UCRL-JC 107417
PREPRINT

Received by OSTI

AUG 12 1991

INHERENTLY SAFE NUCLEAR-DRIVEN INTERNAL COMBUSTION ENGINES

Peter Alesso
Tze-Show Chow
Ralph Condit
John Heidrich
Joseph Pettibone
Ronald Streit

This paper was prepared for submittal to
Sixth International Conference on Emerging Nuclear Energy Systems
Monterey, California, USA
June 16-21, 1991

June 14, 1991

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

Lawrence
Livermore
National
Laboratory

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Peter Alesso, Tze-Show Chow, Ralph Condit,
John Heidrich, Joseph Pettibone, Ronald Streit
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94550
415-422-6949

ABSTRACT

A family of nuclear driven engines is described in which nuclear energy released by fissioning of uranium or plutonium in a prompt critical assembly is used to heat a working gas. Engine performance is modeled using a code that calculates hydrodynamics, fission energy production, and neutron transport self-consistently. Results are given demonstrating a large negative temperature coefficient that produces self-shutoff of energy production. Reduced fission product inventory and the self-shutoff provide inherent nuclear safety. It is expected that nuclear engine reactor units could be scaled from 100 MW on up.

I. INTRODUCTION

Nuclear Otto engines produce pulsed energy by creating an assembly of nuclear fuel and working gas that is supercritical for moderated prompt neutrons.¹⁻⁴ This area of nuclear energy production lies, in a sense, between a conventional reactor which is critical on thermal delayed neutrons and has a time scale of tens of seconds for changes in energy production, and a nuclear explosive that is critical on fast prompt neutrons and has a very short time scale for energy production. Unlike previous work, we have begun modeling working gas and fuel mixtures that provide a strong negative temperature coefficient.

Self-regulation of energy production allows these nuclear engines to have numerous designs and applications. They could provide sources of high instantaneous flux to power fission fragment pumped lasers. Or they could be scaled up to produce 10's of GJ in sub-second pulses, which could be used to power coil guns to launch payloads into low earth orbit. Another application might be as a source of surface power

on the moon or Mars. A significant commercial application could be electrical generation featuring modular (100-MW) generating units. These engines offer on-line refueling thus minimize down time. They are passively safe, because of their low inventory of fission products and self-shutoff. By directly producing mechanical energy that can be efficiently converted into electrical energy, they eliminate the need for a steam cycle. Thus, nuclear engines may produce electricity with less capital, and operation and maintenance costs than present commercial reactors.

The purpose of this paper is to describe some preliminary results on modeling the energy production mechanism, and to present some thoughts on performance scaling, fuel mixtures, nuclear safety, and materials compatibility.

This paper begins with a general description of nuclear engine operation, including the energy production mechanism and possible fuel mixtures. The next section covers modeling of engine operation, and contains subsections on the computational modeling, performance scaling and nuclear safety. Then there is a section on materials compatibility. Finally there is a summary containing comments on some possible configurations for these engines.

II. DESCRIPTION OF OPERATION

A. Energy Production Mechanism

Initially a charge of working gas and fuel is injected into a cylinder and subsequent adiabatic compression by a piston produces a supercritical assembly, shown in Fig. 1. Delayed neutrons emitted by decaying fission products act as a source to begin the chain reaction. High energy (MeV) neutrons from fissioning nuclei go directly to the reflecting walls. Neutrons reflected back

into the fuel region interact with the working gas. This produces a distribution of thermal neutrons controlled by the temperature of the gas. These neutrons then produce further fissions and the system produces energy at an exponentially increasing rate. Fission fragments heat the working gas and subsequently the thermal neutrons are heated as they collide with the gas. The fuel mixture contains at least one element that has a large absorption resonance at about 1 eV, which absorbs a fraction of the heated neutrons. Hence more neutrons are lost from the system than produced, and the fission energy production falls to near zero. As in an Otto cycle, energy release and heating of the working gas occurs under constant volume conditions. Subsequently, the hot working gas expands against the piston to produce direct mechanical energy. After expanding against the piston the working gas and fuel mixture is exhausted and waste heat is extracted through a heat exchanger.

Fig. 1. After compression the fuel region is nearly a square cylinder, with its length equal to twice its radius. Fission fragments heat the working gas. A large negative temperature coefficient shuts off the energy production.

