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Pathways to Cost-effective Advanced Nuclear Technology

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Abstract—In 2018, nuclear energy generated 55% of United States' and one third of the world's carbon free electricity. Nuclear energy can be a key tool in current efforts to mitigate climate change before 2050. However, nuclear construction costs escalated dramatically in recent years: from $3,000/kW in the 1990's to over $7,000 today, and this has severely limited its potential for impact. Nuclear plants are construction megaprojects that require thousands of workers and a decade of construction. The capital costs and construction timelines were double the original estimates for the last five nuclear plants completed or under construction in western nations. Moreover, the current nuclear technology can only provide heat at low temperatures (300°C), which limits its use as a decarbonization tool to the electricity grid. Heat for industrial processes accounts for 10% of carbon emissions. High temperature gas reactors (HTGRs) can meet this need with carbon free nuclear heat. Unfortunately, the estimated cost of advanced reactor alternatives such as HTGRs are even higher than current Light Water Reactors (LWRs). In this paper, we built a simple model to estimate the capital cost of existing nuclear plants and apply it to HTGR designs. We propose a structures-first design framework to minimize cost and apply it to the HTGR, resulting in a horizontal, integrated HTGR. The reactor core and steam generator are mounted on rails and in-line with one another. The rail-mounted horizontal orientation simplifies installation and eliminates the overhead crane. The proposed concept reduced the reactor building size by more than 50%/kW relative to other HTGR designs, putting the building power density on par with LWR designs but with the inherent safety and high temperature capability of an HTGR. Finally, we estimate a >30% cost reduction from the new design and the potential impact on carbon emissions.

Keywords—HTGR, nuclear power plant economics, cost

I. INTRODUCTION

Nuclear fission energy has a unique opportunity to be highly impactful in mitigating climate change. The US electricity grid is responsible for 28% of CO2 emissions, and heat for industrial processes generates another 10% [1]. In scenarios of deep electricity grid decarbonization, Sepulveda et al. showed that firm, dispatchable energy resources lower system costs by up to 60% compared to renewable only grids [2]. Nuclear energy generally, and high temperature gas reactors (HTGRs) specifically, are potential high impact technologies in reducing carbon emissions. Besides clean electricity, HTGRs can produce industrial process heat. Process heat can serve for producing hydrogen to decarbonize the transportation sector or for industrial processes such as refineries, fertilizer plants, or pulp and paper production.

The US Energy Policy Act of 2005 formally launched the Next Generation Nuclear Plant (NGNP) program whose goal was to select, design, and build an advanced nuclear reactor plant capable of cogenerating electricity and heat for industrial processes. The NGNP program, run by Idaho National Laboratory, evaluated molten salt, liquid metal, and gas cooled reactors for technology readiness and economic promise in 2004 and 2010 [3], [4]. Ultimately, the program selected the HTGR as the NGNP for its high degree of passive safety, economic potential and near-term readiness. Given the US operated two HTGRs, one at Fort St. Vrain Generating Station and one at Peach Bottom Atomic Power Station, there was high confidence that the HTGRs could be deployed commercially relatively quickly. After $470 million of trade studies, preconceptual design, and conceptual design, the NGNP was never built for two primary reasons: the price of natural gas dropped by half from 2006 to 2009, and a cost-share arrangement could not be agreed to between the nuclear industry and the Department of Energy [4], [5].

HTGRs are commonly criticized for their large building sizes as a result of the reactor's low power density. Low power density is a tradeoff: it enables a high degree of passive safety, but it also drives structural engineering and construction challenges. For example, the China National Nuclear Corporation currently is constructing two pebble-bed fuel HTGRs called HTR-PM. The design, pictured in Figure 1, is a twin pack of 110 MWe reactors [6]. The reactor building is large relative to the electricity capacity, so the power density, or electricity capacity per volume of the reactor building, is 2 kWe/m^3. In contrast, a Westinghouse four loop PWR has a reactor building power density of 12 kWe/m^3, six times denser than the HTR-PM. In the case of the HTR-PM, the whole reactor building is not a containment that maintains a pressure boundary, so the comparison is imperfect, but the cost of civil structures for HTGR plants is still likely higher per unit of capacity than for a standard PWR.

In this paper, we estimate the magnitude of the cost increase associated with HTGR civil structures relative to LWRs. To do this, we started from code-of-accounts breakdown for a PWR and assumed a scaling between overnight cost for each account. Then, we propose a cost optimized layout for HTGRs that reduces the building volume and increases the reactor building power density to be on par with LWRs. Finally, we estimate the cost savings associated with this design and speculate on the potential impact in mitigating climate change.

