GA–A23593

DIRECT ENERGY CONVERSION FISSION REACTOR

ANNUAL REPORT TO THE U.S. DEPARTMENT OF ENERGY

August 15, 1999 through August 14, 2000

by
L.C. BROWN

Prepared under
Nuclear Energy Research Initiative (NERI)
Program DE-FG03-99SF21893
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DISCLAIMER

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GENERAL ATOMICS PROJECT 30052
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EXECUTIVE SUMMARY

This work was undertaken by Sandia National Laboratories, Los Alamos National Laboratories, The University of Florida, Texas A&M University, and General Atomics to explore the possibilities of exploiting direct energy conversion. Sandia National Laboratories leads the overall project and provides overall project reporting. This report concentrates on evaluation of means of formulating the fuel required for the Magnetically Insulated Quasi-Spherical Fission Electric Cell, as proposed by Sandia, and on the possible operation of a liquid fueled fission reactor in a burst-pulse mode.

1. INTRODUCTION

Direct energy conversion may be defined for fission, in a broad sense, as the production of electrical energy from a fission nuclear reactor without the use of a mechanical energy conversion device. In its purest form, direct energy conversion directly converts the kinetic energy of fission fragments into electrical energy and is the only potential means for producing electrical energy from a fission reactor without the Carnot efficiency limitations. This project was undertaken by Sandia National Laboratories (SNL), Los Alamos National Laboratories, The University of Florida, Texas A&M University and General Atomics (GA) to explore the possibilities of exploiting direct energy conversion. In the initial scoping studies, the broad definition of direct energy conversion was used but the more restricted definition was emphasized in selecting the candidate reactors for detailed investigation. SNL, the lead laboratory, provides overall project reporting and documentation. This report documents the progress of GA in support of the overall project. In particular, this report concentrates on evaluation of means of formulating the fuel required for the Magnetically Insulated Quasi-Spherical Fission Electric Cell (MIQSFEC), as proposed by SNL, and on the possible operation of a liquid fueled fission reactor in a burst-pulse mode. SNL leads the overall project and provides overall project reporting.

2. PROJECT ORGANIZATION

Each of the project participants works at their own institutions. Periodically, project meetings are held (Table 1) at which much of the project coordination and most of the joint decision making takes place. This face-to-face communication is supplemented by teleconferencing, telephone and e–mail.

TABLE 1
PROJECT MEETINGS

Date/Location	Discussion Topics
Nov. 18–19, 1999 Albuquerque	Project goals and organization were discussed. The direct energy conversion literature was reviewed and previously proposed direct energy conversion schemes were discussed. Alternative direct energy conversion concepts were proposed, including the Pulsed MHD Reactor concept proposed by General Atomics. A total of nine concepts were selected for investigation. Action items were assigned to the participants. GA was tasked with investigation of the Pulsed MHD Reactor concept and investigation of possible fuel form applicable to the Quasi-spherical Magnetically Insulated Fission Electric Cell.
March 15, 2000 Albuquerque	Project status was reviewed and each DEC each concept was reviewed in detail. Draft metrics to be used for concept down selection were formulated. Action items were assigned.
June 23–24, 2000 San Diego	Project status was reviewed and each DEC concept was reviewed in detail. Weighting factors were assigned to each metric and for each metric a preliminary assignation numeric scores were made for each concept.
Sept. 7, 2000 Albuquerque	Project status was reviewed and each DEC concept was reviewed in detail. Weighs were finalized for each metric as were numeric scores for each concept and metric. Three concepts were selected to carry forward into Phase 2 as reported by SNL.

3. FISSION ELECTRIC CELL FUEL

Fission energy can be converted to electricity, avoiding the Carnot limit on efficiency, if the kinetic energy of the fission fragments can be directly converted to electricity. If positively charged fission fragments exit the surface of the nuclear fuel, leaving their electrons behind, a high negative voltage will be generated in the fuel (cathode) relative to the fission product collector (anode). Thereafter, the kinetic energy of additional fission products will be retarded by the electric field and the energy can be utilized by flowing electrons through an external power conversion circuit, from the cathode to the anode.

The MIQSFEC (Fig. 1) [1] was conceived at SNL as a means of directly converting fission product kinetic energy into electric energy. The electrons are prevented from following the fission products to the anode by a high magnetic field. Spherical geometry was selected over cylindrical geometry or parallel plates as analysis indicated that only spherical geometry could yield reasonably high efficiencies. The critical aspect of spherical geometry is that the anode be spherical. Spherical geometry gives the highest efficiency because only the component of fission product kinetic energy due to velocity normal to the electric field can be converted to electricity. The fuel cathode is optimally also spherical, but little is lost if it is a disk. Also, the fuel must be in the form of a thin film as only fission products leaving the fuel with close to their original energy can be utilized. Moreover, the fuel film must not be a coating on a bulk substrate, so fission products leaving the backside of the film can also be used.

