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Technical note

A nuclear engine design with ^{242m}Am as a nuclear fuel

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Abstract

A preliminary design for a nuclear engine is presented. The engine is based on the nuclear heating of a gas composed of H_2 and ^{242m}Am as a nuclear fuel. This engine has an initial volume of 0.135 m^3 and at 64 MPa the critical mass is 0.228 kg. The simplicity ^{242m}Am of the engine design might compensate for the use of rare nuclear fuel, such as ^{242m}Am. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The idea of using ^{242}Am as a nuclear fuel was suggested by Ronen and Leibson (1987, 1988). The advantages of ^{242}Am as a nuclear fuel derive from the fact that ^{242}Am has the highest thermal fission cross section. The thermal capture cross section is relatively low and the number of neutrons per thermal fission is high. The half-life of ^{242m}Am is 141 years. These nuclear properties make ^{242m}Am an ideal nuclear fuel. The main disadvantage of this nuclear fuel is its low availability.

The isomer ^{242}Am is obtained by a neutron capture reaction with ^{241}Am, which has a relatively high thermal cross section of 85.7 ± 6.3b (Shinohara et al., 1997). The isotope ^{241}Am (half-life = 432.2 years) is obtained from the beta decay of ^{241}Pu (half-life 14.4 = years).

The fact that ^{242m}Am has a very high fission cross section and very high number of neutrons per fission make ^{242}m Am a very favorable nuclear fuel for special applications like space travel (Kammash et al., 1993). Another application presented in this paper is using ^{242m}Am as a nuclear fuel in an engine. The advantage of a nuclear engine is that nuclear energy is transferred directly into mechanical energy, as

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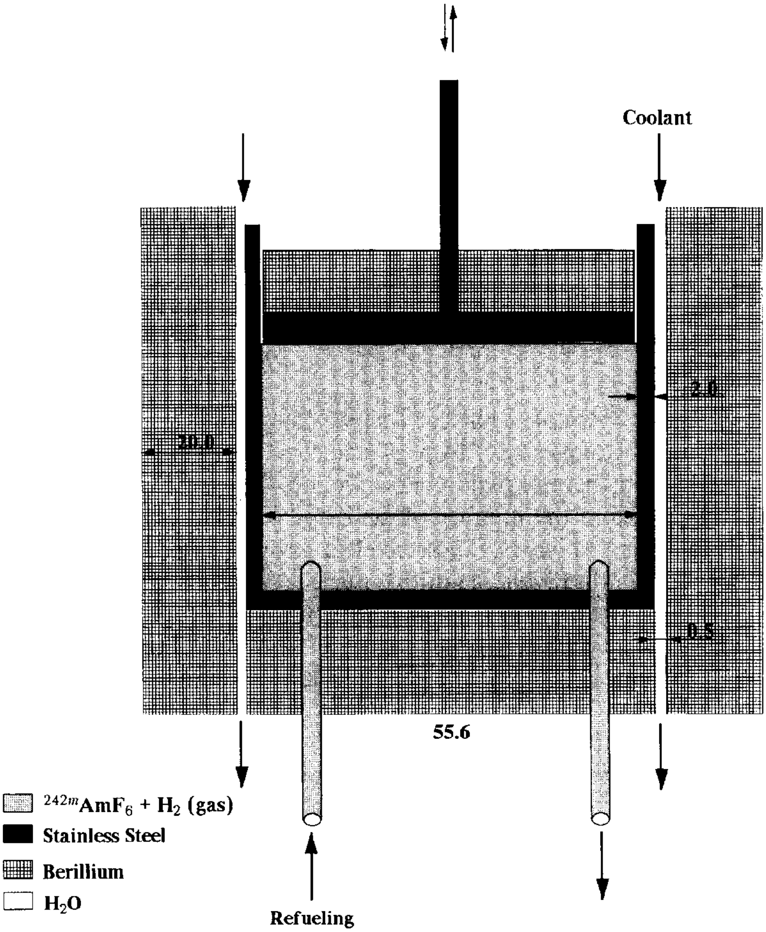
required in propulsion. Nuclear engines using UF_6 were suggested in the early sixties and more recently by Diaz et al. (1980).

A schematic configuration of this engine is given in Fig. 1. Such an engine is composed of a mixture of $^{242m}AmF_6$ in H_2, (hydrogen gas). The pressure of the gas is 64 MPa, the temperature is 400 K and the volume is 0.135 m^3. At this pressure the critical mass of ^{242m}Am is 0.2278 Kg. The hydrogen to ^{242m}Am atomic ratio is 4000. The hydrogen at 64 MPa and 400 K temperature has a density of 28.1 Kg/m^3.