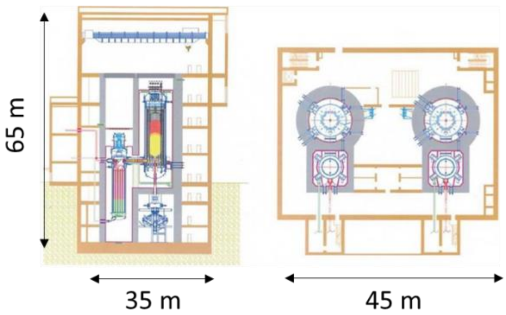

Fig. 1. China National Nuclear Corporation HTR-PM [6]

II. Methodology and Analysis

Here we justify the high cost impact of reactor and auxiliary building volume on nuclear plant overnight cost. We first analyzed nuclear plant cost data in the Energy Economic Database, and then we apply the developed analysis method to the AP1000, a traditional HTGR, and a new HTGR design. The nuclear plant in the EEDB is a 4-loop PWR, referred to as PWR12 from here forward.

A. *Historical context and assumptions*

Using a database of 71 reactors built in the 1970's and 1980's, we compared average overnight costs and average building volume densities. Large reactors were roughly 20% more expensive per kWe than their smaller counterparts, and they were 6-27% less power dense [7, 8]. The historical data could suggest that increasing the plant size without conserving power density can lead to higher cost per kWe. These data are tabulated in Table I.

TABLE I. Building Volume by Reactor Type [7], [8]

	Small (<1000 MWe)		Large (>1000 MWe)	
	Average $/kWe	Average kWe/m^3	Average $/kWe	Average kWe/m^3
BWR	1,552	2.9	1,790	2.8
PWR	1,135	3.7	1,400	2.7

B. *EEDB based methodology*

The premise of our analysis is that the total overnight cost of a nuclear plant, independent of the specific nuclear technology, is closely related to the sizes of its civil structures. According to the Energy Economic Database, structures and improvements accounted for 26% of nuclear plant direct costs for the median experience plant [9]. Containment or confinement buildings, different in the pressure they are meant to withstand, are designed to be only as large as required to accommodate the equipment, operations, and safety functions that are necessary. Further, indirect costs, which are 53% of total costs for the median experience plant, are roughly evenly divided between Construction Services, Engineering & Home Office Services, and Field Supervision & Field Office Services. In other words, indirect costs are primarily driven by construction and civil works tasks.

To estimate the fraction of total cost that comes from each account (Table II), we started with the ratio of total indirect to total direct costs for the better experience plants in the EEDB. For these plants, EEDB reports directs costs are 62% and indirect costs are 38% of total costs, or a ratio of indirect costs to direct costs of 61%. Most of the cost overrun issues with the median experience plants resulted from nuclear related tasks, so we assume this ratio applies to the non-nuclear cost accounts in EEDB: 23 and 24. For the median experience plants, the ratio of total indirect to total direct costs was 113%. So, we implicitly derived the necessary indirect to direct cost ratio for the nuclear related cost accounts to match this total indirect to direct cost ratio. These results are presented in Table II, and structures and improvements account for 30% of total costs. Within account 21, the majority of costs were the containment building and the other seismic class one buildings such as the auxiliary building, control room, and waste process building. Wibowo et al. showed a linear scaling between building size and cost for industrial plants [10]. Therefore, in our estimates account 21 scaled linear with the relative volume of the containment and seismic class one buildings.

HTGR technology uses a functional containment system of barriers as opposed to the traditional containment building, so we correct for the difference between the cost of a containment and a confinement. TRISO fuel, the reactor pressure vessel, and the reactor building, or confinement act together to form the functional containment system. For the HTGR cost estimation, the reactor building had the same cost per unit volume as the auxiliary building in the EEDB, as shown in Table III. This amounted to a 20% cost reduction per unit volume with respect to a containment in a PWR.

As part of the verification, we estimate the overnight cost of the Westinghouse AP1000. The AP1000 design significantly reduced the seismic class one (SC1) building footprint: roughly one third the volume of the PWR12. This change yields significant cost reductions. However, the stand-alone steel containment of the AP1000 is substantively different from the steel-lined concrete containment of the PWR12, so the cost per unit volume is higher. EEDB reported the cost per unit volume of the Advanced LWR6 containment, a stainless-steel containment, as double the cost of a similarly sized concrete containment. Therefore, we applied this doubling when estimating the costs of standalone metal containments.

