Investigation the possibility of burning Cm a curium fuel reactor

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Abstract. Radioactive waste management is one of the main tasks of the nuclear power industry. Spent nuclear fuel poses a threat to the environment if it leaks from the storage facility. A possible solution to reduce waste storage and reduce the economic pressure of natural uranium shortages is to use minor actinides as fuel for nuclear reactors. This article is dedicated to the possibility of burning Cm in a reactor with curium fuel, as a result of which it can be used as fuel for a nuclear reactor. The purpose of the research is to study the possibility of creating a model of a reactor with curium fuel. Calculations were performed for a simplified single-zone model of the RBEC reactor using the «Serpent» software package. Calculations have shown that the use of the actinides as an alternative fuel is possible. That can later play an important role in reducing emissions of nuclear waste in nuclear power.

1. Introduction
Curium is the last element in the group of minor actinides (MA). The MA group includes Am, Cm, and Np [5]. There are only 14 known isotopes of curium with mass number 238-250, of which the longest-lived isotope is 247 Cm. Most isotopes of curium are the source of the α-decay. The accumulation of small amounts of some isotopes of curium in nuclear reactor is possible due to the irradiation of plutonium and uranium with neutrons.

Most curium isotopes are produced by nuclear reactors. During the capture of neutrons by fuel nuclei the accumulation of curium isotopes is occurs. Curium isotopes make the main contribution to the formation of the activity in spent nuclear fuel, and the main source of neutron radiation is Cm-244 [4]. The table 1 shows the neutron-physical characteristics of the main isotopes of curium.

| Nuclide | concentration, grams per ton (heavy nuclei) | $\sigma_t$ (thermal spectrum), barn | $\sigma_c$ (thermal spectrum), barn | $\sigma_t$ (fast spectrum), barn | $\sigma_c$ (fast spectrum), barn |
|---------|---------------------------------|-------------------------------|-------------------------------|-------------------|-------------------|
| $^{242}$Cm | 0.126 | 0.504 | 5.44 | 0.19 | 0.337 |
| $^{243}$Cm | 0.386 | 64.3 | 7.69 | 2.68 | 0.244 |
| $^{244}$Cm | 30.5 | 0.878 | 12.7 | 0.472 | 0.834 |
| $^{245}$Cm | 1.45 | 125.0 | 21.0 | 2.65 | 0.311 |
| $^{246}$Cm | 0.153 | 2.88 | 0.594 | 0.307 | 0.235 |
The purpose of this work is investigation of possibility of burning Cm a curium fuel reactor. It should be noted that curium has a huge heat generation (3 kW/kg for comparison, for plutonium 560 W/kg), consequently, when handling curium fuel, additional cooling in the core is necessary. Technical implementation issues were not discussed in this article. The half-life of 244Cm is 18 years, which is significantly less than that of other minor actinides and, therefore, after 40 years, the question of its storage becomes irrelevant. It is known how fuel behaves with minor actinides. In this work, the contribution of the curium component to MA transmutation was considered.

2. Model of the RBEC reactor with a modified core

In the course of the work, the possibilities of neutron-physical calculation of the reactor were studied using the "Serpent" software package developed at the state scientific and technical center in Finland in 2004.

«Serpent» is a software package that implements the Monte Carlo method and allows you to perform calculations of the reactor plant and its campaign with the highest possible accuracy:

- changes in the nuclide composition of nuclear fuel during irradiation in the reactor;
- fuel-element lifetime;
- microscopic cross-sections using a multi-group approach;
- infinite and effective neutron multiplication factor;
- distribution of energy deposition in the areas of the reactor facility;
- spent nuclear fuel activity;
- temperature effects of reactivity and much more [2].

This program also allows you to simulate the loading of an entire reactor with the ability to describe each individual element, channel or cell of the reactor core.

The Kurchatov Institute developed a new core concept in 2000 with a number of changes for the fast reactor. These changes include: new heat carriers (heavy metal material), a wide spacing grid of fuel elements, fuel assemblies (FA) without a shroud, a heterogeneous U-Pu core arrangement, and others. This new reactor, called the RBEC.

The RBEC reactor uses lead-bismuth material as a coolant.

The RBEC project with a power of 900 MW(t) is a three-circuit reactor cooled by a lead-bismuth coolant [3]. The duration of the fuel cycle is 4 years.