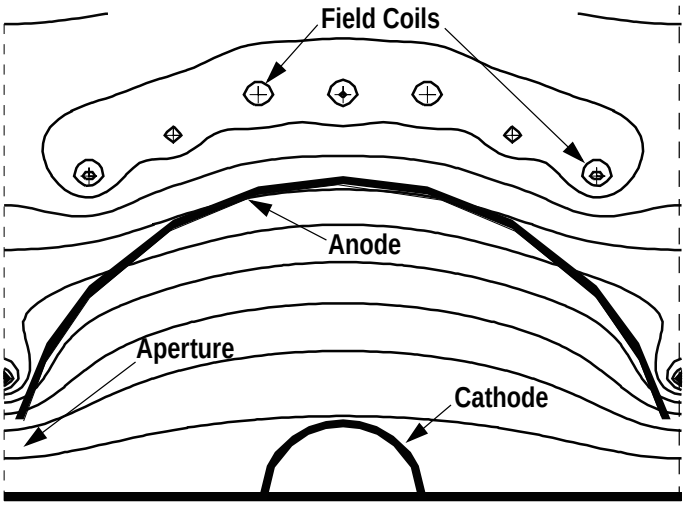

Fig. 1. Schematic diagram of the MIQSFEC.

The kinetic energy of fission fragments, whose velocity is normal to the electric field and whose kinetic energy is exactly equal to the product of the fission fragment charge and the voltage difference between cathode and anode, will have their kinetic energy converted to electricity with 100% efficiency. Excess kinetic energy of particles that reach the anode will be converted to heat in the anode. Particles with insufficient kinetic energy directed normal to the electric field will have all their kinetic energy converted to heat in the cathode. The anode structure can contain coolant passages but the cathode must be cooled by radiant heat transfer as added structural elements in the cathode would attenuate fission fragments and reduce efficiency. If the overall efficiency is to be increased by using the thermal energy, the cathode will have to withstand moderately high temperatures (300°C to 500°C).

Our task was to investigate possible means of fabricating fuel into the requisite shape. Techniques developed to make targets for the DOE Inertial Confinement Fusion (ICF) program show promise in two areas: thin films with edge support and self supporting foam shells. Edge supported thin films are most applicable to the disk cathode concept and foam shells to a spherical cathode. A disk cathode can be twice the thickness of a spherical shell cathode because there is no second surface to be traversed by fission fragments that leave the back side of the film but, for the same diameter, will contain only half the fuel. The target areal density of 0.0086 kg/m^2, for the disk cathode, does not give a very thick fuel layer. This areal density corresponds to 0.46 μm of uranium (18.7 g/cc) or 0.76 μm of uranium carbide (11.3 g/cc).

The ICF program has developed techniques for production of low-density plastic foams and is presently developing the techniques for producing foam shells. Stability at high temperatures can be obtained by heating the foam in an inert atmosphere or vacuum to convert it into graphite. Foams with a micron scale pore structure have been fabricated with densities of 3 mg/cc which, at a 100 μm thickness, corresponds to an areal density of 0.0004 kg/m^2 which would leave 0.0039 kg/m^2 for fuel.

The ICF program has produced large quantities of high quality freestanding thin films of gold and aluminum. The metal is vapor or sputter deposited on a thin plastic film and the film is bonded across the opening of a stainless steel support ring with the metal side of the film towards the ring. The plastic film is then dissolved in an organic solvent leaving the metal film supported only at the edges. Such films have been fabricated at thicknesses less than half a micron. There does not seem any reason to believe such films cannot also be fabricated from uranium or uranium carbide.

Both of these techniques show promise for meeting the requirements of a direct energy conversion cathode. Obviously, a development effort will be required to demonstrate fabrication of the fuel cathodes but little extrapolation of current technology will be required to fabricate experimental cathodes.

4. PULSED MHD REACTOR

Turbostar [2] is a direct energy conversion concept which was proposed for inertial fusion energy. Rather than extracting energy from charged particles, Turbostar suggested that the kinetic energy of an inertial fusion event be directly harnessed using turbines. The pulsed MHD fission energy concept attempts to extend the idea of Turbostar to a prompt critical pulsed nuclear reactor. MHD was chosen over turbines for this concept to minimize moving parts. The pulsed MHD concept is not, strictly speaking, direct energy conversion, for a fission reactor, because the time scale for the prompt critical event is long compared with the time required to equilibrate the energy between species and thus a thermodynamic temperature can be defined throughout the course of the event. Nevertheless, the concept contains some of the desirable characteristics of direct energy conversion, namely simplicity and, in the basic concept, a lack of moving parts.

