

Telescopic Control Rod for Significant Reduction in HTR Height and Cost

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Abstract

High temperature gas-cooled reactors (HTRs) are intentionally tall and thin to enable passive decay heat removal through conduction, with a core height of 8 m being typical. Units are typically embedded in the ground, which has numerous safety advantages but requires excavating a deep silo, the cost of which grows super-linearly with depth. HTRs contain rigid control rods that add additional space above the core and make the silo deeper. A concept for a telescopic control rod containing ~5 concentric annuli is proposed. Depending on the design details of the HTR, this has the potential to significantly reduce the silo depth and hence provide substantial reactor capital cost savings. Neutronic analysis demonstrates that a telescopic control rod consisting of 5 concentric annuli can achieve >90% of the control rod worth of a typical articulated HTR control rod without further compensatory measures. The addition of a more control rods or a minor redesign of the rod can recover the deficit in worth if necessary to ensure shutdown margin requirements are met. The telescopic control rod will deplete faster than the reference control rod, which may necessitate more frequent replacement, but this is not anticipated to be a serious drawback as HTR control rods are not inserted extensively at power (especially in pebble bed reactors). The telescopic control rod can be constructed using materials already qualified for HTR environments. Further work is required to demonstrate comprehensively mechanical design, reactor physics and materials feasibility, and the necessary steps are identified in the paper. For mechanical design, a failure modes and effects analysis is required to identify possible failure mechanisms and their consequences, so that they can be designed out or mitigated. The friction/wear resistance of mechanical components must also be evaluated through experimentation on a prototype control rod in a high temperature helium environment. The arrangement of the upper head must also be considered. For reactor physics, the differential control rod worth must be investigated. Finally, a cost benefit analysis should be performed.

Keywords: HTR, control rod, worth, compact component, telescopic

1. Introduction

HTRs are typically embedded in the ground. This provides substantial benefits for structural support of Nuclear Steam Supply components and the Reactor Cavity Cooling System, security, ease of refueling and prevention of damage due to airplane crash; but is costly due to the need to excavate the silo, along with dewatering and stabilization challenges and external flooding hazards in some potential sites [1].

To enable passive post-accident decay heat removal, HTR cores are intentionally tall relative to other reactor concepts – the Framatome SC-HTGR core [1] is typical, with an 8 m height. Full length control rods are used, which introduces an additional 8 m of height above the core. The positioning of the reserve shutdown system (RSS) and fuel handling system can complicate the design of the upper head in HTRs. This height is also typical of pebble bed designs, for example 8.9 m for the Xe-100 design in Ref. [2] and 11 m for the HTR-PM [3].

In both prismatic and pebble-bed HTRs, control rods are typically inserted into holes several centimeters in diameter. These are in the reflector region [4], and in the case of prismatic HTRs may also be located in the core [1]. Control rods are typically 'black'. i.e., they absorb a large proportion of incident neutrons. There is therefore scope for increasing the density of the absorber (e.g., by removing or changing the matrix material) and for making the absorbing region of the control rod thinner. There are various engineering solutions for HTR control rod drive mechanisms (CRDMs) including cables with a rotating drum, and a rack-and-pinion mechanism [5] [6].

Control rods contain absorber material, which is typically boron carbide or boron carbide in a graphite matrix (Fig. 1). The absorber material is typically annular in shape, as shown below, and is clad internally and externally. The cladding is a nickel-based alloy, codified for use in a HTR (e.g., Alloy 800H [1]). Some concepts postulate a carbon-carbon composite cladding [7], and SiC/SiC composites are also a potential future option. The neutronic performance of the control rod is not sensitive to the composition of the clad or coolant. The number of suitable materials is limited by both the environment and the need for expensive code qualification.

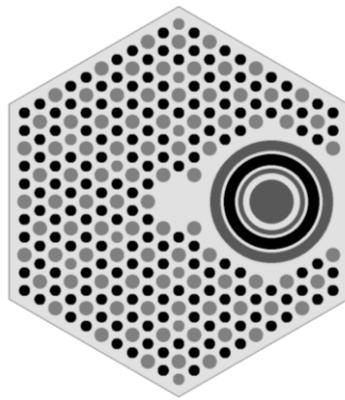


Figure 1: Conventional control rod inserted within a typical fuel block in a prismatic HTR. The black annulus contains boron. The large grey circle is the containing hole.

In addition to control rods, HTRs can typically be shut down through the RSS, in which small boron-containing balls are poured into tubes within the reactor [8]. These holes are typically separate to those used for the control rods. These provide a failsafe if the control rods fail to insert but are not used routinely as it is cumbersome to remove the balls after deployment.

The German pebble bed design, HTR-MODUL, utilized part length control rods, possibly in order to limit the height of the silo. The Chinese HTR-PM, largely based on the German HTR-MODUL design, has investigated an canister-based control rod design with some resemblance to the telescopic control rod proposed here, apparently to enable routine cold shutdown without using the RSS and without needing to increase the silo depth. In this concept, an articulated annular control rod contains an articulated central cylindrical control rod within it. This concept is discussed in a HTR-PM patent [9] but, to our knowledge, not otherwise covered in public domain literature. Novelty of the current paper rests on (1) extension to more than 2 telescoping stages (not proposed or addressed from either the mechanical engineering or neutronic standpoint in Ref. [9]), (2) a preliminary demonstration of the reactor physics feasibility of the telescopic control rod design through calculations. The extent to which the latter has been performed in China is unknown – although Ref. [9] does not extend to a demonstration that control rod worth is maintained for the case where the conventional control rod is full length. Also, for successful

implementation of this concept in the U.S., a domestic research program with public domain analysis and experiment is required.

The rest of this paper is structured as follows:

- Section 2 gives a high-level description of the telescopic control rod concept.
- Section 3 gives an overview of mechanical design considerations.
- Section 4 gives an overview of the materials selection methodology.
- Section 5 presents neutronics calculations that demonstrate proof of principle.
- Section 6 presents conclusions and future work.

This paper is focused on a preliminary demonstration of neutronic feasibility, notably to establish that the integral control rod worth is sufficient. Further work is required to demonstrate or otherwise whether the control rod could be deployed in practice: including high temperature testing of the extension and contraction of the control rod in a high temperature helium environment.

2. Concept Description

A concept for a telescopic control rod containing ~5 concentric annuli (Fig. 2) that nest together when withdrawn is proposed. The height occupied the control rod above the core is then reduced by 80% of the core height, making possible reduced silo depth. With 5 concentric annuli and an 8 m core height, this corresponds to a 6.4 m reduction in the height occupied by the control rod.