2. The engine design

The density of hydrogen was calculated using the Beattie–Bridgeman equation of state (Van Wylen and Sontntag, 1978):



1. Schematic configuration of the nuclear engine (dimensions in cm).

$$P = \frac{RT(1-\varepsilon)}{\nu^2}(\nu + B) - \frac{A}{\nu^2} \tag{1}$$

$$A = A_0\left(1 - \frac{a}{\nu}\right) \tag{2}$$

$$B = B_0\left(1 - \frac{b}{\nu}\right) \tag{3}$$

$$\varepsilon = \frac{c}{\nu T^3} \tag{4}$$

where $1/\nu$ is the density in kmol/m^3 P is the pressure in KPa and T is the temperature in K. The parameters of the equation are:

$$A_0 = 20.0117$$

$$B_0 = 0.02096$$

$$a = -0.00506$$

$$b = -0.04359$$

$$c = 0.0504 \times 10^{-4}$$

$$R = 8.31434 \frac{Nm}{mol\,K}$$

The neutronic calculations of this nuclear engine were performed by the Monte-Carlo MCNP code (MCNP4, 1991). The cylinder of the engine is made of 0.02 m stainless steel with internal radius of 0.278 m (it should be noted that the 20 cm Berillium reflector is also part of the pressure structure). A criticality is obtained when the piston is at 0.556 m height. The engine is cooled on the outside. This nuclear engine has a Be reflector of 0.2 m.

The reaction rates obtained from the MCNP code are:

Fission	0.2808
Capture	0.4494
Leakage	0.2261
(n,2n)	0.0437

where the total absorption and leakage are normalized to 1. The distribution of the captures are 23.7% in the core, 62.3% in the stainless steel, 1.7% in water and 12.3% in the Be reflector.

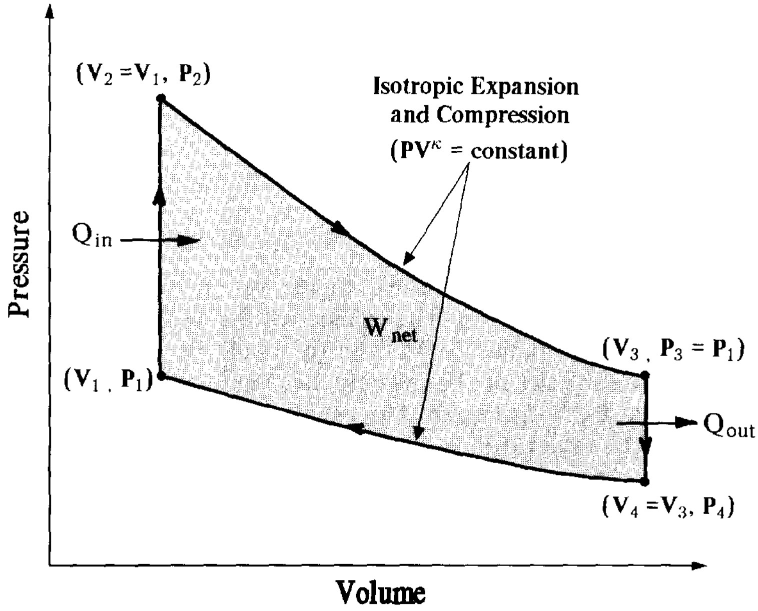
The amount of energy released in the fission of ^{242}Am is 207 MeV (Halsall and Taubman, 1986). The ratio of fission to absorption in the fuel is 0.8320, leading to a fuel consumption of 0.00126 Kg per 1 MWD.

3. Power calculations

Power is obtained by compressing the gas to a supercritical state. The energy released will push the piston and the engine will be subcritical.

The thermodynamic cycle of the nuclear engine is the Otto cycle. At a constant initial volume V_1, the gas is heated as a result of nuclear energy deposition, the pressure increases from P_1 to P_2 and the temperature increases from T_1 to T_2. At the initial conditions P_1, V_1 and T_1, the engine is supercritical and remains critical at P_2, V_1 and T_2. The piston is moved to a volume V_3, the pressure is P_3 and the temperature is T_3. At these conditions the engine is subcritical. At constant volume V_3 the gas is cooled to temperature T_4 and pressure P_4. Then the gas is compressed to the initial conditions V_1, P_1 and T_1. This cycle is presented in Fig. 2.