The original concept [Fig. 2(a)] is overly simplistic, but does present the idea behind the Pulsed MHD Reactor. A liquid fueled reactor, with an electrically conductive fuel, is taken prompt critical. The reactor pulse is terminated by one of several processes, as described in the analysis that follows. The energy released in the pulse is adsorbed in the fuel, which was near its boiling point prior to the pulse, generating vapor. The pressure rise caused by the generation of vapor forces the electrically conductive liquid fuel through a MHD channel and generates electrical power. A problem, for the simplistic concept, is how to reassemble the fuel into the reactor vessel without it going critical prematurely. Figs. 2(b) and 2(c) present alternative means of reducing the reactivity while the reactor is reassembled and rapidly increasing the reactivity to initiate the pulse. The first alternative [Fig. 2(b)] relies upon variations in the reflector to control reactivity. Part of the reflector is isolated from the reactor by neutron adsorbing plates. The plates rotate until apertures in the plates align with the reflector and neutrons are reflected back into the core causing the prompt critical excursion. A multiplicity of plates rotating at different speeds, and with different aperture shapes, makes it possible to precisely define pulse timing, frequency, length and shape. For the second alternative, the pulse is initiated in the same way a pulse is initiated in a TRIGA reactor — by rapid removal of a control rod using a gas flow. The rotating plate concept is significantly more complicated than the pulse rod removal technique, and the ability to modulate the reactivity sufficiently may be an issue. The pulse rod technique may not be able to increase the reactivity fast enough. The reactivity must be increased rapidly to generate sufficient pulse energy before the core disassembles sufficiently to quench the reactivity.

Al Marshall of SNL analyzed the nuclear aspects of the pulse reactor. His findings of the minimum critical mass and the pulse energy output as a function of the rate of reactivity increase are presented in Appendix A for both aqueous and metal core reactors. These results indicate that, for an aqueous core pulse reactor, the core volume is approximately that of a 2 m diameter sphere. His results raise serious doubts as to the possibility of raising the reactivity fast enough to generate sufficient pulse energy to be practical.

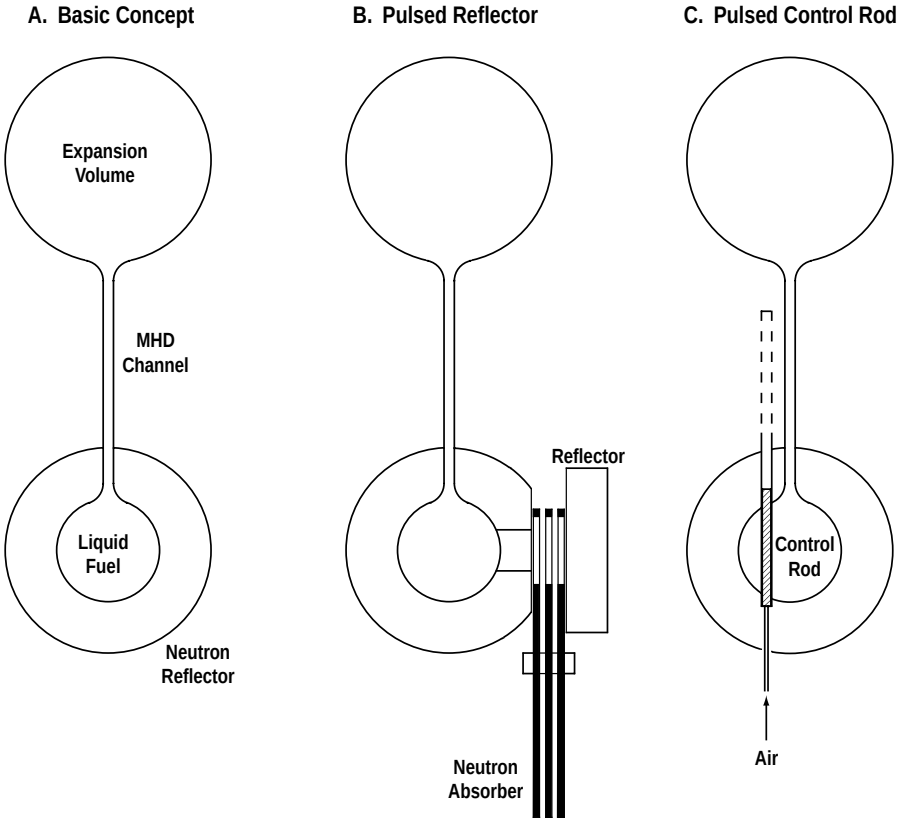

Fig. 2. Pulsed MHD Reactor Concept.

If the pulse reactor is to generate power, each pulse must generate a sufficient pressure difference to drive the liquid through the MHD generator. The temperature resulting from the pulse determines the theoretical maximum efficiency of the reactor. The effect of operating the pulse MHD reactor at alternative base conditions can be determined from Fig. 3 which shows the thermodynamic properties of water [3] displayed in the form of a plot of specific volume versus specific internal energy. The phase equilibria will be somewhat different for an aqueous reactor fuel, but the diagram is qualitatively correct. On this plot, a prompt critical pulse (if it could occur in pure water) would be indicated by a horizontal line connecting conditions before the pulse with conditions after the pulse. Immediately before and after an energy pulse, the volume

of the working fluid is unchanged; thus, conditions before and after the pulse are linked by a horizontal line on the diagram. The length of the line represents the energy in the pulse adsorbed in the working fluid. The volume of working fluid considered is the volume of liquid fuel in the core and that volume of vapor which is well connected to the core, such that the core liquid can rapidly expand into the vapor volume at the time of the pulse.