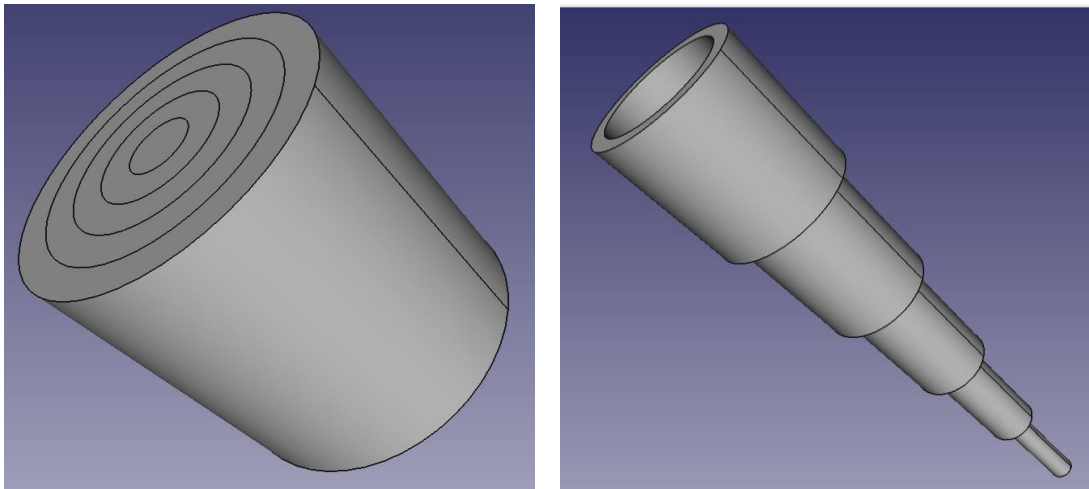


Figure 2: Telescopic control rod retracted (left) and extended (right). Drawing is simplified illustration. The actual control rod has a much larger aspect ratio.

Representative dimensions for the 5-annulus telescopic control rod are given in Table 1 for a 6.5 cm control rod hole, which is typical. These were determined through engineering judgement based on neutronics considerations (see Section 5). The absorber is clad in an Inconel alloy. The clad thickness is 0.6 mm, and clearance between surfaces is 1 mm, both of which are readily achievable. These parameters are unlikely to be optimal, but serve to validate the concept. It is assumed that the absorber material is clad both internally and externally. Plan views of the control rod located within a fuel block are given in Fig. 3. The rings get progressively thinner moving outwards, as the boron towards the outside of the control rod becomes more volumetrically efficient by intersecting a larger number of neutrons (see Section 5).

Table 1: Representative telescopic control rod dimensions.

Annulus	1	2	3	4	5
Inner clad radius (cm)	-	3.327	4.366	5.241	5.898
Inner absorber radius (cm)	-	3.387	4.426	5.301	5.958
Outer absorber radius (cm)	3.167	4.206	5.081	5.738	6.340
Outer clad radius (cm)	3.227	4.266	5.141	5.798	6.400

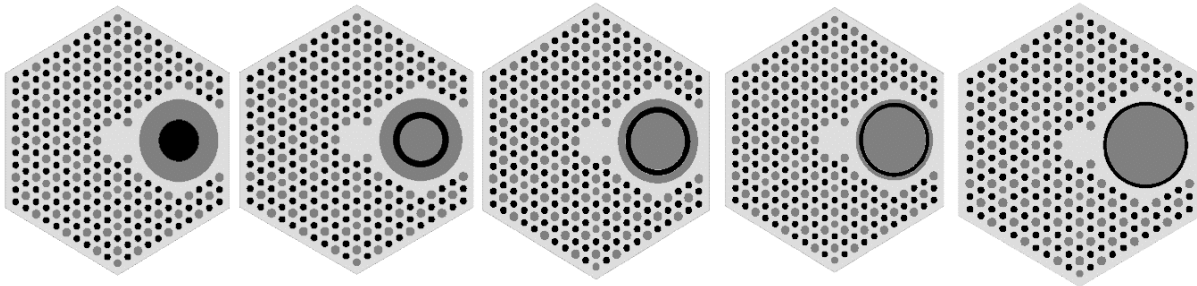


Figure 3: HTR fuel block with five-ring telescopic control rod (absorber material in block) inside of control rod hole (dark grey).

HTRs have high technology readiness [10] and hence a crucial issue in HTR commercialization is construction cost (along with first of a kind licensing and performance demonstration) HTRs are tall compared to competitor nuclear reactors, which means that the cost of constructing the silo is significant and grows super-linearly with silo depth. Nuclear cost of construction dominates the total electricity cost from nuclear power [11]. If a ~6m saving in the silo height is realized, an initial, high-level estimate of the capital cost saving based on Framatome's expert judgement is 15-20%. Even if the actual height saving is significantly reduced through practical considerations, there remains significant potential for meaningful reduction in cost.

The increased complexity of the telescopic control rod relative to standard approaches, along with any additional design complexities that are introduced (e.g., in the refueling machine) must be weighed against the savings from reduction of the silo height. Nevertheless, the design of the control rod will be standardized and is amenable to offsite factory manufacture. The philosophy of small modular reactors (SMRs) recognizes on-site costs as the key driver of new reactor capital cost [12], and hence the telescopic control rod is consistent with this through reducing on-site construction cost by off-site volume manufacture of a standardized component.

The shorter control rods may also make it practical to extend the RPV to house the control rods within the vessel. The concept may hence provide a pathway to integral HTR technology, with significant reduction in vessel penetrations with potential safety benefits through simplifying RPV code compliance.

2. Mechanical Design

Current CRDMs typically use either gravity for rod deployment and cable or chains for retraction, or a rigid rod with a rack-and-pinion mechanism (or equivalent) for rod deployment and retraction. A telescoping control rod can use either of these drive mechanisms, which will simplify the design, manufacturing, and qualification processes.

The key difference to current control rod designs is the titular telescoping mechanism. While this design could reduce capital cost, it has the potential to introduce failure modes that impact safety and

manufacturability and could introduce regulatory challenges. A full failure modes and effects analysis (FMEA) will be performed in future work. However, key considerations are given below. Although it will likely be possible to design out these risks, the introduced complexity may reduce the original cost savings.

- The sequence of extension of the nested annular elements must be deterministic, to deliver a controllable level of neutron absorption as a function of control input. The telescoping rod can therefore be designed so that the minimum potential state is assumed at all stages of deployment, i.e., each annulus will be as low as possible (right of Fig. 4). The configuration on the left, or other intermediate configurations, may occur if there is substantial friction. To ensure this is successfully achieved between multiple sets of sliding contacts, it is important to:
 - control interface friction to acceptable levels, accounting for the effect of differential thermal expansions, and
 - provide such pressure relief as may be necessary to avoid an adverse pressure gradient from the inside to the outside of the control rod.
- Rod ejection accidents are typically designed out in HTRs as there is no mechanism for a conventional control rod (consisting of a set of connected canisters) to eject. However, the telescope mechanism has the potential to introduce this failure mode through contraction of the telescope.
- The CRDM should also be capable of resisting accidental insertion caused by pneumatic loading from coolant flows (HTRs typically have downward flowing coolant in the core). This is not a major concern and can be addressed in the engineering design.
- Rod-drop accidents have higher potential consequences. A conventional control rod can only fall into the core and insert negative reactivity. However, if not designed out, mechanical failure of the telescopic control rod could cause the rod to fall to the bottom of the core and contract so that only the bottom fraction of the core is 'rodded', hence requiring the RSS to insert sufficient negative reactivity to shut down the core. The locking of the control rod to the guide tube should therefore be sufficiently robust to not overly increase the safety demands placed on the RSS. Nested flanges at the top of each annulus offers a straightforward solution to limit the motion of each annulus relative to its neighboring elements.

