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# Fuel design and core layout for a Gas Cooled Fast Reactor

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Two core concepts are presented for a Gas Cooled Fast Reactor using helium coolant with high outlet temperature. The fuel design should achieve the goal of a self-sustaining core. Two fuel elements are proposed: coated particles redesigned from conventional TRISO (HTR) particles, and hollow fuel spheres, an innovative fuel element featuring a shell of fuel with ceramic cladding. For both fuel elements a rudimentary core layout is presented, featuring a high thermal output of 2400 MWth and a low power density of 50 MW/m$^3$. All core materials are ceramics because of the high temperature output. The results indicate that a self-sustaining core is possible without the use of blankets. The irradiation period is rather long (1900 days) because of the low specific power. The core with coated particles requires a slightly higher fuel inventory. Using hollow fuel spheres it is possible to design a fuel with a positive burnup reactivity swing.

***KEYWORDS: Gas Cooled Fast Reactor, fuel, fuel cycle, coated particles, Generation IV, core layout, self-sustaining core.***

## 1. Introduction

The Gas Cooled Fast Reactor (GCFR) is a nuclear reactor with a fast neutron spectrum and gas cooling. In the late sixties and early seventies, several research programmes for GCFR concepts were initiated. Because of fundamental safety and materials issues the GCFR was abandonned in favour of the liquid metal cooled fast reactor. Recently, the Generation IV International Forum has included the GCFR as one of the six reference reactor concepts for the future, focusing on the advantages of a gaseous coolant: helium is neutronically and chemically inert, cannot boil and enables operation at high temperatures. With nuclear fuel in plentiful supply there is no need for short doubling times and extreme core power densities, enabling safe operation of the GCFR. The key goal selected within the Generation IV framework for the GCFR is sustainability, which implies a closed fuel cycle with full and integral recycling (i.e. recycling in the same type of reactor with on-site reprocessing if possible) of all trans-uranics (TRU), minimal use of uranium resources, and minimal waste production. In this paper a fuel design and rudimentary core layout are prepared for a 2400 MWth GCFR with self-breeding capability.

## 2. Fuel design for GCFR

GCFR research currently focuses on two values of thermal output: a small-scale modular system of 600 MWth and a large-scale 2400 MWth system, the latter system attracting the main focus in our group. Both systems are intended to be used for direct cycle electricity generation (efficiency of 50%), and feature helium cooling and an outlet temperature of 850°C. We are currently developing a fuel composition, burnup and reprocessing strategy for

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a 2400 MWth GCFR. Some key features of the system under investigation are:

- Cilindrical core with height $h_c$ = 3 m. and radius $r_c$ = 2.25 m., with an average volumetric power density $\overline{P}$ of 50 MW/m$^3$, giving a core volume $V_c$ of 47.71 m$^3$, and a power output of 2386 MWth.
- Fuel is a mix of depleted uranium (U-238 > 99.8%) and recycled LWR plutonium (70% fissile).
- Nitride fuel, enriched in N-15 to 99.9%.
- Fuel elements cooled directly by helium.
- Helium pressure 10 MPa, $T_{in}$ = 450°C, $T_{out}$ = 850°C.
- Conversion ratio equal to 1 (self-breeding capability), if possible without the use of blankets (enhanced proliferation resistance).

The fuel options include CERCER and CERMET dispersion fuels, and coated particles. We have selected coated particles because of the symbiosis with thermal (V)HTR systems and safety. Because of basic limitations of coated particles, a new type of hollow fuel element (fuel element: lump of fuel with cladding) is proposed too. Both types of fuel element are used for neutronic calculations.

### 2.1 Coated Particles for Gas Cooled Fast Reactors

The TRISO coated particle (CP) as developed for thermal HTR systems features a fuel kernel, surrounded by a porous, low density (50% of theoretical density) graphite buffer layer, an inner pyrocarbon (IPyC) layer, a sealing layer (usually SiC for HTRs) and an outer pyrocarbon layer (OPyC). The function of the buffer layer is to store gaseous fission products, to accomodate kernel swelling and to protect the outer layers from recoiling fission fragments. The OPyC layer provides a good thermal contact between the TRISO particle and the surrounding graphite matrix. The IPyC and OPyC layers contract under irradiation, releaving the stresses in the SiC layer caused by the pressure of the fission gasses [1]. However, the IPyC and OPyC layers fail under irradiation by highly energetic neutrons, causing failure of the particle. Coated particles for a GCFR with direct cooling do not require the IPyC and OPyC layers, leaving a CP with a fuel kernel, a buffer layer and a sealing layer. This reduces the amount of non-fuel materials in the CP, reducing parasitic capture. To obtain a high fuel volume fraction in the CP, the volume of the buffer and sealing layer must be made as small as possible.