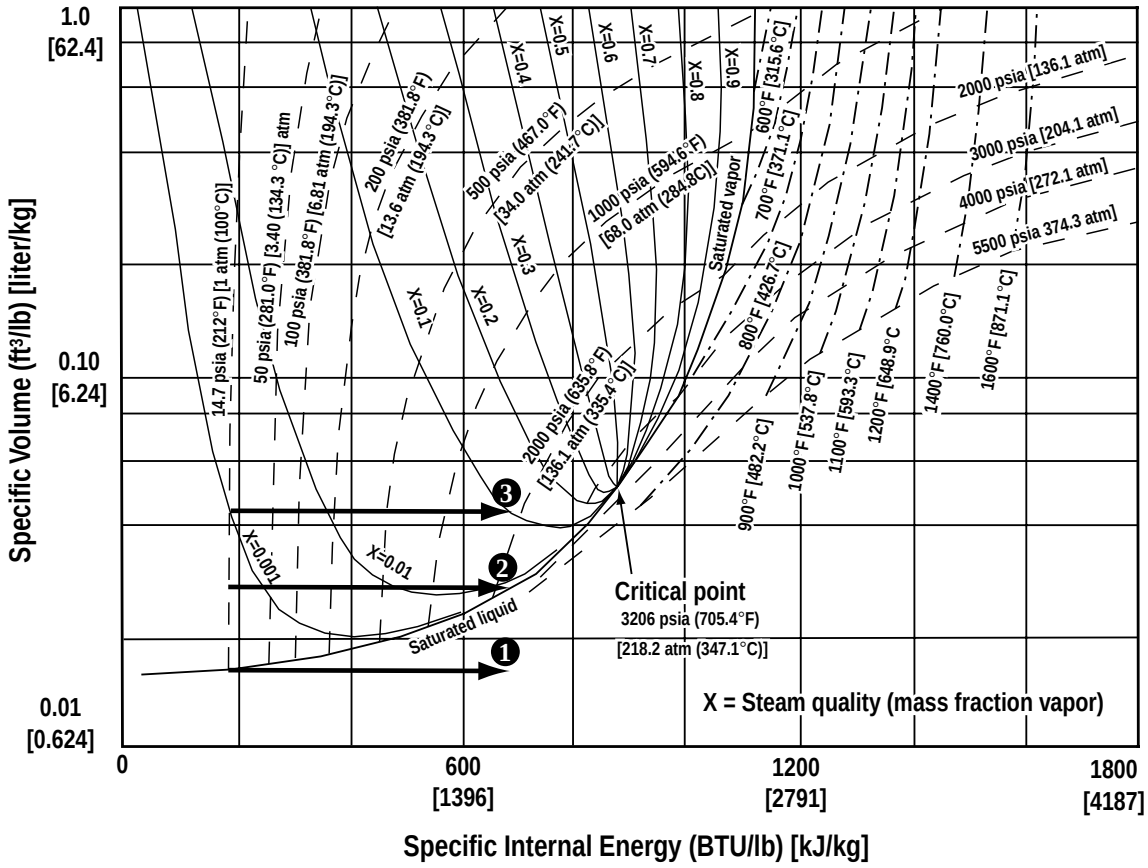

Fig. 3. Thermodynamic properties of water.

The three arrows on Fig. 3 represent three different cases, all starting with the same temperature and pressure (100°C, 1 atm) and each representing a pulse energy of 1200 kJ per kilogram of water in the working volume. The three cases differ in the fraction of the water that is initially present in the form of vapor. The vapor space must be either in the reactor core or immediately adjacent to the core such that there is essentially no restriction to flow from the liquid space to the vapor space. Table 2 gives the final temperature and pressure resulting from the three different initial conditions. Case 1 shows that extremely high pressures can result when the final conditions are in the pressurized water region. In particular, the reactor volume cannot be completely full of liquid or pressures will be reached that cannot be contained by any practical means.

Cases 2 and 3 represent the range of conditions that might lead to practical operation. Case 2 probably has a higher Carnot efficiency but, if the pulse power cannot be precisely regulated, the post pulse condition could be in the compressed liquid region with its concomitant high pressures. The Carnot efficiencies of Cases 2 and 3 are 39.2% and 37.6%, respectively. The actual efficiencies will, of course, be much lower for an actual cycle.

TABLE 2
EFFECT OF 1200 KJ/KG PULSES IN WATER-STEAM MIXTURES AT 100°C, 1 ATM

Case	Initial Steam Quality	Initial Vapor Volume	Final Steam Quality	Final Vapor Volume	Final Temperature	Final Pressure	Carnot Efficiency
1	0	0	(liquid)	(liquid)	342°C	5800 atm	39.35%
2	0.0005	45%	0	0	341°C	146 atm	39.25%
3	0.001	62%	0.1	36%	325°C	118 atm	37.62%

Both Case 2 and Case 3 have an additional source of mechanical stress. If the vapor and liquid volumes are not intimately mixed, as would be the normal case when the vapor is separated from the liquid by gravity, there will be a sudden shift in the center of gravity of the system as material redistributes to the post-pulse conditions. Assuming that the aqueous core is a cylinder 2 m in diameter and 2 m tall, the center of gravity would jump 0.86 and 0.59 m for Cases 2 and 3 which correspond to 53 and 36 kJ of energy. These energies are small compared to the total pulse energy of 7.5×10^9 J, but they are still significant and could lead to shock waves.