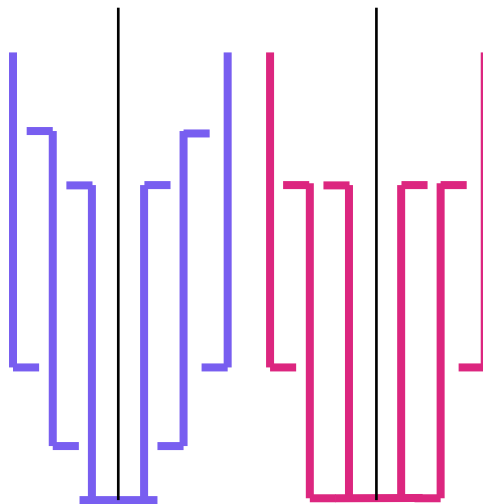


Figure 4: Telescopic mechanism with cable controlling extension of central column.

3. Materials Selection

The control rods in HTRs experience high temperatures. A typical temperature for the core inlet (top) and core outlet (bottom) are 325°C and 750°C respectively (for the SC-HTGR [1]). Higher temperatures are

possible in some designs (for example HTTR in Japan has an outlet temperature of 950°C [13]) and may ultimately be targeted for Very High Temperature Reactors (VHTRs).

Control rods will typically experience the temperature at the inlet if withdrawn or if inserted into the reflector, and may experience higher temperatures if partially inserted into the core, or during transient/accident scenarios. Due to the intrinsic safety of HTRs, the insertion of the control rods is sometimes delayed during loss of forced cooling transients to limit the temperature experienced by the control rods, depending on the choice of materials.

Near-term implementation of the telescopic control rod is targeted and the reference concept uses standard HTR control rod materials, i.e. B₄C or B₄C-graphite absorber clad in Alloy 800H, which are codified for use in HTR. The use of advanced materials for higher temperature operation is not however precluded by the concept, e.g. carbon-carbon or SiC/SiC composite cladding.

The tribological performance of the mechanical components is also important. Annulus sections have to slide in and out with limited friction and wear. The relatively low temperature experienced by the Ni-alloy rod in operating conditions should ensure the formation of a thin oxide layer [14], which is beneficial for wear resistance, provided it is mechanically stable. Indeed, under wear and friction at these temperatures, a low friction glaze oxide layer is formed which is beneficial for wear resistance relative to the metal-metal friction [15].

Testing of the control rod in a high temperature helium environment is nonetheless required to determine that the control rod can extend and contract under operating conditions, and that wear of the sliding interfaces is not a life-limiting factor.

Irradiation swelling is not anticipated to be an issue as control rod insertion at power is relatively limited in prismatic HTRs (slight insertion of the reflector rods to manage excess reactivity), and is even lower in pebble bed reactors where excess reactivity is essentially zero.

4. Nuclear Performance

4.1. Development of Neutronic Model

Proof-of-concept calculations were performed on a reactor physics model of the Gas Turbine Modular Helium Reactor (GT-MHR) as this is the subject of an IAEA international benchmark [16]. The GT-MHR core (Fig. 5) is very similar to the Framatome SC-HTGR, and hence is representative of contemporary prismatic HTRs. This also provides a means of ensuring that calculated control rod worths for the conventional control rod are consistent with reported values. The goal of these calculations is to quantify the change in control rod worth from the telescopic control rod and hence evaluate its impact on shutdown margin depletion performance is also investigated.

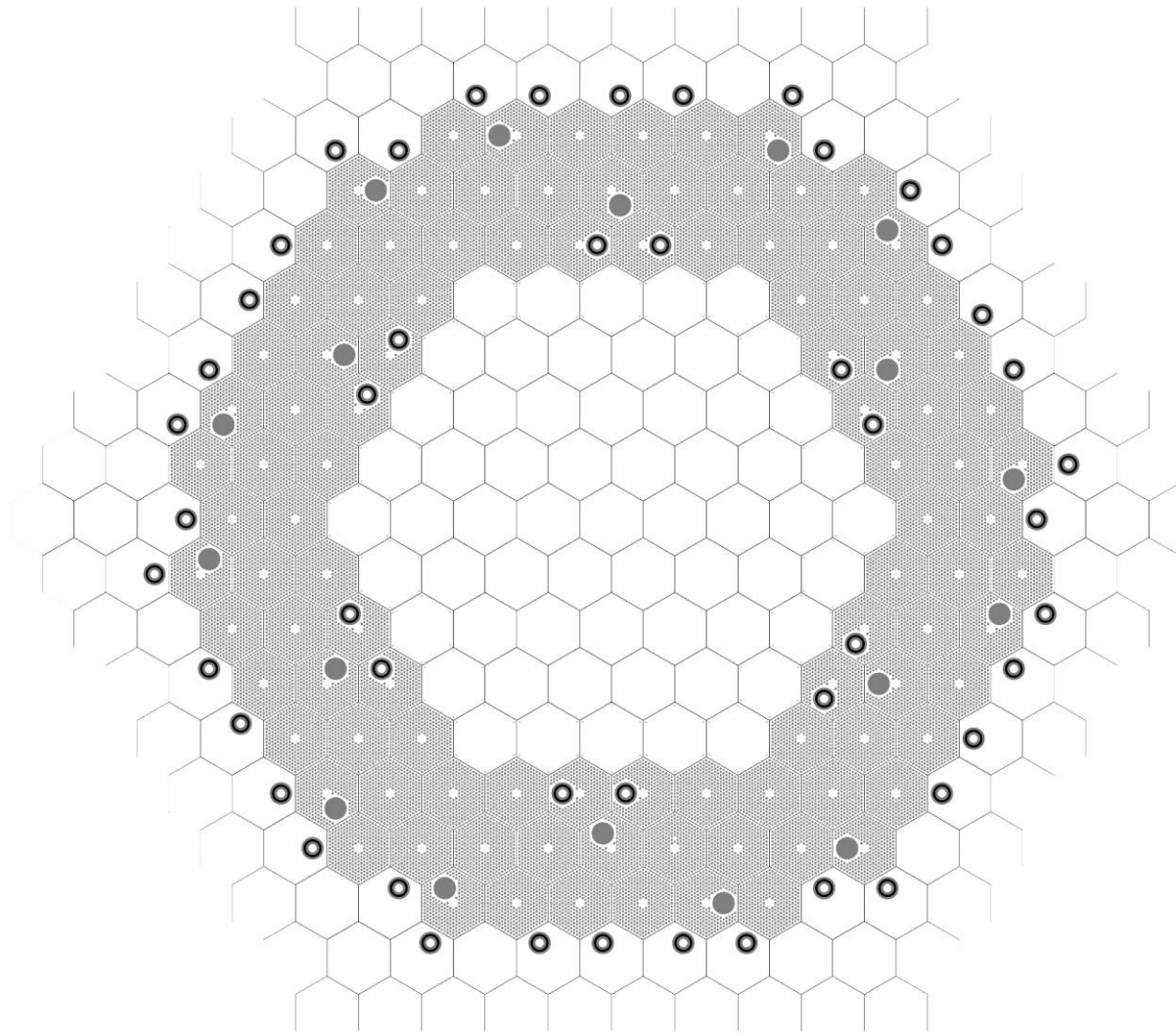


Figure 5: GT-MHR core as described in Ref. [16] (white = reflector, grey = core, black annuli = control rods, dark grey circle = RSS positions)