A simplified model was used in the calculations. Instead of the design three zones, a single-zone model was used in the calculations. The geometry of the simplified model is shown in figures 1-2.

Figure 1. Geometry of the simplified model of the RBEC core (1-active core, 2-blanket region, 3-core reflection).
U+Cm) N was used as the fuel. The volume fractions at which the operation of this reactor would be possible are calculated: 0.79-UN and 0.21-CmN. Uranium is the waste uranium with an enrichment of 0.1% by the isotope $^{235}$U.

The most interesting isotopes are $^{243}$Cm, $^{244}$Cm and $^{245}$Cm. Their half-lives, respectively:
- 30 years $^{243}$Cm,
- 18.1 years $^{244}$Cm,
- 8500 years $^{245}$Cm.

The volume fractions of these isotopes will be equal to:
- 0.2% $^{243}$Cm,
- 94.08% $^{244}$Cm,
- 5.72% $^{245}$Cm.

3. Calculation of the investigation of transmutation Cm a curium fuel reactor.

3.1. Neutron-physical properties of a uranium-curium reactor

Calculations have shown that the fuel-element lifetime for such a reactor is 12 years. Figure 3 shows the change in the multiplication factor over 12 years of the fuel-element lifetime RBEC reactor with curium fuel. The increase in the effective multiplication coefficient at the beginning of the fuel-element lifetime is associated with the appearance of new fissile isotopes and a decrease in their ratio during fuel burn-up.

![Figure 3. Variation of the multiplication coefficient from the time of irradiation.](image-url)
In the first 2 years, the multiplication coefficient increases, since the amount of the fissile element is included not only by the amount of 244Cm, but by the produced isotope (for example, 245Cm, which can be a fissile material). Plutonium is also being produced. From 238U, 239Pu appears. From 2 years to 4 years, the multiplication coefficient does not change significantly. Then it decreases evenly. Consider how the concentration of all curium isotopes changes during irradiation. Table 2 shows the results of calculating the change in the nuclide composition of the fuel from the time of irradiation in the reactor.

Table 2. Change in the isotopic composition of fuel during its burn-up (units of measurement 1/cm3).

| Nuclide | 0 days | 100 days | 300 days | 500 days | 2 years |
|---------|--------|----------|----------|----------|---------|
| 234U    | 0      | 6.20102×10^{14} | 1.96811×10^{15} | 3.98355×10^{15} | 7.55481×10^{15} |
| 235U    | 9.63828×10^{18} | 8.53862×10^{18} | 6.88937×10^{18} | 5.72389×10^{18} | 4.69869×10^{18} |
| 238U    | 9.53974×10^{21} | 9.38825×10^{21} | 9.12512×10^{21} | 8.90317×10^{21} | 8.67188×10^{20} |
| 237Np   | 0      | 7.22792×10^{17} | 1.98723×10^{18} | 2.91584×10^{18} | 3.75704×10^{18} |
| 238Pu   | 0      | 2.41681×10^{16} | 1.94791×10^{17} | 4.38085×10^{17} | 7.64198×10^{17} |
| 239Pu   | 0      | 1.19784×10^{20} | 3.02657×10^{20} | 4.27203×10^{20} | 5.32014×10^{20} |
| 240Pu   | 0      | 2.40409×10^{19} | 7.05536×10^{19} | 1.13212×10^{20} | 1.57467×10^{20} |
| 241Pu   | 0      | 2.78934×10^{17} | 1.97837×10^{18} | 4.69000×10^{18} | 7.92315×10^{18} |
| 242Pu   | 0      | 2.05528×10^{15} | 3.85861×10^{16} | 1.34294×10^{17} | 3.28829×10^{17} |
| 241Am   | 0      | 1.23005×10^{15} | 2.61331×10^{16} | 1.00519×10^{17} | 2.58750×10^{17} |
| 242Am   | 0      | 3.06991×10^{12} | 1.68671×10^{14} | 9.32552×10^{14} | 3.16636×10^{15} |
| 243Am   | 0      | 5.58788×10^{14} | 1.84437×10^{15} | 4.62826×10^{15} | 1.15528×10^{16} |
| 242Cm   | 3.29687×10^{19} | 2.76062×10^{19} | 2.01194×10^{19} | 1.52737×10^{19} | 1.13690×10^{19} |
| 244Cm   | 2.26247×10^{21} | 2.11896×10^{21} | 1.88014×10^{21} | 1.68849×10^{21} | 1.50169×10^{21} |
| 245Cm   | 2.43006×10^{20} | 2.71866×10^{20} | 3.02250×10^{20} | 3.12200×10^{20} | 3.11254×10^{20} |