The sealing layer fails when the overpressure inside the CP is too large. The maximum allowable overpressure within the CP can be calulated as follows: assume a sphere of radius $R$ surrounded by a shell of thickness $\delta$. If the pressure inside the shell is higher than outside, the tangential stress in the shell can be expressed as a function of the pressure difference $\Delta P$ acting on the shell. If $\delta << R$ (thin shell approximation), the tangential stress in the shell is given by:

$$\sigma_{xx} = \sigma_{yy} = \frac{R}{2\delta} \cdot \Delta P \qquad (1)$$

Note that $\sigma_{xx}$ is a function of the ratio $R/\delta$. The maximum allowable $\Delta P$ is fixed by the choice of material ($\sigma_{max}$) and the geometry ($R/\delta$) of the particle.

The fission process leads to swelling of the fuel and the generation of gaseous fission products (FP). If we assume an ideal gas model for the gaseous FP in the buffer, the pressure in the buffer can be written as a function of burnup as:

$$P_{buf} = \frac{FIMA \cdot n_0 \cdot z \cdot k \cdot T_{buf}}{V_{buf}} \tag{2}$$

in which FIMA stands for Fissions per Initial Metal Atom, $n_0$ is the number of heavy metal atoms in the fuel kernel at Begin Of Cycle (BOC), $z$ is the number of gas atoms released into the buffer per fissioned metal atom, $k$ is Boltzmann's constant, $\varepsilon$ is the porosity of the buffer layer, and $T_{buf}$ , $V_{buf}$ are the temperature and free volume of the buffer respectively. Note that $V_{buf}$ is a function of burnup. The pressure in the buffer layer must not exceed the limits of the sealing layer. It can be readily inferred from eqs. (1) and (2) that a coated particle with a small buffer and thin sealing layer cannot be used up to high burnups. A solution could be to increase the volume of the buffer, but this reduces the fuel volume fraction in the CP and increases the amount of moderating and absorbing material in the CP.

For GCFR applications ZrC seems more suitable than SiC for the sealing layer: it is more easily soluble than SiC and energy transfer to the Zr nuclei, and thus material damage, is smaller because Zr has a higher atomic mass than Si.

### 2.2 Hollow fuel sphere

The hollow fuel sphere is an innovative type of fuel element, featuring a hollow shell of fuel, surrounded by a cladding layer (see figure 1). This fuel element is similar to the one proposed in [2]. The main advantage of this design is that the amount of voidage (empty space) is increased: in a TRISO CP, about 50% of the buffer volume is empty space, whereas in the hollow fuel sphere 100% of the inner void is empty space. A hollow fuel sphere with the same volume fraction of fuel and cladding as a TRISO-like CP has more room to store FPs, and at the same time there is less moderating material, yielding a harder spectrum and decreasing parasitic absorption. A buffer between fuel and cladding is not necessary as long as the penetration depth of fission fragments is much smaller than the thickness of the cladding layer. We propose a hollow fuel sphere with a diameter $d_{fuel}$ = 3 cm., a cladded by a layer of ZrC of thickness $t_c$ = 2 mm. A hollow fuel sphere can be manufactured as follows: UPuN powder with some glueing agent is pressed to form hollow hemispheres, which are sintered to form a hollow sphere. Then the cladding is applied using Chemical Vapour Deposition (CVD) or a similar process.