The IAEA benchmark utilizes plutonium oxide fuel rather than the typical uranium oxide or uranium oxycarbide. While a departure from conventional HTR configurations, this will not have a significant impact on the control rod worth of the telescopic control rod relative to that of the reference control rod, which is the calculation to be performed using the model. The core height is 8 m, consisting of 10 layers of 80 cm axial blocks. The core fuel load is 701 kg. There are 12 control rods in the core region and 36 in the side reflector. There are 18 reserve shutdown system channels in the core region. The fuel blocks contain an erbium burnable poison.

The reference control rod consists of an annular absorber element of boron carbide of density $\sim 1.3 \text{ g/cm}^3$ (i.e., $\sim 54\%$ of theoretical density), clad in coaxial graphite tubes. The dimensions of the reference control rod are given in Table 2. It is shown in Fig. 6.

Table 2: Reference Control Rod Dimensions from Ref. [16]

Outer Diameter (mm)	Region
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4.6	Central hole
6.2	Graphite tube (part of articulated control rod structure)
7.0	Gap
7.8	Absorber material inner cladding
10.2	Absorber material
11.0	Absorber material outer cladding

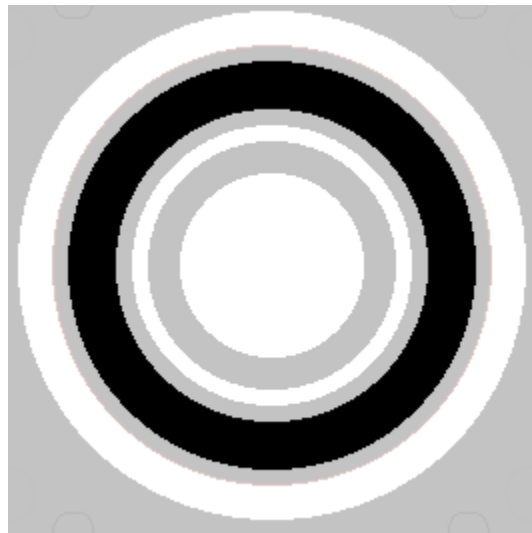


Figure 6: Control rod as described in Ref. [16]. Graphite block (grey) containing hole (white) containing coaxially clad annular absorber (black)

Detailed isotope breakdowns are provided for the fuel at 0, 1/3, 2/3 and 3/3 of the discharge burnup (72 GWd/t). At equilibrium, three axial loading schemes are used, with axial shuffling of fuel between cycles. Beginning and end of cycle (BOC and EOC) burnup distributions are hence defined (Table 3) which translate to six cases for which k-eff and control rod worth are calculated. For each of these six cases, calculations are performed with all rods out, all rods inserted, reflector rods inserted, and core rods inserted. This gives a total of 18 different control rod worth calculations. By performing control rod worth calculations in such a range of configurations, the relative performance of the telescopic control rod under a range of operational conditions can be investigated.

Table 3: Equilibrium loading scheme axial burnup distribution from Ref. [16]

Variant		Layer through core height									
		1	2	3	4	5	6	7	8	9	10
1	BOC1	2/3	0	2/3	0	1/3	1/3	0	2/3	0	2/3
2	EOC1	3/3	1/3	3/3	1/3	2/3	2/3	1/3	3/3	1/3	3/3
3	BOC2	2/3	0	1/3	0	1/3	1/3	0	1/3	0	2/3

4	EOC2	3/3	1/3	2/3	1/3	2/3	2/3	1/3	2/3	1/3	3/3
5	BOC3	2/3	0	2/3	1/3	1/3	1/3	1/3	2/3	0	2/3
6	EOC3	2/2	1/3	3/3	2/3	2/3	2/3	2/3	3/3	1/3	3/3

Steady-state 3D core neutronics calculations were performed using the OpenMC Monte Carlo code [17] using the ENDF/BVII.1 nuclear data library. The TRISO particles were smeared into the graphite matrix to speed up calculations, particularly given that OpenMC does not use delta tracking, and hence enable a wider set of full core calculations to be run. As the purpose of these calculations is to calculate control rod worth, i.e., the difference between k-eff with and without the control rods present, this is an acceptable assumption. It is more important to investigate control rod worth over a wide number of core operating states than to establish reference k-eff to a high degree of accuracy. As demonstrated below, the control rod worth accuracy using this assumption is within typical values, validating the assumption. TRISO particle heterogeneity has a limited impact on the spatial distribution of the neutron flux, so the control rod worth will be sufficiently accurate for the purposes of this study. Core calculations were converged to a standard deviation of 8 pcm, which is a sufficient convergence to calculate the control rod worth to within 0.008-0.6% depending on the case, again within the accuracy required to reach firm conclusions. An appropriate number of settling stages were used to ensure that the source was sufficiently converged. A uniform temperature of 294K was used.

4.2. Benchmarking of Neutronic Model

Control rod worth are reported in Table 4 for the OpenMC model and results reported in Ref. [16]. Results reproduced from France were performed using the JEF3.1 cross-section library with the TRIPOLI4 Monte Carlo code at 300K. The reproduced results from Korea used the MCNP code with the ENDBF/B-VI library at 300K. Results here are on average ~7.5% (rms) higher than those for Korea, which are themselves ~7.5% (rms) higher than those from France. A typical accuracy for a control rod worth calculation is ~10%. The OpenMC model therefore achieves good agreement with published results for control rod worth for the GT-MHR, and therefore there is confidence that the model is fit for purpose. Differences are likely due to the nuclear data libraries, different approximations to the TRISO particle stochastic geometry (e.g., the French calculation models this explicitly but assumes a regular array of particles), and, to a lesser extent, statistical error.