In order to obtain the order of magnitude of the thermodynamic parameters for the nuclear engine, we have assumed an ideal gas. In such a case the net work is obtained:



2. The Otto cycle of the nuclear engine.

$$W_{\text{net}} = \frac{P_3V_3 - P_2V_2}{1-\kappa} + \frac{P_1V_1 - P_4V_4}{1-\kappa} \tag{5}$$

The specific work is:

$$\frac{W_{\text{net}}}{V_1} = \frac{P_3\dfrac{V_3}{V_1} - P_2}{1-\kappa} + \frac{P_1 - P_4\dfrac{V_3}{V_1}}{1-\kappa} \tag{6}$$

with $V_4 = V_3$ and $V_2 = V_1$.

For κ we took the value of 1.4 and assumed that it is a constant in these temperature and pressure ranges.

The volume V_3 is obtained from:

$$\frac{V_3}{V_2} = \frac{V_3}{V_1} = \left(\frac{P_2}{P_2}\right)^{\frac{1}{\kappa}} \tag{7}$$

Using Eqs. (6 and 7) and assuming that $P_1 = P_3 = 64$ MPa, $T_1 = 400\,\text{K}$, $P_2 = 128$ MPa and $T_2 = 800\,\text{K}$, we obtain:

$$\frac{W_{\text{net}}}{V_1} = 28.74\frac{MJ}{m^3} \tag{8}$$

for the specific work.

The thermodynamic efficiency is given by:

$$\eta_{\text{Otto}} = 1 - \frac{1}{\left(\dfrac{V_3}{V_1}\right)^{\kappa-1}} = 1 - \frac{1}{1.64^{0.4}} = 0.18 \tag{9}$$

The specific heat supplied by those nuclear reactions must be 159.67 MJ/m^3. The specific power of this engine is:

$$\frac{\text{Power}}{V_1} = \frac{W_{\text{net}}}{V_1}\cdot\frac{D}{60}, \tag{10}$$

where D is the revolutions per minute (r.p.m.). The value of D should be determined by the cooling capacity of the system.

For the current design, the initial volume V_1 is 0.135 m^3. Thus, the power of the engine will be:

$$\text{Power} = 28.74\cdot 0.135\cdot\frac{D}{60} = 3.88\cdot\frac{D}{60}[\text{MW}]. \tag{11}$$

The value of D in r.p.m. is determined from the time it takes to cool the engine from T_3 to T_4 at volume V_3 (Q_{out} in the Otto cycle, Fig. 2). At this stage of the design the cooling aspects are not addressed and, therefore, D cannot be determined.

However, it is possible that at V_3 the gas fuel will be taken out of the engine for cooling and a cooled gas at temperature T_4 will be introduced. To do so would require a more sophisticated gas system, but D can have a large value leading to high power.

4. Summary

In this paper we present a very preliminary design of a nuclear engine. The novelty in the present approach is the use of ^{242m}Am as a nuclear fuel leading to a very small critical mass of 0.228 kg. This critical mass was calculated by the MCNP Monte Carlo code and the density of hydrogen was calculated using the adequate Beattie–Bridgeman equation of state. To calculate the power we have used the ideal gas equation in the Otto thermodynamic cycle. At the temperatures and pressures of the current design, the ideal gas equations are merely approximations and up to 40% uncertainty is expected. So the analyses presented, with respect to power, should be seen as an order of magnitude, rather than an actual design.

Using the ideal gas equations for the Otto cycle, we calculated that the power of the engine is $3.88 \times D/60$ [MW], where D is the revolution per minute of the engine. The power is mechanical. The value of D can be determined by a detailed analysis of the Otto cycle, and in particular the stage of Q_{out} in Fig. 2. However, if at stage 3 (in Fig. 2), the gas is removed from the engine for external cooling and introduced at point 4, the value of D might be large, leading to a higher power. However, in such a case, we would need quite a sophisticated gas system. At this stage of the design, such a system was not detailed. Furthermore, all the questions of cooling were not dealt with at this point.

Another aspect, not considered in the design, was the formation of AmF_4 from the chemical interaction of the hydrogen with AmF_6. However, circulating the gas in the engine would prevent any AmF_4 formed from precipitating on the engine surfaces.

The main advantage of the engine presented is its ability to produce a quite high quantity (order of MW) of mechanical power in a very simple engine, without the need to produce electrical power. The simplicity of such an engine might compensate for the fact that ^{242m}Am is an expensive fuel. As a result, such an engine might be suitable for propulsion applications.

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