Kungliga Tekniska högskolan

Small Reactors (SH2611)

Final Project

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1 Introduction

This report presents the conceptual design and safety analysis of a 300 MW_e helium-cooled, graphite-moderated HTR, developed as part of the final project for the Small Reactor Design course. The project objectives include designing a core configuration that achieves an average fuel burn-up of 50 GWd/t while maintaining a control rod worth below 0.5 $. Passive safety measures were assessed for station blackout scenarios using air-cooling of the reactor vessel, and iodine retention requirements were evaluated to restrict the emergency planning zone to 100 m. An economic analysis was also conducted to estimate the Levelized Cost of Electricity (LCOE) for both single-unit and multi-unit installations.

2 Design of our HTR of 300 MWe

2.1 Overall design

The proposed reactor is a 300 MW_e HTR using helium gas as coolant and graphite as moderator. The thermal power is approximately 700 MW_{th}, assuming a 43% thermal efficiency, in line with similar high-temperature gas-cooled systems.

The fuel is uranium dioxide (UO_2) enriched at 9.9% in ^{235}U. Burnable poison in the form of B_{10} is included via B_4C in the control rods. The core adopts a hexagonal lattice layout, with a total diameter of 6 m. Reflective boundaries are assumed for simplification.

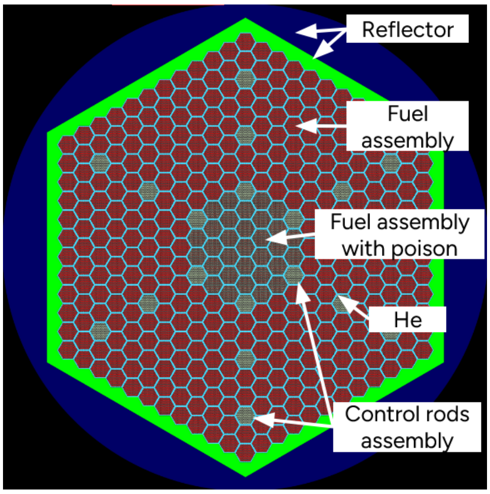

Figure 1: Core descrption.

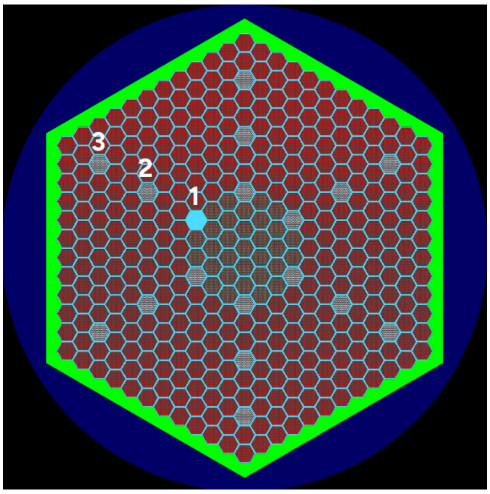

Figure 2: Control rod assemblies.

2.2 Control rod value

To limit the control rod worth below 0.5$, we adopted a symmetric control rod configuration. A layout with 3-fold rotational symmetry was selected to ensure effective reactivity control while preserving radial symmetry and minimizing perturbations in the neutron flux.

The final configuration allows for adequate shutdown margin with a total assembly worth maintained below the 0.5$ limit.

Table 1: Control rod assembly worth

Control Rod Assembly No.	Worth ($)
1	0.18
2	0.50
3	0.44

2.3 Reactivity swing

The reactivity swing over a burn-up of 50 GWd/t was evaluated using parameters obtained during the course. Assuming the full cycle from beginning-of-life (BOL) to end-of-life (EOL), the total swing was found to be approximately 8257 pcm. The reactivity gain at EOL was estimated at 656 pcm, which corresponds to roughly 1$, confirming the adequacy of the control rod design.

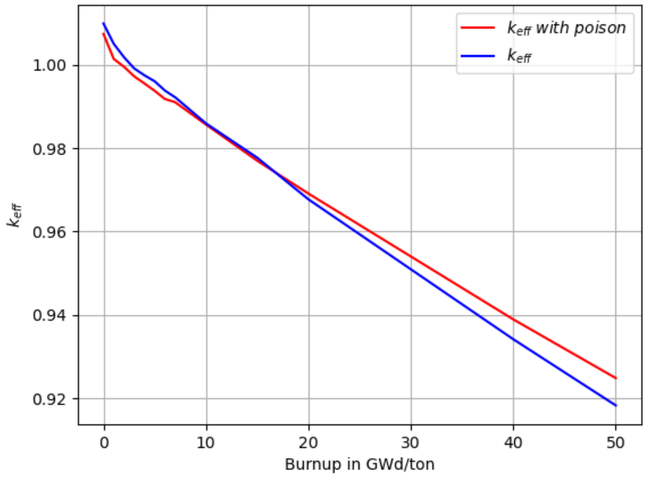

Figure 3: Reactivity swing with and without burnable poison.