## 3. General core layout

Two core layouts have been prepared, one using the CP fuel, and one using the hollow fuel spheres. The fuel elements are arranged in packed beds and cooled directly by the helium. The pressure drop, which should not exceed about 2% of the system pressure [3], limits the height of the bed of fuel elements. The pressure drop over a packed bed of particles can be estimated using the Ergun-relation [3,4]:

$$\frac{\Delta p}{L} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu_f}{d_k^2} u + 1.75 \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho_f}{d_k} u^2 \tag{3}$$

in which $\varepsilon$ is the porosity of the bed, $\mu_f$ is the viscosity of the fluid, $d_k$ is the diameter of the particles, $u$ is the superficial fluid velocity, and $\rho_f$ is the density of the fluid. The superficial velocity of the coolant is proportional to the mass flow rate of fluid:

$$\dot{m} = \rho_f A u \qquad (4)$$

in which $\dot{m}$ is the mass flow rate of fluid, and $A$ is the flow area. The mass flow rate required to transfer the heat from a cilindrical bed of fuel using axial flow is proportional to the volume of the bed multiplied by $\overline{P}$:

$$\dot{m} = \frac{\overline{P}LA}{c_p \Delta T} \qquad (5)$$

in which $L$ is the bed height, $A$ the surface area in axial direction, $\Delta T$ is the temperature rise over the core of the coolant, and $c_p$ the heat capacity of the fluid. Combining eqs. (3), (4) and (5) results in:

$$\Delta p = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu_f}{\rho_f d_k^2} \frac{\overline{P}L^2}{\Delta T c_p} + 1.75 \frac{1-\varepsilon}{\varepsilon^3} \frac{1}{\rho_f d_k} \frac{\overline{P}^2 L^3}{\Delta T^2 c_p^2} \qquad (6)$$

This alternative version of Ergun's relation can be used to estimate the pressure drop over a bed of spherical fuel elements. Using $\overline{P}$ = 50 MW/m$^3$ and taking the values of $\rho_f$, $\mu_f$ at $T$ = 650°C, and $c_p$ = 5.195.10$^3$ J/kg.K [3], the pressure drop can be estimated for a given geometry of the fuel elements and bed height. For the hollow fuel spheres ($d_k$ = 3 cm) we find a maximum bed height of about 1 m[a]. For the coated particles ($d_k$ = 1 mm) the maximum bed height is several cm. With these figures it is now possible to make a general core layout.

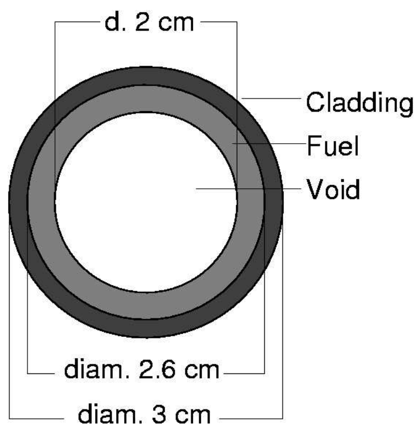


**Fig 1:** a hollow fuel sphere. The central void is empty to accommodate fission gas release and fuel swelling.

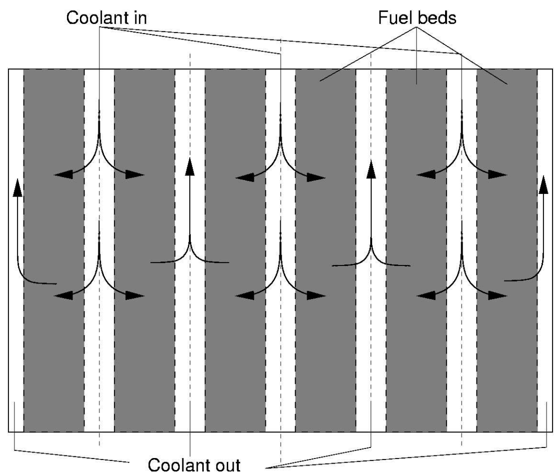


**Fig 2:** General layout for a GCFR core using hollow fuel spheres (axial cross section through cilindrical core, not to scale). The coolant enters from the top, flows radially through the beds and exits again at the top.

[a] For $d_k$ = 6 cm, which is the size of the pebbles in a thermal pebble bed reactor, the maximum bed height is less than 1.5 m at a power density of 50 MW/m$^3$. The 'classical' pebble bed as used in thermal HTR concepts, is thus not applicable for a GCFR.