Table 4: Control Rod Worth (pcm) for GT-MHR Benchmark. Available results reproduced from [16]

Case	Configuration	France	Korea	Current Study
All Rods In	1	20512	21205	22191
All Rods In	2	21194	23369	25349
All Rods In	3	20355	20891	21691
All Rods In	4	21179	22802	24584
All Rods In	5	20703	21820	22836
All Rods In	6	21712	24164	26277
Reflector Rods In	1	-	14037	14664
Reflector Rods In	2	-	15449	16765

Reflector Rods In	3	-	13859	14390
Reflector Rods In	4	-	15098	16369
Reflector Rods In	5	-	14346	15167
Reflector Rods In	6	-	15946	17406
Core Rods In	1	-	2745	2746
Core Rods In	2	-	3214	3256
Core Rods In	3	-	2733	2624
Core Rods In	4	-	3112	3150
Core Rods In	5	-	2408	2923
Core Rods In	6	-	3379	3487

Lattice calculations are also performed for the configuration shown in Fig. 1 with control rod both inserted and withdrawn, with reflective boundary conditions. Results for control rod worth are given in Table 5. This clearly gives extremely high control rod worth so is less meaningful than for the full core analysis, but lattice calculations are useful for design of the telescopic control rod. Results agree to within 2.5% which constitutes good agreement.

Table 5: Control Rod Worth (pcm) for single fuel block

	Korea	Current Study
Control Rod Worth	-92992	-90810

4.3. Design of Telescopic Control Rod

Telescopic control rod dimensions were specified using engineering judgement with the objective of achieving roughly the same worth for each stage of the telescope. The dimensions are given in Table 1 and are shown graphically in Fig. 3. The control rod materials are as in the GT-MHR benchmark, except that, as space is at a premium, a coaxial Inconel clad is used with a representative 0.6 mm thickness.

The outer rings of the control rod can be progressively thinner for a given worth as a higher proportion of neutrons incident on the control rod hole will intersect the absorber material and thus spatial self-shielding is lower. It is likely desirable to maintain equal worth for all stages, so to make it easier to ensure adequate control rod worth across all possible core configurations. However, optimization of the telescope dimensions is complicated by the following factors:

- Thinner rings will deplete faster if the control rod is inserted at power.
- Spatial self-shielding effects are different between lattice and core models. In the lattice model, a much higher proportion of all neutrons in the problem intersect the control rod hole.
- Depending on the core flux shape, different axial positions into the core may contribute differently to the overall control rod worth. In general, at full extension stages axially deeper into the core are most important.
- The average worth of each stage is not necessarily maximized when the worth of each individual stage is identical.

A rigorous optimization was therefore not attempted at this stage – the goal of this paper is proof of principle. Nevertheless, the configuration utilized is the result of a degree of heuristic iteration, notably an increase around the inner regions relative to the outer ones in an attempt to balance the rod worth of each stage. This prevents the central core of the control rod having an extremely low worth due to relatively few neutrons passing through it.

Calculations were performed with translational boundary conditions on the fuel block surfaces for this case. A single alternative configuration was also analyzed, characterized by an (even) thicker central core (Table 6). The control rod worth relative to the reference control rod worth (i.e., control rod worth calculated in OpenMC for the reference control rod configuration) is given in Table 7.

Table 6: Alternative Telescopic Control Rod Configuration

Annulus	1	2	3	4	5
Inner clad radius (cm)	-	3.545	4.584	5.350	5.952
Inner absorber radius (cm)	-	3.605	4.644	5.410	6.012
Outer absorber radius (cm)	3.385	4.424	5.190	5.792	6.340
Outer clad radius (cm)	3.445	4.484	5.250	5.852	6.400

Table 7: Relative worth of each stage of the telescopic control rod in single assembly calculations

Telescope Annulus (from center)	Worth Relative to Reference Control Rod	
	Configuration in Table 1 (Main Configuration)	Configuration in Table 5 (Alternative Configuration)
1	0.69	0.76
2	0.75	0.80
3	0.86	0.83
4	0.85	0.82
5	0.88	0.83

The mean relative worth is 81% that of the reference control rod for both the main and alternative configurations. As discussed above, spatial self-shielding is higher for a lattice configuration, so the worth reduction is significantly lower for the more realistic core configuration (see following section). Despite the absorber area being significantly higher for the central ring, the worth of this ring (and the second annulus) are lower than those for the outer annuli. The central region could be made even thicker, at the expense of the outer regions, but this is not pursued here for the reasons discussed above.

The alternative configuration demonstrates the difficulty of achieving complete equality in worth between the five rings without compromising the worth of the outer rings. It does bring the stages closer to equality in worth (making the control rod worth more consistent across different axial burnup profiles). However, this must be traded off against depletion performance for the thin outer ring (see below).

4.4. Core Analysis

Control rod worth calculations are now performed with telescopic configurations. Five configurations are considered:

- The main configuration of the telescopic control rod described in Sections 2 (Table 1) and 4.3.
- The reference configuration with the boron 90% enriched in ^{10}B
- The reference configuration with six extra control rods in positions as shown in Fig. 7. The rationale for this configuration is that there is potentially room for an additional control rod inside the stovepipe containing the CRDMs, so these additional control rods will not require an increase in the number of vessel penetrations.

The main configuration is analyzed for all rods in, core rods and reflector rods cases. The variant configurations are analyzed for the “all rods in” cases only, as this is sufficient to gain insight into the performance relative to the main configuration. Results are shown in Table 8.