B. Fuel Mixtures

Two fueling schemes can be used; one fissioning uranium and the other fissioning plutonium. In the first scheme, U233 acts as the fissile material. Due to large absorption resonances at about 1 eV, either Hf177, In115, or Rh could be used to provide the large negative temperature coefficient. A fertile material, Th232, could be added to breed U233. A second scheme uses Pu239 as the fissile material and Pu240, with its large absorption resonance at 1 eV, to provide the large negative temperature coefficient. In this scheme, U238 could be used as a fertile material to breed Pu239. These fuel

mixtures can be in the following forms: A mixture of hexafluoride gas in a neutron moderating, working gas mixture of HF and F2; or an aerosol of oxide microparticles (5 to 10 μm) suspended in a neutron-moderating working gas of H2 or He.

III. MODELING OF ENGINE OPERATION

A. Modeling the Energy Production

We have begun modeling energy production using a code⁵ that calculates the hydrodynamics, neutron transport and fission energy production. A self-consistent, time dependent, 2-dimensional calculation of the spatially dependent neutron transport and fission energy production is performed during compression and subsequent expansion of the working gas and fuel mixture. Hydrodynamics is Lagrangian and neutron transport and slowing down are done with Monte Carlo calculation using 175 energy groups each split into two cross section ranges or bands. Following a collision, neutrons produced in each energy group and are allowed to interact statistically with either of the two cross sectional values of that group. If the statistical probabilities of interaction with each of these two cross section bands is properly defined this model can simulate variations in cross section and flux.⁶

Some results are shown in Figs. 2 and 3. These were obtained using a cylinder with inside diameter and length of 100 cm. The cylinder walls were 48-cm thick Be for the calculation and the piston was stationary. The temperature of the cylinder wall and piston was held at 800 $^{\circ}\text{K}$. The fuel was 5.25-kg Pu239, 2.25-kg Pu240, and the working gas was 8.5-kg H2. To start the chain reaction, a source of $1.8 \times 10^{16} \text{ s}^{-1}$ of 450-keV neutrons was placed in the fuel region. This source corresponds to the neutron production expected from decay of fission fragments. (Energy production in these supercritical systems is insensitive to this rate). Material temperature in the fuel region is shown in Fig. 2. The initial temperature of H2 is 938 $^{\circ}\text{K}$. Since interactions of the neutrons reflected back into the fuel region are dominated by thermalizing collisions with H2, the neutron energy spectrum follows the H2 temperature. The system is supercritical, $K_{\text{eff}} = 1.11$ at 10 ms. Fissioning of Pu239 results in power production, initially growing at an exponential rate, as shown in Fig. 2. As energy is

Fig. 2. H_2 temperature and normalized power. The temperature rises to 2100°K on axis in the fuel midplane and to 2700°K near the cylinder wall. A large negative temperature coefficient forces the power production to zero.

produced, the hydrogen temperature goes to 2100°K on axis in the fuel midplane and to 2700°K near the cylinder wall. A smaller temperature occurs in the middle of the fuel region, because less reflected neutrons get there and so there is less production of specific power. As the temperature of the H_2 and the energy of the neutron population increase, power production ceases to grow. Maximum power production is 17 MJ/ms at 30 ms. Spectral distributions of neutron flux, normalized so their integrals are $1/\text{cm}^2\text{ms}$, are shown in Fig. 3. Flux is suppressed at 0.3 and 1 eV due to the Pu^{239} fission resonance and Pu^{240} absorption resonance, respectively. Increase in temperature results in a neutron spectrum that has a high energy tail extending up into the 1-eV absorption resonance of Pu^{240} . Absorption of neutrons by this resonance results in a subcritical system, $K_{eff} = 0.90$ at 50 ms. And as seen in Fig. 2, the power production falls to near zero. A total energy of 190 MJ was produced in this calculation.

B. Performance Scaling

An analysis of scaling including calculations with moving pistons is presently underway for both uranium and plutonium fueled cylinders. It is anticipated that cylinders having an inside diameter of about 1 m will produce 100 MJ/pulse. These cylinders will have a compression ratio of about 10:1 and piston speeds of 1 cycle/s or so. Peak temperatures are expected to be about

Fig. 3. Spectral energy distributions of neutron flux before and after heating of the working gas.