The pulse reactor concept does not seem to warrant further consideration. The maximum credible efficiency does not exceed that of current power reactors. The apparent simplicity of the initial concept rapidly disappears when the concept is examined in detail.

ACKNOWLEDGEMENT

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APPENDIX A
ANALYSIS OF PROMPT-BURST LIQUID CORE REACTOR CONCEPTS

by Al Marshall, SNL

A.1. WATER SOLUTION CORE

The following analysis was carried out for the proposed prompt-burst liquid core. The assumed concept uses a reflected spherical core containing highly enriched UN fuel in a water solution.

A.1.1. Criticality Analysis

For a moderated reactor, it can be shown from (Ref. A–1) that the relationship of the material buckling B^2 to the moderator to fuel molecular ratio R is given by

$$R = \frac{N_w}{N_{235}} = \left\{ \frac{\left[\eta \Big/ \left(1 + L_1^2 B^2\right)\left(1 + L_2^2 B^2\right) \right] - 1}{\left(1 + L^2 B^2\right)} \right\} \left(\frac{\sigma_{au}}{\sigma_{aw}} \right) \quad . \tag{A1}$$

Here, N_w = water atom density
N_{235} = uranium-235 atom density
η = neutrons produced per neutron absorbed = 2.06 (for thermal range)
L = water neutron diffusion length = 2.76 cm
L_1 = empirical constant = 1.6202 cm
L_2 = empirical constant = 5.1516 cm
σ_{au} = uranium thermal absorption cross section = 683 barns
σ_{aw} = water thermal absorption cross section = 0.66 barns

The uranium density is related to the moderator to fuel ratio by

$$\rho_u = \frac{235}{18R} \quad , \tag{A2}$$

and the core radius r is related to the buckling by

$$r = \left(\frac{\pi}{B} - \delta\right) \quad . \tag{A3}$$

The parameter δ is the reflector savings, assumed to equal approximately 2 cm. Using these relationships, we obtain plots of uranium density versus R and core radius versus R presented in Fig. A–1 and A–2, respectively.

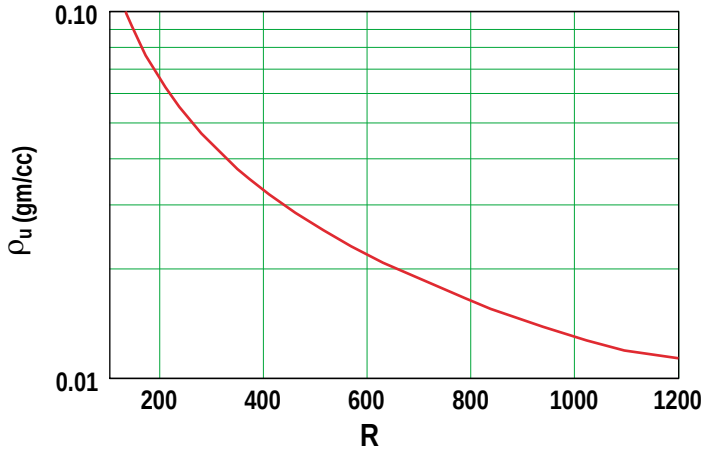

Fig. A–1. Uranium concentration versus moderator to fuel ratio for reflected spherical core UN–water solutions.

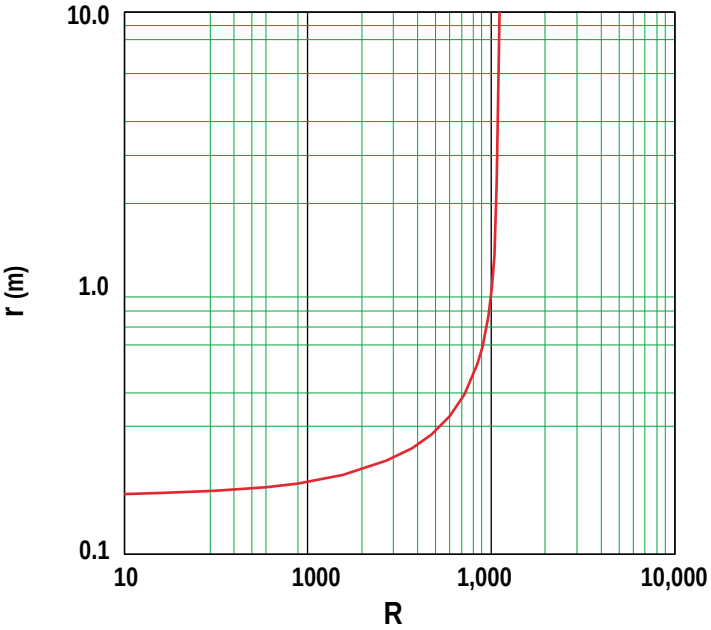

Fig. A–2. Critical core radius versus moderator to fuel ratio for reflected spherical core UN–water solutions.