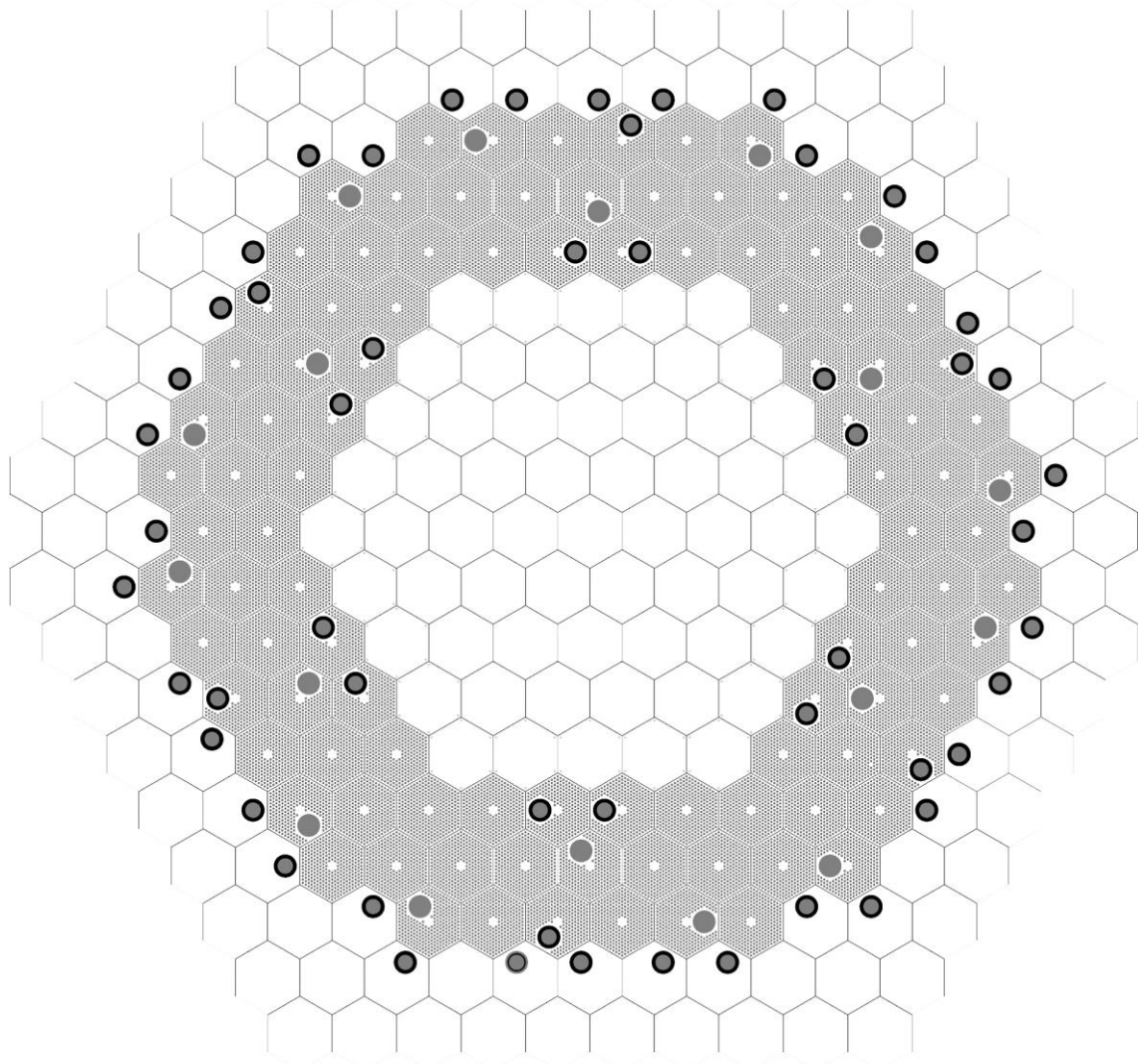


Figure 7: Core with six extra control rod positions approximately midway along each core edge

Table 8: Worth of Telescopic Control Rod Configuration Relative to Worth with Reference Control Rod

Case	Core Variant	Main Configuration	Enriched Boron	Six Extra Control Rods
All Rods In	1	0.94	1.05	1.02
All Rods In	2	0.96	1.07	1.05
All Rods In	3	0.94	1.05	1.01
All Rods In	4	0.95	1.06	1.03
All Rods In	5	0.91	1.02	1.00
All Rods In	6	0.97	1.08	1.05
Reflector Rods In	1	0.94	-	-
Reflector Rods In	2	0.96	-	-
Reflector Rods In	3	0.92	-	-
Reflector Rods In	4	0.93	-	-
Reflector Rods In	5	0.91	-	-
Reflector Rods In	6	0.96	-	-
Core Rods In	1	0.98	-	-
Core Rods In	2	0.98	-	-
Core Rods In	3	0.97	-	-
Core Rods In	4	0.97	--	-
Core Rods In	5	0.95	-	-
Core Rods In	6	0.99	-	-

The telescopic control rod worth is on average 95% that of the reference control rod, although in some cases this drops to 91%. The case with the minimum control rod worth is Case 3, for which the telescopic control rod has 94% of the worth of the reference control rod (all rods in).

Adding six extra control rods can restore the control rod worth to the reference value in all cases. Increasing the amount of ^{10}B in the control rod can also restore the control rod worth. This is shown here for the case with enriched boron, but higher boron concentration can also be achieved through increasing the boron carbide density.

4.5. Partial Insertion

If the configuration on the right of Fig. 4 is maintained, then all stages of the control rod are always at their lowest positions. Hence, when the control rod is partially inserted, the worth of the lowest component of the control rod is relatively high, as it contains multiple stages nested together. The worth at this height in the core then reduces as the control rod is extended further. This acts to increase the differential control rod worth for relatively small insertions, while decreasing it for relatively large insertions. The differential control rod worth will nevertheless always remain positive.

The effect of this on the core axial power shape with partial insertion remains to be established. It can be anticipated that there will be an increased dip in the power at the control rod tip compared to a conventional control rod.

The impact of both effects (differential worth and axial power shape) will be limited by the strong spatial self-shielding of the control rod, and hence there is confidence that this is a manageable effect. Nevertheless, this should be investigated in future work.

4.6. Depletion Analysis

When inserted at power, the telescopic control rod will deplete faster than the reference control rod due to the lower amount of boron and reduced self-shielding. This reduces absorber worth and increases helium production (from $^{10}\text{B}(n, \alpha)$) per unit volume of absorber material. This is not a serious issue as few control rods are inserted at power (particularly for pebble bed reactors), and control rods are replaceable. It is also anticipated that costs incurred from any increase in control rod replacement frequency will be significantly outweighed by reduced reactor capital costs. This effect should nevertheless be quantified.

An OpenMC model of a single fuel block with (a) control rod(s) inserted was utilized. OpenMC allows the user to specify a custom depletion chain and this feature was utilized so that the depletion of ^{10}B and ^{11}B only were modelled. This enabled the worth of the control rod to be derived through keeping the fuel composition constant while simulating the evolution of the absorber material. Dummy depletion chains for the fissile isotopes (where each fissile isotope was specified to fission into itself) were also required to provide the fission power for flux normalization.

The standard deviation on the calculations was also increased to 30 pcm (i.e., 30×10^{-5}) due to computational constraints. This is sufficiently converged to resolve the depletion behavior of the control rod for a 2D lattice burnup calculation. Five years of depletion was modelled with a specific power of 6.5 W/cm^3 as specified in [16].

Results are shown in Fig. 8, in which telescope average depletion is the simple mean of the worth of the five stages. In all cases, the depletion relative to the initial worth of the stage is calculated. This is because control rods are typically replaced when one section of their length is depleted to a specified value. On average, the telescope depletes around 1.7x as fast as the reference control rod. There is significant spread between the stages of the telescope, with the outer ring depleting more quickly (as it is thinner) and the central core depleting more slowly. The replacement frequency of the control rod will depend on its configuration when inserted. If all stages are in their lowest possible configuration (on the right of Fig. 4) then the outer ring may experience most of the fluence when the control rod is slightly inserted. However, this may not have as much of an impact on the shutdown margin, as the worth of the intermediate stages towards the center of the core may be more important. Also, for the configuration analyzed, the worth of the 1st ring (central core) of the telescopic control rod is the lowest when undepleted.

Nevertheless, if the control rod depletion limit is set by materials considerations (helium generation from ^{10}B), this may motivate increasing the size of the outermost ring to improve its depletion performance. This is likely to trade-off against control rod worth, so the optimal configuration will be design specific.