2500°K, as determined by type and quantity of the neutron absorbing nuclei utilized, and peak pressures are expected to be about 1000 atm. Theoretical thermodynamic efficiencies of 60% are possible, when using hydrogen as the working gas and a 10:1 compression ratio. An analysis of energy loss to the cylinder and piston surfaces is underway. It is anticipated that these losses will be relatively small and that overall actual thermodynamic efficiencies will be approximately 40%. Finally, larger cylinders could produce 10's or 100's of GJ/pulse for pulsed power applications.

C. Nuclear Safety

These engines do not require careful safeguards against overcompression or overloading of fuel. First, over compression will not cause excess energy production. Adiabatic compression would heat the working gas to temperatures where the negative temperature coefficient would produce a subcritical system. Second, energy release is controlled by the temperature of the working gas and is insensitive to the amount of fuel loaded into the cylinder. Fission cross sections of Pu^{239} and U^{233} go up by two orders of magnitude at sub-eV energies relative to MeV energies. Consequently, a nuclear engine design to be critical for thermal neutrons would need to be overloaded with fuel by nearly two orders of magnitude in order to be thick to MeV neutrons and produce a runaway reaction.

Runaway reaction is possible if two conditions are met: (1) if working gas were loaded into the cylinder in a small enough amount so that the neutron energy spectrum was not controlled by collisions with the gas; and (2) if wall material reflected neutrons back into the system with energies in the sub-eV range. These conditions would result in a neutron temperature staying below that required for self-shutoff. However, choosing a wall material that reflects neutrons into the fuel region at or above the 1-eV absorption resonance could mitigate this effect. Also proper choice of an aerosol particle coating could lead to collisional control of the neutron temperature.

Too much working gas injected into the cylinder could lead to overpressurization, since energy production proceeds until the gas reaches about 2500 °K and pressure is therefore proportional to gas density. Passive pressure relief could be implemented to reduce the probability of over pressurization.

Calculations are underway to quantify criticality and energy production for various amounts of compression and loading of fuel and working gas, and for various wall and aerosol particle coatings.

IV. MATERIALS COMPATIBILITY

A. Gaseous Fuel

A gaseous fissile material would serve the dual functions of energy producer and working gas. Unfortunately, there are no good uranium or plutonium gaseous compounds. Uranium hexafluoride is thermodynamically stable, particularly at high temperatures. A small addition of F_2 , $1:10^4$ of $F_2:UF_6$, would provide thermodynamic stability. However, plutonium hexafluoride could only be stabilized using large excesses of F_2 , 100:1 of $F_2:PuF_6$. Fluorine will not provide the neutron moderation that is attained with hydrogen. Addition of HF would help with the neutron moderation, but it is another corrosive agent that would have to be dealt with.

Cylinder and piston surfaces could be made of Monel, a nickel alloy. Monel has served as a suitable container for hexafluorides up to about 850 °K in laboratory experiments, but their serviceability in a cycling system over long times would need to be demonstrated. Pistons would

require a lubricant at the sliding interface with the cylinder. Molten fluoride salts, e.g., LiF, BeF_2 , CaF_2 , or NaF, which melt above 670 °K might be attractive for this.

B. Aerosol of Fuel and Working Gas

Some of the advantages of gaseous fuel could be achieved using an aerosol of UO_2 and HfO_2 , or PuO_2 suspended in a working gas of H_2 , or He. Such particles will thermally equilibrate with the working gas in about 10 μs . This mixture would be thermodynamically stable. When using H_2 if partial decomposition occurred at high temperature or by radiolytic action, a trace of H_2O would regenerate the oxide.

The aerosol mixture needs to be circulated outside the piston chamber for several reasons: (1) to cool the fuel before recompression and re-ignition, (2) to maintain the proper particle size distribution, (3) to remove fission products, and (4) to refuel the working gas with fresh UO_2 and HfO_2 , or PuO_2 . Some work has been done on techniques to perform these processes with aerosols.⁷ After exhausting from the cylinder, cyclones can be used to separate large particles from the aerosol. Heat can be removed by a heat exchanger. Removal of fission products could be achieved in two "scrubber" units, one a cyclone separator and the other containing activated charcoal. Electrowinning could be used to recover the fissile material for regeneration of aerosol. Aerosol particles could be manufactured in a number of ways. The simplest might be to oxidize the metals. The size distribution of oxide particles is a strong function of the temperature of oxidation; the higher the temperature the coarser the particles. Oxidation of either U or Pu at about 800 °K would yield a large fraction in the 10- μm range.