### 3.1 Core layout for hollow fuel spheres

Because the maximum allowable bed height is smaller than $h_c$, the fuel elements are arranged in annular concentric cilindrical beds of height $h_c$ and thickness $d_{ac}$, with the coolant flowing radially. Doing so, all coolant must enter and leave the reactor at the non-fueled parts between the fuel beds. This is illustrated in Fig. 2. Since the coolant velocity should not be too high at the inlet(s) and outlet(s), the space between the fuel beds cannot be made arbitrarily small, which implies that the volume fraction of the fuel beds in the core is limited. With $\overline{P}$ = 50 MW/m$^3$, and $u_{He,max}$ = 125 m/s [5,6], the allowable volume fraction of the fuel beds is about 77%. For higher $\overline{P}$, the volume fraction of fuel beds must be decreased to limit the velocity of the coolant at the outlet(s) (e.g. for $\overline{P}$ = 100 MW/m$^3$ the volume fraction of fuel beds should be decreased to around 65%). Using a packing fraction of fuel spheres in the beds of 0.63 and a fuel bed volume fraction of 77%, the coolant volume fraction becomes 51%, the fraction of fuel spheres 49%, and the fuel fraction about 32% for a fuel sphere as described in section 2.2. Because the maximum bed height is the limiting factor, the core is divided into 3 concentric zones with equal thickness ($r_i$ - $r_{i-1}$ = 75 cm). The inner and outer radii of the fuel beds are chosen to give a volume fraction of 77% of each zone. The fissile enrichment per zone is selected to give a flat power profile.

### 3.2 Core layout for coated particles

In this core design the fuel particles are arranged in annular cilinders with the coolant flowing radially through the fuel bed, as illustrated in Fig. 3. The annular cilinders are arranged in a hexagonal lattice. Depending on the size of these cilinders, 3 or 7 (or more) can be arranged to make up 1 fuel sub-assembly. The fuel beds occupy 75% of the cilinder volume, the limit being set by the velocity of the coolant at the in- and outlet. This configuration has a coolant volume fraction of 57% of $V_c$, a volume fraction of CPs of 43%, and a fuel fraction of $(r_k/r_t)^3$ * 0.43 of fuel, with $r_k$ the radius of the fuel kernel and $r_t$ the radius of the entire particle. In order to get a good overall core fuel volume fraction, $r_k/r_t$ has to be rather large. A large kernel is required with small buffer and coating volume. An improvement can be found if annular hexagons are used instead of annular cilinders: with annular hexagons the fuel beds occupy a larger fraction of the core volume, and the fuel kernel can be reduced in size whilst maintaining the overall fuel volume fraction. For calculations using these assemblies the core is divided into 3 zones of equal volume, and the fissile enrichment per zone is selected to give a flat power profile.

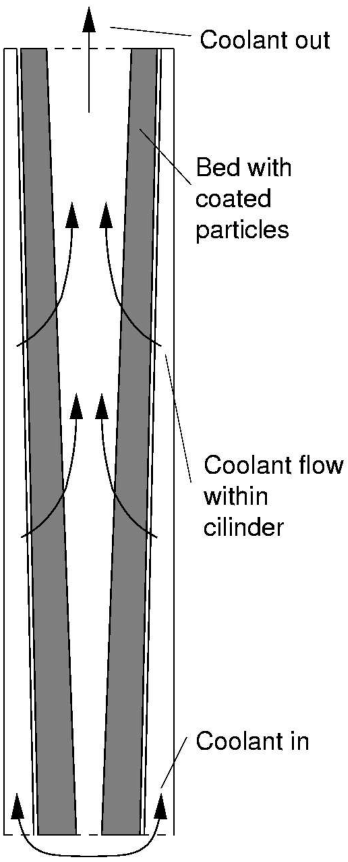


**Fig. 3:** Cross section of an annular cilinder with a fuel bed of CPs (not to scale).

## 4 Neutronics calculations

1-D neutronics calculations were done using a 172-group cross section library based on JEF-2.2 [7]. SCALE [8] CSAS (BONAMI - NITAWL - XSDRNPM) is used to generate the cell-weighted cross-sections to calculate the flux pattern and power profile. Fuel depletion in each zone of the reactor is calculated with COUPLE - ORIGEN-S. The plutonium is initially assumed to be recycled from LWR MOx-fuel, with isotopic vector at BOC as given in table 1 [9]. Non-cladding structural materials were simulated as SiC, 5% of $V_c$, and the core is surrounded by a stainless steel reflector.