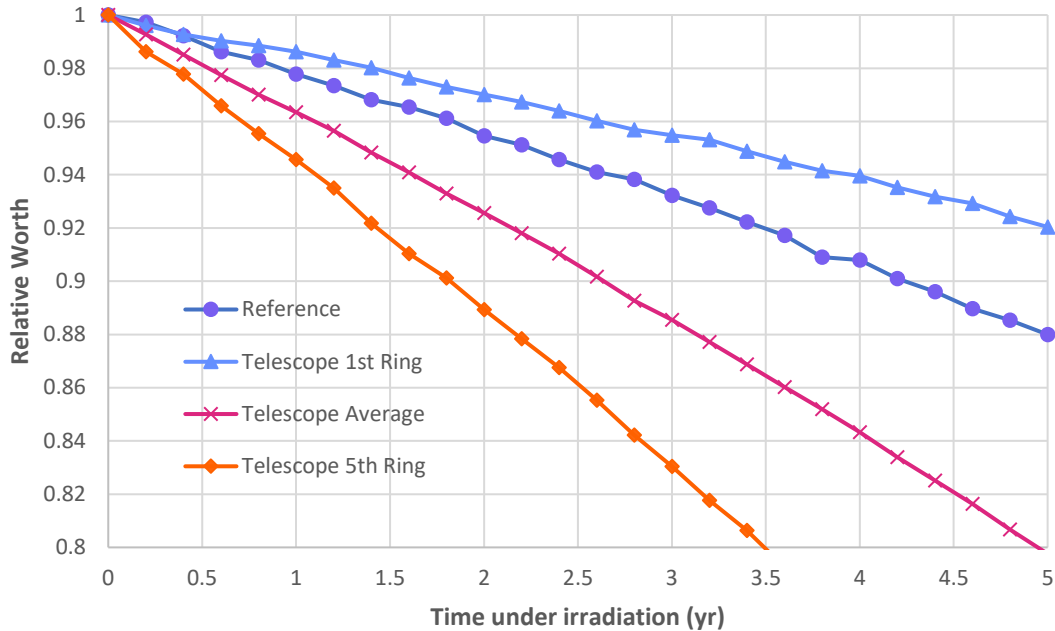


Figure 8: Reduction in control rod worth under irradiation.

4.7. Sensitivity Analysis with Boron Carbide in Graphite Matrix

HTR control rod configurations may use boron carbide in a graphite matrix rather than boron carbide as the control rod material, for example MHTGR [6]. The GT-MHR model is now modified to use a boron carbide in graphite matrix absorber containing 40 wt% natural boron carbide. The material contains 0.0034 at/barn-cm ^{10}B , 70% less per unit volume than the boron carbide absorber considered in the rest of this paper. The material was modelled homogeneously rather than explicitly resolving the boron carbide particles. This assumption will increase the control rod worth through dispersing the boron more evenly, and hence further investigation of this configuration may be required if this configuration is taken forward. However, this approximation is nevertheless acceptable for investigating the impact of reducing the amount of absorber material on the performance of the telescopic control rod relative to the reference.

The worth of both the reference control rod and the telescopic control rod will both be decreased by the reduction in ^{10}B . However, it is postulated that the telescopic control rod will experience a more severe worth reduction than the reference control rod because the self-shielding effect for the reference control rod is greater. I.e., the telescopic control rod uses boron more efficiently and hence is more sensitive to a reduction in boron concentration.

To confirm and quantify this, the core analysis cases were reanalyzed with the matrix material. The reference control rod worth reduced by ~6% relative to the boron carbide material. Results for relative performance of the telescopic control rod are shown in Table 9 for the “all rods in” cases. Cases with reflector and core rods inserted follow the same trends. There is indeed a reduction in relative worth compared to with the boron carbide absorber material, but this is <1%. Therefore, the relative performance of the telescopic control rod is not particularly sensitive to the absorber material, where this is the same in both reference and telescopic control rods.

Table 9: Worth of Telescopic Control Rod Configuration Relative to Worth with Reference Control Rod where both Telescopic and Reference Control Rods contain Boron Carbide in Matrix Material.

Case	Core Variant	Main Configuration	Six Extra Control Rods
All Rods In	1	0.94	1.02
All Rods In	2	0.96	1.05
All Rods In	3	0.94	1.01
All Rods In	4	0.94	1.03
All Rods In	5	0.91	0.99
All Rods In	6	0.97	1.05

Depletion analysis is also performed as in the previous section (Fig. 9), in which as before telescope average depletion is the simple mean of the worth of the five stages. Relative results and trends are almost identical to the boron carbide absorber case although both the reference and telescopic control rod burn out more quickly.

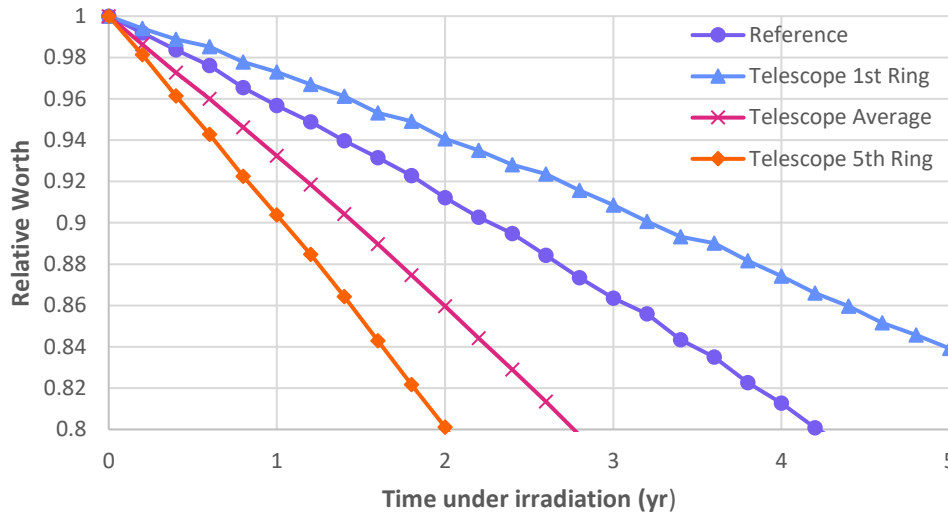


Figure 9: Reduction in control rod worth under irradiation with boron carbide in matrix material.

Finally, it is noted that both the steady-state and depletion performance of the telescopic control rod with the boron carbide material is very similar to the steady-state and depletion performance of the reference control rod with boron carbide in matrix material. I.e., for a HTR with boron carbide in matrix absorber material control rods, switching to boron carbide absorber is sufficient to compensate for the loss of worth and depletion performance when moving to the telescopic control rod. This is an illustrative comparison only as it depends on the exact specification and density of the absorber material but does serve to highlight that there is likely room for compensating for reduced absorber volume by increasing the absorber density.

4.8. Discussion

It has been shown that a replacement of a reference control rod with a 5-stage telescopic control rod will lead to a ~5% reduction in worth and a need to replace any control rods inserted at power more frequently. Given the significant reduction in core height made possible by the telescopic control rod, this

is a highly promising result. The relative performance of the telescopic control rod is not particularly sensitive to the density of boron carbide in the absorber, so these results are anticipated to generalize to other boron-carbide based absorber materials.