3 Safety study

3.1 Vessel height and buffer volume of graphite

For passive decay heat removal in a station blackout scenario, we assessed the required graphite buffer volume to ensure sufficient heat conduction and air-side convective cooling. Following the methodology from course materials (J. Walenius, 2025), a chimney height of 20 m and air flow cross-section of 6.5 m^2 were assumed. First, The time τ required to reach peak temperature is obtained:

$$\tau = \left(\frac{a_d\, \dot{Q}_{\text{nom}}}{c_P^{\text{air}}\, c_\rho^{\text{air}}\, A_{\text{air}} \sqrt{g\, H_{\text{air}}}} \times \frac{\sqrt{T_{\text{in}}\, T_{\text{out}}\, (T_{\text{in}} + T_{\text{out}})}}{\Delta T_{\text{air}}^{3/2}} \right)^{1/\lambda_d}$$

From the time τ it is possible to estimate the required buffer mass as follows:

$$m_{\text{buffer}} = \frac{\dot{Q}_{\text{nom}}}{\Delta T_{\text{buffer}}\, c_p^{\text{buffer}}} \left(-\frac{0.11\, \beta_{\text{eff}}}{\Delta\rho} + \frac{a_d\, \lambda_d}{1 - \lambda_d}\, \tau^{1-\lambda_d} \right)$$

Table 2: Key parameters for thermal and safety calculations

Parameter	Value	Units	Description
Q_{nom}	700×10^6	W	Reactor thermal power (300 MW_e × 2.33 efficiency factor)
ΔT_{buffer}	50	K	Temperature rise in the graphite buffer (800 K – 750 K)
$c_{\text{buffer},P}$	710	J/kg·K	Specific heat of graphite at constant pressure
β_{eff}	0.0065	$\Delta k/k$	Effective delayed neutron fraction (650 pcm)
$\Delta\rho$	0.0065	$\Delta k/k$	Negative reactivity inserted during SCRAM (5 × β_{eff})
a_d	0.12	–	Design parameter (dimensionless)
λ_d	0.275	–	Average decay constant ($1/s$)
$c_{\text{air},\rho}$	352	J/kg·K	Specific heat of air at constant density
$c_{\text{air},P}$	1000	J/kg·K	Specific heat of air at constant pressure
A_{air}	6.5	m^2	Cross-sectional area for air flow
g	9.81	m/s^2	Acceleration due to gravity
H_{air}	25.0	m	Air flow height (chimney height)
T_{in}	298	K	Inlet air temperature (25°C)
T_{out}	398	K	Outlet air temperature (125°C)
ΔT_{air}	100	K	Air temperature rise ($T_{\text{out}} - T_{\text{in}}$)

The required buffer mass was estimated at 519 tons, corresponding to a buffer volume of approximately 230 m^3. This results in a total vessel height of 10 m to accommodate the heat-conducting graphite.

3.2 Retention factor of iodine

To restrict the emergency planning zone to 100 m, we estimated the necessary iodine retention factor. Atmospheric dispersion was modelled assuming stability condition F, a wind speed of 1.0 m/s, and surface roughness of 1 cm. Also assuming release and plume heights of 20 and 50m.

First of all, let's assess the iodine inventory for 700 MW_{th}:

Table 3: Radiological characteristics of iodine-131 and iodine-133

Nuclide	Half-life	ε (nSv/Bq)	Inventory (PBq)
^{131}I	8.02 days	20	1412
^{133}I	20.8 hours	4	1421

It should be noteduel rods is assumed to be dais assumed to beed and 10% of the iodine pellet inventory is released into the gas gap. Key parameters for evaluating plume dispersion:

- Friction velocity $v_f = 0.127\ \frac{m}{s}$
- Monin-Obukov length, assuming $T_{surf} - T_{air} = -2K$, is $L_{MO} = 37.36\ m$
- Mixing height, at latitude = 60°N, is $H_{mix} = 77.41\ m$

Then we evaluate the dispersion widths and then apply the necessary correction to obtain:

- Horizontal dispersion width $\sigma_y^{\text{corr}} = 43.87\ m$
- Vertical dispersion width $\sigma_z^{\text{corr}} = 43.47\ m$

Once the plume has been characterized, the dilution factor can be evaluated as:

$$\frac{A_{\text{ground}}(r,z)}{A_{\text{source}}(0,h)} = \frac{1}{2\pi v_{\text{plume}}\sigma_y(r)\sigma_z(r)} \sum_{n=-2}^{2} \left[\exp\left(\frac{-nH_{\text{mix}} - h - z}{2\sigma_z(r)}\right)^2 + \exp\left(\frac{-nH_{\text{mix}} + h + z}{2\sigma_z(r)}\right)^2 \right]$$

The value of this ratio is $F_{diluition} = \ m^{-3}s^{-1}$,represents the ratio between the activity released at the chimney and the activity in the interested distance and height of 1.7 to simulate the average height of a person.