**Table 1:** Isotopic vector of the plutonium at BOC

| Isotope | Pu-238 | Pu-239 | Pu-240 | Pu-241 | Pu-242 |
|---|---|---|---|---|---|
| Fraction at BOC | 1 % | 62 % | 24 % | 8 % | 5 % |

### 4.1 Results for hollow fuel spheres

A burnup calculation was done with the hollow fuel spheres. Two fuel compositions were used: one using an average Pu content in the core of 12.44%, and one using 15.44%. For the core with higher Pu content the total amount of fuel is reduced to give roughly the same $k_{eff}$ at BOC. The main results are summarized in table 2 and illustrated in Fig. 4 and Fig. 5. With a low Pu content $k_{eff}$ shows an increasing trend, as does the amount of fissile material (Pu-239 + Pu-241) in the core. At EOC, the burnup is 3.96% FIMA, and the amount of plutonium is larger than at BOC. A higher Pu content was selected to reduce breeding. The core with the high Pu content has a decreasing $k_{eff}$ and a net conversion factor just below 1. The Fuel Temperature Coefficient (FTC) is negative for both cores for all times in the burnup cycle and its magnitude shows a decreasing trend. The FTC is calculated by determining $k_{eff}$ at $T = T_0 + 100$ K, and then taking 1/100 * ($\Delta k/k$). The reason for the decreasing magniture of FTC has not yet been identified.

**Table 2:** Summary of core inventory of the hollow fuel sphere GCFR concept. All masses are at BOC. Burnup period: 1900 equivalent full power days

| | Low Pu content | High Pu content |
|---|---|---|
| Zone 1<br>Zone 2<br>Zone 3<br>Total: | HM/Pu: 12899/1419 kg<br>HM/Pu: 38278/4593 kg<br>HM/Pu: 63370/8238 kg<br>HM/Pu: 114547/14250 kg | HM/Pu: 9697/1358 kg<br>HM/Pu: 28778/4317 kg<br>HM/Pu: 47641/7623 kg<br>HM/Pu: 86116/13298 kg |
| Pu content 1 / 2 / 3 / average | 11% / 12% / 13% / 12.44% | 14% / 15% / 16% / 15.44% |
| EOC:<br>FIMA average<br>Change Pu<br>Change Pu fissile | <br>3.96 %<br>+ 6 %<br>+ 4.8 % | <br>5.26 %<br>- 0.25 %<br>- 4.4 % |
| $d_{sphere}$ / $t_{clad}$ / $t_{fuel}$ | 3 / 0.2 / 0.325 cm | 3 / 0.2 / 0.25 cm |

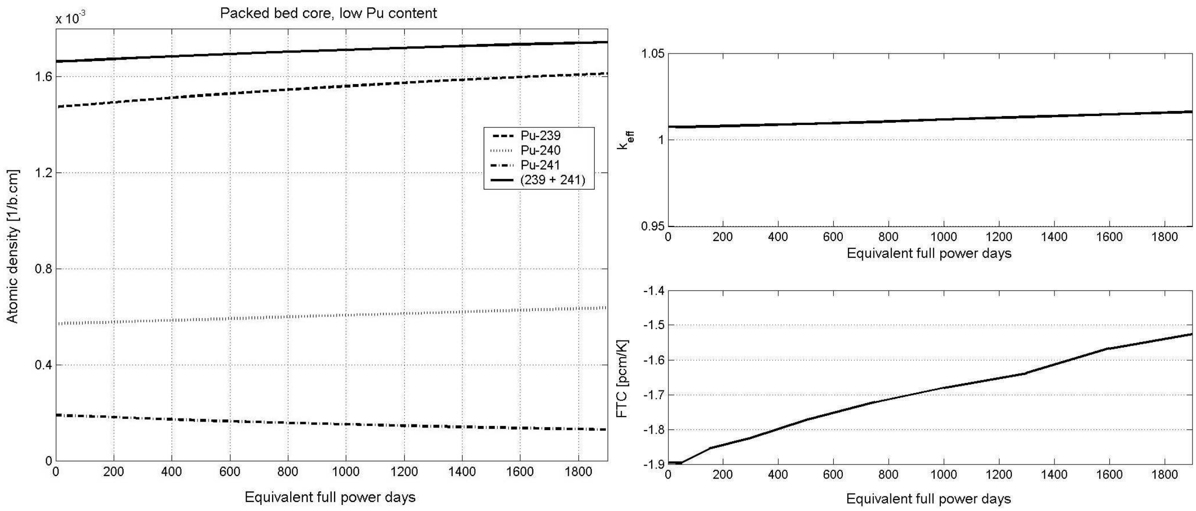


**Fig 4:** Hollow fuel sphere core, low Pu content. Left: atomic density of 3 Pu isotopes, atomic density of fissile material (Pu-239 and Pu-241). The total atomic density of fissile material at EOC is larger than at BOC. Right: $k_{eff}$ and FTC during burnup. Note the increase in $k_{eff}$ with burnup.