The uranium mass *M* is simply given by

$$M = \frac{4\pi}{3} r^3 \rho_u \quad . \tag{A4}$$

The critical mass curve given in Fig. A–3 is in qualitative agreement with experimental data (Ref. A–2). Both the simple analysis and the experimental data show a rapid increase in required critical mass and critical radius for fuel densities above about 0.012 kg/liter (or g/cm^3). The rapid increase in critical mass is due to neutron absorption by hydrogen in the water molecule. Typically, reactors are designed with much smaller moderator-to-fuel ratios in order to avoid the severe critical mass penalty associated with high R values. For the burst design, however, our principal concern is achieving a high burst energy, rather than a low critical mass. In the following section, we next examine the parameters influencing prompt burst energy.

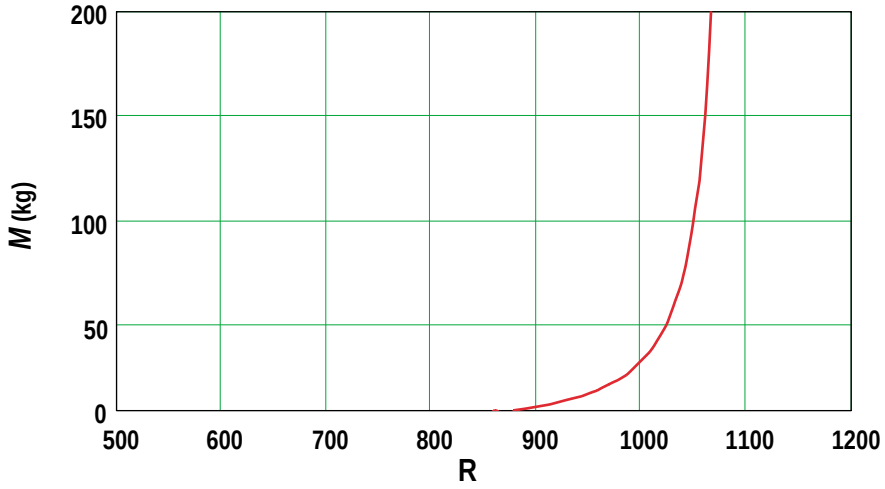

Fig. A–3. Critical mass versus moderator to fuel ratio for reflected spherical core UN–water solutions.

A.2. BURST ENERGY EQUATION

The classic Bethe-Tait analysis examines a fuel melt reconfiguration accident resulting in a large reactivity insertion rate. The rapid fuel heating results in fuel vaporization causing rapid fuel dispersion and termination of the excursion. The Bethe-Tait equation is used to determine the energy yield from the prompt burst.

The analysis is typically restricted to fast reactors because:

1. Fuel melting and reconfiguration in fast reactors could, in principle, lead to a large and sudden reactivity excursion whereas thermal reactors typically loose reactivity during fuel reconfiguration.

2. Doppler feedback from uranium-238 resonance results in rapid neutron poisoning as the core heats up. Fast reactors are typically highly enriched; thus Doppler feedback from uranium-238 resonance is usually small. For thermal reactors, however, enrichment is usually very low resulting in significant Doppler feedback and rapid termination of the power ramp.

3. The prompt neutron generation time for fast reactors is very small compared to Λ for thermal reactors. The short generation times for fast reactors ($\sim 10^{-7} - 10^{-8}$ s) results in a rapid increase in the neutron flux before feedback mechanisms come into play.

The first two considerations do not apply to the moderated core design, because (1) the large reactivity insertion rate will be intentionally introduced by ejecting poison rods, and (2) the design is assumed to use highly enriched fuel. The third consideration does apply to pulse reactor concept, but we can show that the long generation time can be compensated for by designing the core to have a large core radius.

The Bethe-Tait equation for a prompt disassembly accident accounts for the inertial effects associated with dispersing the fuel mass following vaporization (Ref. A–3). For a spherical core the Bethe-Tait equation is given by

$$E = \frac{3k_\infty \rho_{core}}{2\pi^5 M^2 (\gamma - 1)} \left\{ \ln \left[\frac{\wp}{\Lambda} \left(\frac{E_v}{P_0} \right)^2 \right] \right\}^{3/2} \frac{r^2}{\sqrt{\Lambda}} (\wp)^{3/2} \quad . \tag{A5}$$

The parameters in Eq. (A5) are defined in the following:

E = energy released during burst
r = core radius
ρ_{core} = core density
k = neutron multiplication factor for an infinite core
γ = specific heat ratio in core
M = core migration area
$\wp$ = reactivity insertion rate
Λ = prompt neutron generation time
E_v = energy required to vaporize core
P_0 = initial core power

Moderated reactors typically yield very little burst energy due to their characteristically long prompt neutron generation times Λ. Prompt neutron generation times for moderated reactors typically range between 10^{-4} and 10^{-3} s. However, from Eq. (A5) we observe that the energy yield goes as the core radius to the seventh power. Thus, it should be possible to compensate for the long Λ by designing the core to have a

large radius. Figures A–1 and A–2 show that by intentionally choosing a fuel concentration close to the limiting value for criticality (about 0.014 kg/liter), the core can be designed to have as large a radius as desired. Although unfavorable when attempting to minimize critical mass, a large core radius is desirable when attempting to extract a large energy yield from a pulse. For this analysis, a core radius equal to 1.0 m was found to give energy yields in the desired range, although somewhat larger or smaller core radii can be used if desired.