The present body of experience gives little indication as to how a highly radioactive, high temperature aerosol would behave. Particles having a diameter of 10 μm will have a settling rate of much less than 1 cm/s. Settling of the particles should be not be a problem in the combustion region and blowers can keep them levitated in the waste heat removal and fuel reprocessing loop.⁷ Agglomeration of particles tends to occur in 1- μm or smaller range. This would return the particle size to the 5- to 10- μm size, which could be kept levitated.

The cylinder walls and pistons could be surfaced with tungsten or molybdenum, refractory metals which do not corrode or embrittle in hydrogen. Beryllium metal does not react with hydrogen and could be placed in the piston and cylinder wall to act as a neutron reflector. Another option for cylinder wall and piston surfaces might be BeO. Generation of helium in beryllium might present problems and needs to be assessed further.

Particles would be too small to cause much abrasion except if they become trapped at sliding contact areas such as between the piston and cylinder. An active mechanism for sweeping out the aerosol from such regions may have to be devised. Perhaps the injection of high pressure hydrogen gas between the piston and the cylinder wall could serve this purpose. In a free piston design,⁴ allowing a small amount of blowby may mitigate abrasive effects. Finally a liquid piston, e.g., molten lead, would not have the problems of abrasion.⁴

V. SUMMARY

We have proposed a class of nuclear-driven prompt critical internal combustion engines. The engines use fuel mixtures that result in a large negative temperature coefficient, which results in self-shutoff of the nuclear chain reaction at elevated temperatures. These engines eliminate the steam cycle associated with present nuclear reactors; consequently, they could produce energy much more economically from nuclear fission than has been done to date.

Due to the self-shutoff mechanism, these engines are inherently safe from nuclear detonation. They do not require careful control of the critical assembly (reaction volume or neutron reflector), unlike previously published schemes. With on-line refueling they do not have significant energy production from decay of fission products. Thus emergency core cooling systems are not required and any melt-down is essentially impossible.

These engines offer the potential of high fuel burnup and actinides can be burned as part of the on-line refueling. Addition of fertile materials in the fuel region would allow breeding of fissile fuel, thus greatly enhancing the supply of fissionable material for nuclear energy applications.

Due to the dramatic self-shutoff mechanism, many configurations for these engines are

possible because energy production per cycle is insensitive to control of the reaction volume and neutron reflector. Engines can be free piston or connected to a flywheel through a crank shaft. They can be two cycle or four cycle, and the piston can be solid or liquid (e.g., molten lead). Examples of some configurations and their operation are given in a patent disclosure.⁴

ACKNOWLEDGMENTS

We are indebted to George Zimmerman for development and adaptation of a code that can perform the complex time-dependent, 2-D calculations required to model these nuclear engines. We also greatly appreciate many useful discussions with George on calculation of neutron transport using Monte Carlo techniques.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract #W-7405-Eng-48.

REFERENCES

1. G. H. CRISTEA, "Questions About the Feasibility of an Alternating Nuclear Engine," IFA-FR-115-1973, Institute for Atomic Physics, Bucharest, Romania (1973).
2. E. T. DUGAN, 1976. Nuclear Piston Engine and Pulsed Gaseous Core Reactor Power System, Ph.D. Dissertation, University of Florida at Gainesville, Florida.
3. B. A. ROSS and M. K. DROST, "Nuclear Closed-Cycle Gaseous Heat Engine Concept," 24th Intersociety Energy Conversion Engineering Conference, Vol. 5 (1989).
4. H. P. ALESSO, T. S. CHOW, R. H. CONDIT, J. E. HEIDRICH, J. S. PETTIBONE, and R. D. STREIT, Inherently Safe Nuclear-Driven Internal Combustion Engines, LLNL Patent File No. IL-8732 (April 15, 1991).
5. G. B. ZIMMERMAN, Lawrence Livermore National Laboratory, Livermore, CA. Private communication.
6. D. E. CULLEN, "Nuclear Cross Section Preparation," CRC Handbook of Nuclear Reactors Calculations, vol. 1, pp.102-127.
7. D. KRUCOFF, "Armour Dust-Fueled Reactor," Nucleonics, 100-106 (June, 1959).