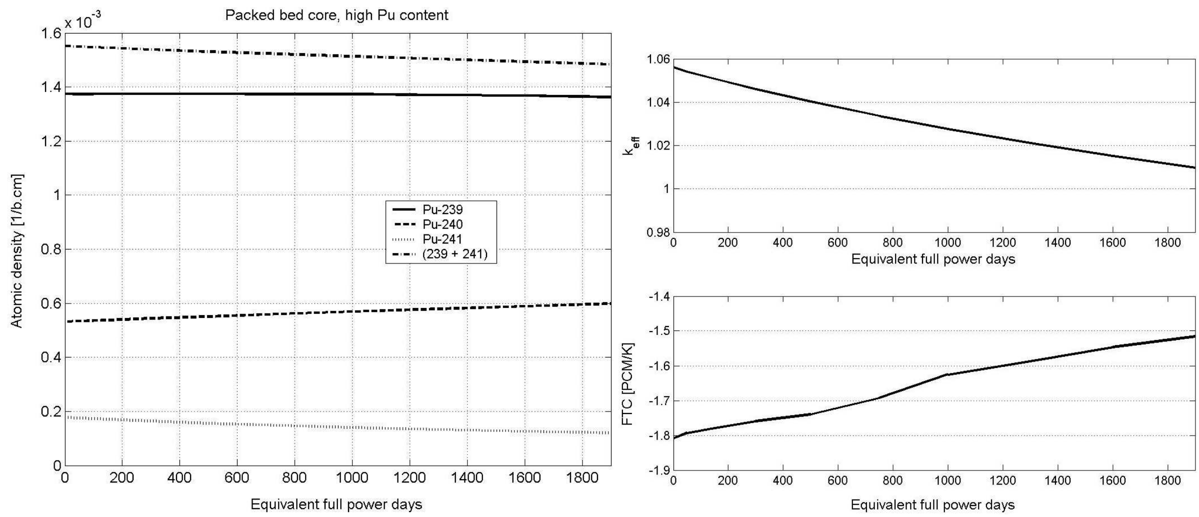


**Fig 5:** Hollow fuel sphere core, high Pu content. Left: atomic density of 3 Pu isotopes, atomic density of fissile material (Pu-239 and Pu-241). The total atomic density of fissile material at EOC is smaller than at BOC. Right: $k_{eff}$ and FTC during burnup. $k_{eff}$ decreases but is always larger than 1 during burnup.

## 4.2 Results for coated particles

The core with coated particles has a lower volume fraction of fuel elements (43% for CPs, 49% for hollow spheres), hence the CPs must have a larger volume fraction of fuel in order to obtain the same overall core fuel volume fraction. The CPs have $r_t$ = 500 µm, with $r_k$=760 µm (700 µm for high Pu content), and a cladding thickness $t_c$ of 50 µm. This means that the buffer volume is about 25% to 30% of the total particle and hence the porous graphite cannot be neglected in the calculations. Again two Pu contents were used to perform the calculations (average 13.3% and 15%). For the higher fissile content the total amount of fuel was reduced to give approximately the same $k_{eff}$ at BOC. The results are summarized in table 3 and illustrated in Fig. 6 and Fig. 7. Using a low Pu content results in a slight increase of the fissile mass at EOC, a decreasing $k_{eff}$ and a burnup of 3.8% FIMA after 1900 days at full power. The core with high Pu content has a lower total fuel loading, a decrease in fissile mass at EOC, a decreasing $k_{eff}$ and an average burnup of 4.8% FIMA. The burnup is higher because the fuel loading at BOC is lower. Both cores always have a negative FTC, and again the magnitude of FTC decreases with burnup.