Consequently, it can be calculated the equivalent dose, considering an inhalation period of 1h and a breathing rate of 1 $\frac{m^3}{h}$:

$$H(r,z,\tau) = \epsilon \times \dot{B} \times \Delta t_B \times \int_0^{\tau} A(r,z,t)\,dt = \epsilon \times \dot{B} \times \Delta t_B \times \left[\frac{A_{source}}{\lambda} F_{diluition} \ \left(1 - e^{-\lambda\tau}\right) \right]$$

Where τ = 7 days, according to the Swedish dose criterion of max 10 mSv in that absorption period. Summing the contributions of the two nuclides, the equivalent dose is $H = 2.65 * 10^{10} Sv$ which basically means that a retention of 100% is necessary to respect the criterion.

4 Economic assessment

Using the HTR-PM cost benchmark of 2500 €/kWe and assuming a 20-year debt repayment period and 90% plant availability, we estimated the Levelized Cost of Electricity (LCOE).

4.1 CAPEX

To determine the value for the CAPEX we adopted a weighted average cost of capital (WACC) equal to 0.06 that corresponds to the European average value [1]. The WACC is a weighted average of the cost, split between equity and debt. Once we have set the value for the WACC, we proceeded to estimate the CAPEX:

$$CAPEX = Cost_{construction} \times \frac{WACC}{1 - \frac{1}{(1+WACC)^n}},$$

where n is the debt repayment period in years (20 years in this case).

4.2 OPEX

We calculated the value for OPEX considering 5 different categories of cost:

- Operations and Management
- Fuel
- Waste
- Tax

- Electricity

The cost for each category shown in Table 4, excluding the fuel cost category, is estimated after the data from the course material for a 50 MWe module [1]. The data were originally provided in SEK but were converted to euros using an exchange rate of 11 SEK/EUR. For waste management, we have applied the LWR value as no reliable TRISO-specific disposal cost data were found.

Table 4: Costs for a 50 MWe unit

Category	**50 MWe SMR (SEK/MWh)**
O & M	331
Fuel	101 [2]
Waste	34
Tax	2
Electricity	9
Total	**477**

The category $O\&M$ is scaled from a 50 MWe reference unit to a 300 MWe unit based on the assumption that costs scale with the square root of the power capacity, reflecting economy of scale:

$$\frac{Cost(P_{small})}{Cost(P_{large})} \approx \left(\frac{P_{large}}{P_{small}}\right)^{0.5}$$

4.3 Final economic assessment

The levelized cost of energy (LCOE) is calculated:

$$LCOE = \frac{CAPEX + OPEX}{Annual\ Energy\ Production}.$$

Results for a single unit and a 10 units plant are shown in Table 5

Table 5: Economic assessment of single vs multi-unit HTR deployment

Parameter	**Single Unit (300 MWe)**	**10 Units (3000 MWe)**
Energy Production [GWh/yr]	2365.2	23652.0
Construction Cost [€/kWe]	4000	4000
CAPEX [M€]	96.29	962.91
OPEX [M€]	60.44	405.79
LCOE [€/MWh]	66.27	57.87

For a single unit, the LCOE is significantly impacted by fixed capital and operational expenditures. However, when scaling to 10 installed units, operational and maintenance costs benefit from economy of scale, scaling with the square root of the number of units. This results in a noticeable decrease in LCOE for multi-unit configurations, making the deployment of HTRs in clusters more economically viable.

5 Conclusion:

This study demonstrates the feasibility of a 300 MWe HTR design with robust passive safety and competitive economics. Key design constraints such as reactivity swing and shutdown margin, however the emergency planning zone requirements are difficult to satisfied. The design is well-suited for modular deployment in future low-carbon energy systems.

References

[1] Janne Wallenius. *2025 Economy of Small Reactors*. Lecture notes, retrieved from course material. 2025.

[2] Astute Analytica. *TRI-Structural Isotropic (TRISO) Fuel Market Report, 2025*. Accessed: 2025-07-09. 2025. URL: `https://www.astuteanalytica.com/industry-report/tri-structural-isotropic-fuel-market`.