since initial studies show a much higher degree of mass symmetry and a higher total kinetic energy than previously observed in spontaneous fission. The availability of larger quantities of ^{257}Fm would permit detailed studies of its spontaneous fission, including the variation in neutron emission from the fragments as a function of mass and energy, the determination of Z as well as A for the fragments, and radiochemical measurements of the fragment mass yields.

A high-flux, steady-state reactor would play an important role in a proposed expansion in the research, development, and application program in neutron radiography at LASL. Specifically, such a reactor would serve as the neutron source for the following applications.

1. A production thermal neutron radiographic facility for the following programs:
   a. Quality control of LASL-designed pyrotechnics manufactured by other laboratories could be established and monitored.
   b. The determination of high explosive density variations in HE firing systems could be made.
   c. Heat pipe performance can be analyzed.
   d. Irradiated fuel may be radiographed.
2. The development of resonance neutron radiographic techniques using beam tailoring for the inspection of individual laminates of re-entry vehicles.

3. Experimentation in defining neutron radiographic standards and the development of theoretical systems models.

4. The development of advanced neutron imaging systems to be used in the cold, thermal, and resonance neutron energy regions.

5. Production instrumental analyses are now made of components and compounds germane to the weapons program. One of several techniques used is that of activation analysis. The proposed reactor fluxes would permit high sensitivity determination to be made with extreme accuracy.

If the KING reactor is designed to optimize the fission spectrum in the central flux trap by replacing the water with a peripheral neutron converter, it can also provide a source of degraded fission spectrum neutrons of the order of 10^{15} to 10^{16} neutrons/cm^2-sec so that multiple neutron capture processes of interest in our weapons diagnostic program could be studied. Some examples of interest are: $^{169}\mathrm{Tm}(n,\gamma)^{170}\mathrm{Tm}(n,\gamma),^{171}\mathrm{Tm}$; $^{186}\mathrm{W}(n,\gamma)$, $^{187}\mathrm{W}(n,\gamma)^{188}\mathrm{W}$; $^{181}\mathrm{Ta}(n,\gamma)$, $^{182}\mathrm{Ta}(n,\gamma)$, $^{183}\mathrm{Ta}$. Determination of the capture cross sections for $^{238}\mathrm{U}$ in such a "fast" flux by analysis of the plutonium nuclides ultimately formed would also be of interest.

Studies of fission product yields from various fissile materials could be carried out with such an intense source of fission spectrum neutrons. The high intensity becomes particularly valuable in studies of short-lived fission products and where only limited amounts of the fissile material (for example, $^{242m}\mathrm{Am}$, $^{248}\mathrm{Cm}$, $^{250}\mathrm{Cf}$) are available. The presently available critical assemblies at Los Alamos are unique in being able to provide fission spectrum neutrons, but at much lower intensity levels ($\approx 10^{11}$ neutrons/cm^2-sec) which are not sufficient for many of these studies.

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