**Table 3:** Summary of core inventory of the CP GCFR concept. All masses are at BOC, burnup period: 1900 equivalent full power days.

| | Low Pu content | High Pu content |
|---|---|---|
| Zone 1 | HM/Pu: 39166/4700 kg | HM/Pu: 30605/3979 kg |
| Zone 2 | HM/Pu: 39298/5109 kg | HM/Pu: 30710/4607 kg |
| Zone 3 | HM/Pu: 38870/5831 kg | HM/Pu: 30376/5164 kg |
| Total: | HM/Pu: 117334/15640 kg | HM/Pu: 91691/13750 kg |
| Pu content 1 / 2 / 3 / average | 12% / 13% / 15% / 13.3% | 13% / 15% / 17% / 15% |
| EOC: | | |
| FIMA average | 3.84 % | 4.9 % |
| Change Pu | 3.48 % | 0.33 % |
| Change Pu fissile | 0.96 % | -4.7 % |
| $r_k/r_b/r_t$ | 760 / 450 / 500 μm | 700 / 450 / 500 μm |

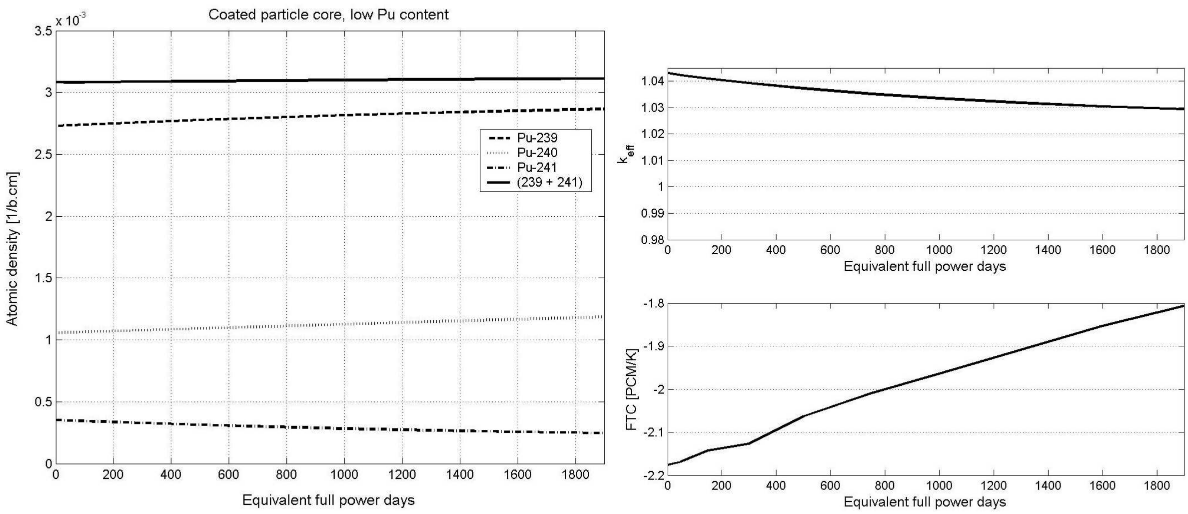


**Fig 6:** Coated particle core, low Pu content. Left: atomic density of 3 Pu isotopes, atomic density of fissile material (Pu-239 and Pu-241). The total atomic density of fissile material at EOC is slightly larger than at BOC, but the increase is very small. Right: $k_{eff}$ and FTC during burnup. The inital value of $k_{eff}$ is larger than 1.04, so the Pu content can be reduced further to improve conversion.

**4.3 Discussion of results**

The results indicate that it is possible to design a fuel and core layout for both hollow fuel spheres and CP fuel that will lead to a self-sustaining fuel cycle, i.e. there will be enough fissile material after reprocessing to start a new cycle. The average Pu content should be around 13% (average over core) at BOC. A self-sustaining core without blankets will also yield a low burnup reactivity swing, with the possibility of an increasing $k_{eff}$ during burnup as illustrated by the hollow sphere core with low Pu content. The optimal (integral) fuel cycle requires recycling of all MA in the same reactor, but the MA loading is probably limited by safety constraints [10].