A.3. ENERGY YIELD CALCULATION

In this analysis, the core radius and fuel density used were:

$$r = 1.0 \text{ m}$$
$$\rho_u = 0.14 \text{ kg/liter}$$

Equation (A5) shows that the energy yield is a logarithmic function of the parameters E_v and P_0; consequently, the energy yield is highly insensitive to the values of E_v and P. Furthermore, the parameters ρ_{core}, k_∞, γ and M do not appreciably impact the energy yield. The following values were used for these parameters:

$$\rho_{core} = 1 \text{ g/cm}^4$$
$$k_\infty = 1.1$$
$$\gamma = 1.33$$
$$M = 36.2 \text{ cm}^3$$
$$E_v = 1.2 \times 10^{10} \text{ W·s}$$
$$P_0 = 1 \text{ W}$$

Using the parameters in Eq. (A5), the energy yield as a function of reactivity insertion rate was obtained for prompt neutron generation times of 10^{-3} and 10^{-4} s. The predicted energy yields (W·s) are plotted versus reactivity insertion rate ($/s) in Fig. A–4. The figure shows that one MW·s of energy is produced for a reactivity insertion rate of only $5/s, when $\Lambda = 10^{-4}$ s; for $\Lambda = 10^{-3}$ s, about $10/s is required. The actual neutron generation time for the concept will need to be determined by more detailed analysis. In any event, the analysis shows that significant burst energy can be produced by modest reactivity insertion rates for the moderated fluid core.

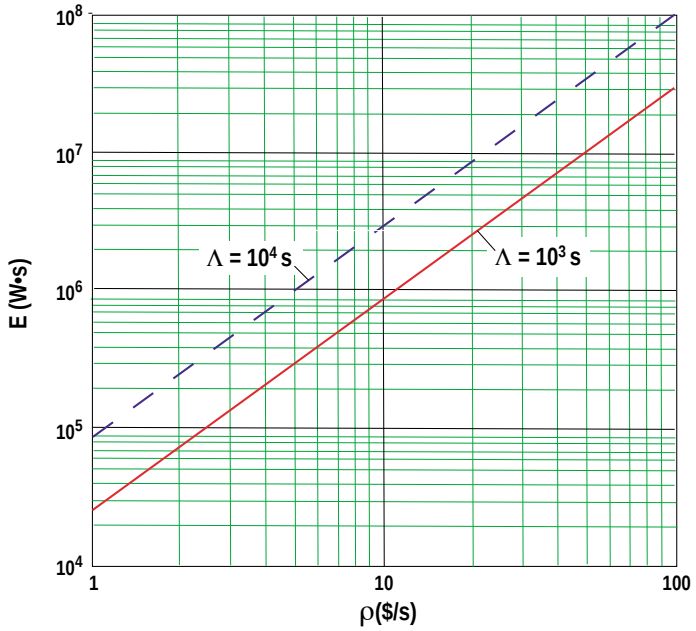

Fig. A–4. Burst energy yield versus reactivity insertion rate.

A.2. LIQUID METAL CORE

A fast reactor option was also investigated. For this design, the core was assumed to consist of fully enriched uranium in a NaK solution.

A.2.1. Criticality Analysis

For an unmoderated core, I have shown (Ref. A–4) that the critical mass can be estimated using the relationship

$$M = M_{ref} \left(\frac{\rho_{ref}}{\rho_u} \right)^{1.5} , \qquad \text{(A6)}$$

where M_{ref} and ρ_{ref} are the critical mass and fuel density for a reference case. The parameter ρ_u is the core average fuel density for the case under consideration. For a compacted UC_2, sphere 93% enriched in uranium-235, a critical mass of 18 kg is predicted (Ref. A–5). The fuel density for the reference case was 13.6 g/cm^4. From Eq. (A6) and simple geometry arguments, the critical mass and critical radius were obtained. The critical mass and critical radius are plotted as a function of fuel density in Figs. A–5 and A–6, respectively.