If the neutron-absorbing performance of the telescoping control rod worth is reduced below that needed for the operational envelope (e.g. shutdown margin requirements), several mitigations are possible. These illustrate that the concept can be implemented without radical or difficult changes to the design. For example:

- Increasing the number of control rods through placing more control rods in the same standpipes. In HTRs, for example, for the configuration in Fig. 2, six additional control rods could be included as shown in Fig. 8. If these additional rods are placed within the core, they displace some fuel. Additional standpipes could also be used and placed within the reflector, although this is subject to limits on the spacing of vessel penetrations within design code constraints. Locating any additional control rods is hence design dependent.
- Introducing additional control rods through allowing the RSS and control rods to use the same holes.
- If an integral design is pursued, there are fewer constraints on adding control rods to the core as number of vessel penetrations ceases to be limiting.
- The boron content of the absorber material can be increased either through
 - For boron carbide in matrix material as reference: increase the boron-carbide-to-graphite ratio or switch to pure boron carbide.
 - For boron carbide material as reference: increase the density of the boron carbide closer to the theoretical maximum .
 - Enrichment in boron-10 although this is likely less desirable from an economic perspective.
- Increasing the radius of the control rod and receiving hole. In the core, this would only displace a small amount of fuel, but perhaps more importantly require a slightly different fuel block configuration than that typically considered. In the reflector, there is potentially little disadvantage to a slightly wider control rod provided it can be fit within the standpipe and is not too heavy for the CRDM.

These calculations are bounding on a lower number of annuli. I.e., a telescopic control rod with four stages will have performance at least as good as a five stage control rod. Ultimately there are diminishing returns. The trade-off between number of rings and potential reduction in the silo height is shown in Fig. 10. One ring is equivalent to a conventional rod. The potential height reduction is $(1 - 1/n)$ where n is the number of telescoping annuli. Hence, while the number of annuli can potentially be increased, there are decreasing returns.

Ultimately, calculations are required for a specific HTR configuration to ensure that the shutdown margin remains acceptable across all scenarios. This includes cases where control rods failure to insert, or where control rods are withdrawn to give access to the fuel handling machine (prismatic HTRs). The number of such configurations will be higher for prismatic reactors compared to pebble bed reactors. The calculations presented here demonstrate feasibility, quantify likely worth reductions and identify means of mitigation. Next steps can include design-specific calculations.

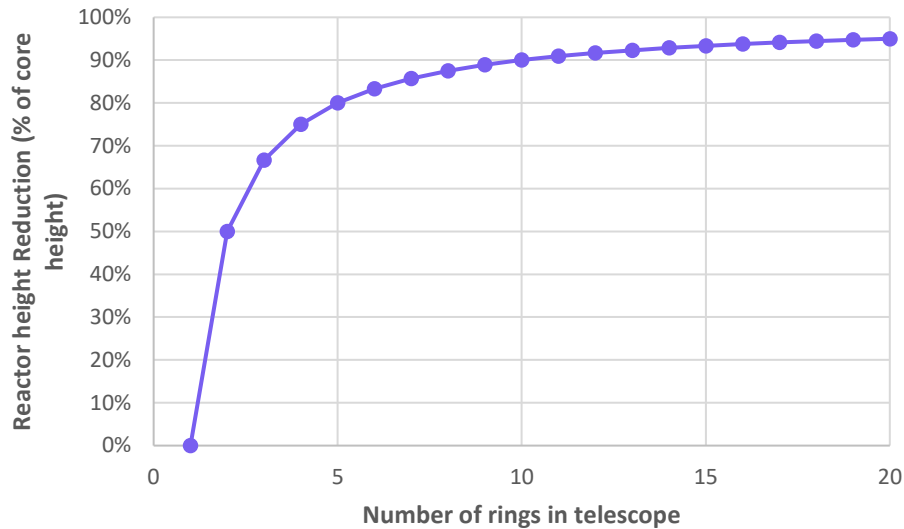


Figure 10: Trade-off between number of rings in telescope and reactor silo height reduction.

5. Conclusions and Further Work

A multi-stage telescopic control rod for HTRs can significantly reduce the overall height of the reactor silo and therefore the reactor capital construction cost. For a typical HTR of 8 m core height, the silo depth can potentially be reduced by more than 6 m, which can potentially reduce the total system cost by a substantial proportion. The telescopic control rod can be constructed using materials already qualified for HTR environments and so implementation amounts to a detailed mechanical design.

Neutronic calculations indicate an ~5% reduction in core shutdown worth compared to the reference control rods. This is fairly modest and may be accommodated in many HTR configurations without further alteration. Nevertheless calculations also indicate that small modifications to the design can compensate for losses in control rod worth. When inserted at power, control rod depletion is on average ~1.7x as fast as the reference solid control rod, with the thin outer rings depleting faster than the central core. This is not a serious concern, as the control rods are mostly withdrawn at power, and can also be replaced if necessary.

The number of rings in the telescopic control rod is an important variable as there is a trade-off between mechanical complexity and the overall height reduction. There will likely be an optimum, which may vary with reactor type.

Further work is required to demonstrate mechanical design, reactor physics and materials feasibility. For reactor physics, the differential control rod worth must be investigated. The differential worth may vary significantly with insertion as the telescope extends. With a top peaked power distribution (typical in pebble bed reactors), it is even possible that the differential worth could be negative as the rod extends towards the bottom of the core as control rod worth is moved from the area of highest impact to areas of lower flux. Calculations are required to confirm or otherwise that the control rod worth increases monotonically with insertion, and a redesign of the control rod (re-specification of region thicknesses) may be needed to confirm this.

The mechanical design exercise should develop the concept to a preferred embodiment design, guided by a system-level quantitative requirements specification, FMEA, and analytic quasi-static structural analysis. The viability of the target solution space should then be verified with an example detailed design,

providing a detailed 3D CAD model to enable dynamic numerical simulation. Key elements of the design should be prototyped, including scaled versions of key interfaces and mechanisms.

The tribological performance of the sliding components must also be evaluated on a scaled prototype in a high temperature helium environment. The prototype control rod can be subjected to high temperature He gas up to 800°C in furnace to investigate the effects of differential thermal expansion and surface degradation on the operation of the drive mechanism in-situ. Wear testing and characterization will ideally be performed in situ. After testing, the rod can be sectioned and characterized using electron microscopy.

Depending on the specific design of HTR, reducing the silo height may also require a redesign of other components such as the fuel handling machine in a prismatic HTR. A preliminary concept for the upper head can be developed in CAD for a simplified version of prismatic and pebble bed HTRs. This can incorporate locations of the control rods, housing of the RSS and fuel handling concept. This can demonstrate a more compact HTR concept and establish whether reduction in control rod height can lead to corresponding or near-corresponding reduction in silo height.

The possibility of extending the RPV to house the telescopic control rods – potentially rendered practical by their shorter length – can also be investigated. This would reduce vessel penetrations, although some will still be required for refueling. A cost-benefit analysis of the control rod should be performed to determine or otherwise the economic case for the concept.

A cost-benefit analysis of the concept should be performed to determine if the additional cost (driven by novelty, complexity, and possibly more frequent replacement) outweighs the benefits, with particular consideration of the number of reactors that is required to justify the investment

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