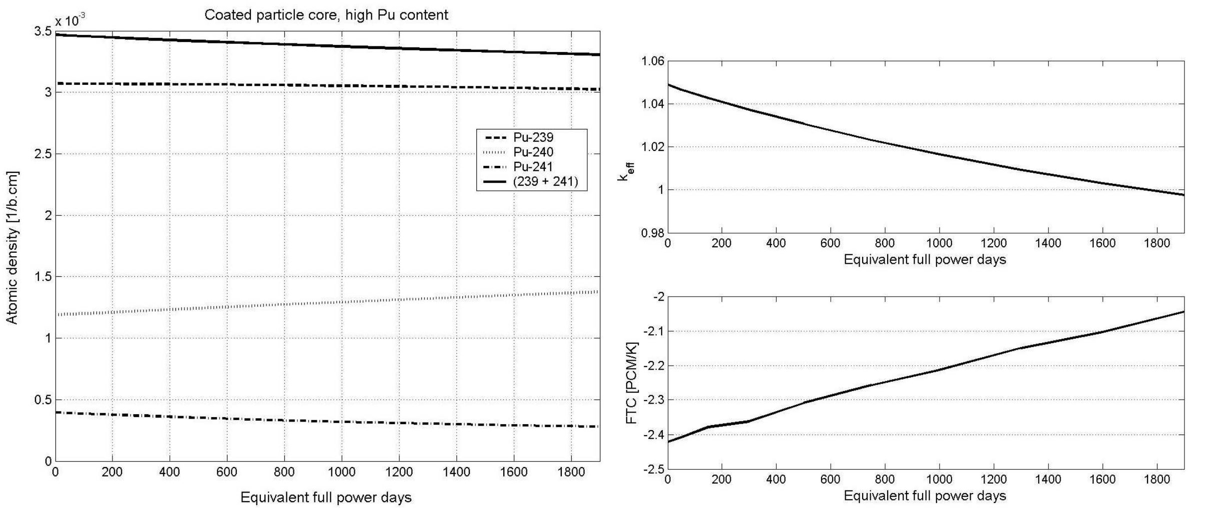


**Fig 7:** Coated particle core, high Pu content. Left: atomic density of 3 Pu isotopes, atomic density of fissile material (Pu-239 and Pu-241). The total atomic density of fissile material at EOC is smaller than at BOC, even though the density of Pu-239 is almost constant. Right: $k_{eff}$ and FTC during burnup. At the end of the irradiation $k_{eff}$ is 0.98.

The fuel cycle presented in this paper has a length of 1900 days (5.2 years). The length of the fuel cycle is determined by the (fissile) specific power $P^*$, which is rather low for the GCFR: $P^*$ = 21 W/gHM, $P^*_{fiss}$ = 250 W/g (Compare: $P^*_{fiss}$ = 1 kW/g for LWR, 1.2 kW/g for HTR). To reach the same FIMA, an irradiation in a GCFR takes roughly 4 times longer than an LWR irradiation. The fuel cycle of 1900 days leads to a reprocessing interval of the same length. This will deteriorate the Pu-vector after reprocessing, because $T_{1/2}$ of Pu-241 is 14.4 years.

## 5 Conclusion, further research

The results presented in this paper are not yet completely satisfying the criterion of a self-sustaining fuel cycle, and the calculations are not very detailed because of the 1-D codes used. However, there are still many possibilities to improve the design:

- Core H/D ratio can be varied. The choice for H/D ratio depends on LOCA-behaviour and has not yet been treated in detail.
- The volume fractions of the fuel beds have been estimated using rather crude methods based on a conservative approach , and a more detailed (thermal and flow) analysis will probably allow a larger volume fraction for the fuel beds. This reduces the volume requirement of fuel in the fuel elements, which is especially beneficial for the CP fuel.
- The fissile enrichment can be varied, as well as the total fuel loading. The designs presented here are all far away from the tentative limits set in the Gen IV GFR R&D plans regarding maximum power density and Pu loading. The limits are: maximum Pu loading 15 tons/GWe (the presented designs have 12 tons/GWe for hollow fuel spheres and 13

tons/GWe for CPs), and $\overline{P}$ between 50 and 100 MW/m$^3$ [11].

- The fuel elements can be split into two groups: breeder elements and burner elements. The breeder elements contain a large volume fraction of U-238. There are almost no fissions in these elements so a large buffer is not required. The burner elements are loaded with TRU only and feature a large buffer to accommodate the fission gasses and kernel swelling. The elements should be mixed to give the required TRU content.
- Small blankets could be added to make sure conversion is adequate for the self-sustaining fuel cycle. More efficient (fast) neutron reflectors using $Zr_3Si_2$ [12] or high Ti-alloys are under development and could improve neutron economy.

Current plans are to treat the reprocessing of the fuel in more detail, and to extend the core calculations to 2-D. When a satisfactory fuel composition and reprocessing strategy have been established, safety and control mechnisms will be studied. Other core layouts for the 2400 MWth GCFR will also be studied.

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