| Nuclide | 4 years | 6 years | 8 years | 10 years | 12 years |
|---------|---------|---------|---------|----------|----------|
| 234U    | 3.01362×10^{16} | 7.22168×10^{16} | 1.34801×10^{17} | 2.17679×10^{17} | 3.18863×10^{17} |
| 235U    | 2.60087×10^{18} | 1.48886×10^{18} | 8.49809×10^{17} | 4.79966×10^{17} | 2.70762×10^{17} |
| 238U    | 8.00807×10^{21} | 7.41652×10^{21} | 6.84894×10^{21} | 6.28967×10^{21} | 5.73533×10^{21} |
| 237Np   | 5.45985×10^{18} | 6.21636×10^{18} | 6.38662×10^{18} | 1.61064×10^{18} | 5.69947×10^{18} |
| 238Pu   | 1.97894×10^{18} | 3.27317×10^{18} | 4.59259×10^{18} | 5.84633×10^{18} | 6.90829×10^{18} |
| 239Pu   | 7.23280×10^{20} | 7.94990×10^{20} | 8.08909×10^{20} | 7.89896×10^{20} | 7.50662×10^{20} |
| 240Pu   | 2.68002×10^{20} | 3.39857×10^{20} | 3.82932×10^{20} | 4.04306×10^{20} | 4.09181×10^{20} |
| 241Pu   | 2.06903×10^{19} | 3.24061×10^{19} | 4.21493×10^{19} | 4.93399×10^{19} | 5.39110×10^{19} |
| 242Pu   | 1.62742×10^{18} | 3.84306×10^{18} | 6.85722×10^{18} | 1.04839×10^{19} | 1.44443×10^{19} |
| 241Am   | 1.27184×10^{18} | 2.86154×10^{18} | 4.60430×10^{18} | 6.13726×10^{18} | 7.22516×10^{18} |
| 242Am   | 2.61910×10^{16} | 7.73542×10^{16} | 1.52727×10^{17} | 2.38496×10^{17} | 3.17238×10^{17} |
| 243Am   | 8.52344×10^{16} | 2.77668×10^{17} | 6.34938×10^{17} | 1.18939×10^{18} | 1.94375×10^{18} |
| 242Cm   | 4.65466×10^{18} | 1.97810×10^{18} | 8.30559×10^{17} | 3.48669×10^{17} | 1.61119×10^{17} |
| 244Cm   | 1.04768×10^{20} | 7.37465×10^{20} | 5.14212×10^{20} | 3.52360×10^{20} | 2.36372×10^{20} |
| 245Cm   | 2.70207×10^{20} | 2.13146×10^{20} | 1.59195×10^{20} | 1.13377×10^{20} | 7.75275×10^{19} |
Figure 4. Change in the fraction of Cm in fuel during burn-up.

Figure 4 shows that the Cm mass will decrease by 8 times over the 12 years of the fuel-element lifetime. Separately, you should see how the concentration of each Cm isotope will change during the burn-up process (figure 5).

Figure 5. Change in the nuclear density of Cm isotopes during burn-up.

The concentration of the 245Cm isotope increases at the beginning of irradiation, and then decreases evenly. Since the value of the fission cross-section in the fast area of this isotope is greater than that of the others, this explains the increase in the effective multiplication coefficient in the first 2 years of operation of the reactor.
When considering all minor actinides (with the exception of Cm), a significant increase in the concentration of isotopes $^{239}$Pu and $^{240}$Pu occurs in the reactor during the fuel-element lifetime (figure 6).

### 4. Conclusion

Investigations have shown that it is possible to use Cm as a fuel in a fast reactor. The $k_{eff}$ value increases at the beginning of irradiation, and then falls. This is due to the appearance of new fissile isotopes and a decrease in their ratio during the fuel-element lifetime. During the fuel-element lifetime, the Cm concentration decreased by 8 times, and the total concentration of MA actinides will decrease by 1.6 times. The successful building of a reactor with curium fuel will open up opportunities for using minor actinides as an alternative fuel for uranium. This plays an important role in reducing nuclear waste emissions in the nuclear power industry.

### References

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