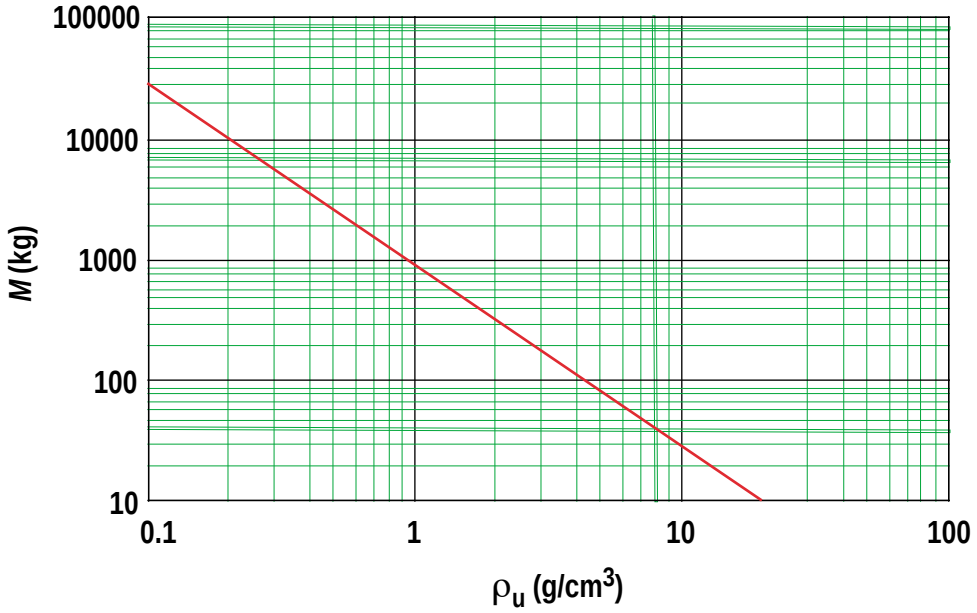

Fig. A–5. Critical mass for liquid metal core versus fuel density.

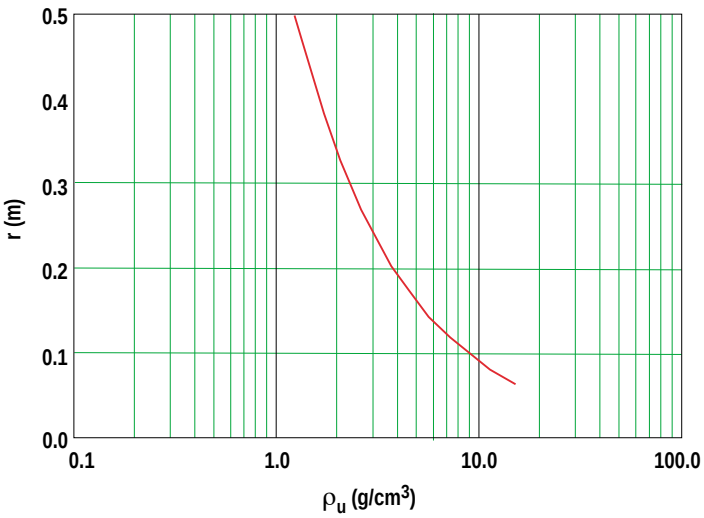

Fig. A–6. Critical core radius (meters) versus fuel density for reflected spherical liquid metal core.

A.2.2. Energy Yield Calculation

From Figs. A–6 and A–7 a compromise was made between minimizing critical mass and maximizing critical radius. In this analysis, the core radius and fuel density used were:

$$r = 0.25 \text{ m}$$

ρ_u = 3 kg/liter

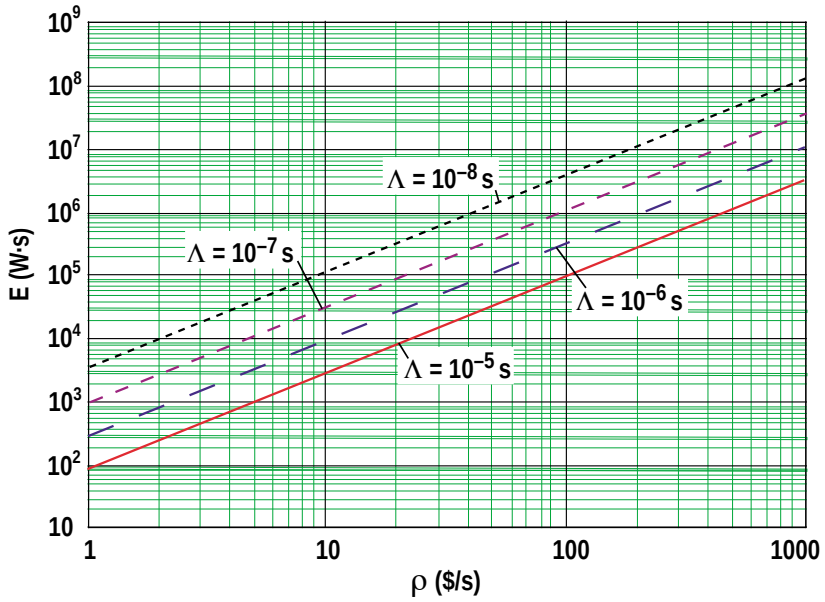

Fig. A–7. Burst energy yield versus reactivity insertion rate.

The following values were used for Equation A5 parameters:

ρ_{core} = 4.2g/cm^4
k_∞ = 2.0
γ = 1.4
M = 42 cm^3
E_v = 7.3 × 10^7 W·s
P_0 = 1 W

Using the parameters in Eq. (A5), the energy yield as a function of reactivity insertion rate was obtained for prompt neutron generation times of 10^{-8} through 10^{-5} s. The predicted energy yields (W·s) are plotted versus reactivity insertion rate ($/s) in Fig. A–7. The figure shows that one MW·s of energy is produced for a reactivity insertion rate of $100/s, when $\Lambda = 10^{-7}$s. The fast reactor thus requires a higher fuel density and a much greater reactivity insertion rate than for the moderated concept. Based on this comparison, the moderated design appears to be the better choice.

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