The other cost accounts in Table II scale with a power law fit:

$$C_i = C_{baseline}\left(\frac{K_i}{K_{baseline}}\right)^n$$

where C is cost, K is the base unit, and n is the scaling factor. The power law is to account for the economy of scale, and processes scale with different base units and scaling factors. The EEDB reported base unit for accounts 23 and 24 was plant electrical power, and the scaling factors were 0.8 and 0.6, respectively. Scaling factors and base units came from the work of Saccheri et al. for the other accounts [11]. Account 26 scaled on the rejected thermal heat with a 0.8 factor. Account 25 scaled total non-containment SC1 building volume. Westinghouse made an intentional effort to reduce the valves, components, and systems, and this allowed a reduced SC1 building volume. Our model estimated the equipment cost savings of this design thinking by scaling the miscellaneous plant equipment on the non-containment SC1 building volume. Account 26 scaled on the rejected thermal power based on the turbine efficiency. Table IV summarizes these assumptions.

The base unit for reactor plant equipment, Account 22, was reactor thermal power, not plant thermal power. Some plant layouts consist of multiple reactors, so the base unit is the individual reactor size to account for duplicate equipment. Gandrik et al., in their cost estimation for the SC-HTGR, used a shared maintenance building cost reduction factor of 0.8 for reactor plant equipment cost when considering a four-unit HTGR versus a one-unit HTGR, and we followed the same practice [16]. Further, the low power density of HTGRs translates to larger reactor equipment per unit of energy produced than the PWR12. For example, the traditional HTGR core is five times larger than the Westinghouse AP1000 core and produces one fifth the power. To account for the difference in reactor plant equipment costs, in the case of the HTGR, we scale the reactor plant equipment cost by 1.3 based on the work of Gandrik [12].

TABLE II. MEDIAN EXPERIENCE PWR12 COSTS [9]

	Direct %	Indirect/ Direct	Indirect %	Total %
21-Structures & Improvements	26%	1.43	33%	30%
22-Reactor Plant Equipment	31%	1.43	39%	35%
23-Turbine Plant Equipment	22%	0.61	12%	17%
24-Electrical Plant Equipment	10%	0.61	5%	8%
25-Misc. Plant Equipment	6%	1.43	8%	7%
26-Condensing Heat Rejection	5%	0.61	3%	4%

TABLE III. PWR BUILDING SPECIFIC COSTS (1987 USD) [9]

	Cost per volume ($/m^3)
211-Reactor Containment Building	1,050
215-Primary Auxiliary Building	841

TABLE IV. POWER LAW COST SCALING ASSUMPTIONS

Account	Base Unit	n
21-Structures & Improvements	Building Volume	1
22-Reactor Plant Equipment	Thermal Power	0.8
23-Turbine Plant Equipment	Electrical Power	0.8
24-Electrical Plant Equipment	Electrical Power	0.6
25-Misc. Plant Equipment	Aux. Bldg. Volume	0.8
26-Condensing Heat Rejection	Rejected Thermal Power	0.8

C. Plant building volume estimates

EEDB directly reported the PWR12 building volumes for the containment and every seismic class one building. Table V reports these building volumes. The relative costs for the containment and all other SC1 buildings in Account 21 were approximately equivalent.

The key building volumes for the AP1000 were the containment, auxiliary building, and waste processing building. The containment and auxiliary building are pictured in Figure 2. We approximated the containment as a cylinder 45m diameter and 65m high, the auxiliary building as two boxes 37x22x19m and 27x30x27m, and the waste processing building as a box 54x24x13m. Shown in Figure 3, we considered the Framatome SC-HTGR as the traditional HTGR, and using Figure 3, we estimated the volume as a box: 150x50x50m and 4 cylinders 30m in diameter and 45m tall. The total SC1 volume is approximately = 500,000m^3, and there is no containment volume. The four-unit traditional HTGR has a 1100 MWe capacity. Table V also reports the building volumes for the AP1000 and the traditional HTGR.

The traditional HTGR does not have a containment, and this should result in a decrease in cost Account 21. However, the SC1 building volume increased 3X over the PWR12 and almost 10X over the AP1000. As a result, there was not an expected cost decrease in Account 21 but a cost increase. The large building volume was a result of the shared maintenance building and the system of overhead cranes for installing reactor plant equipment. This building must be sufficiently tall for components to be installed inside the embedded reactor buildings. We propose the Modular Integrated Gas-cooled High Temperature Reactor (MIGHR) to alleviate the expensive construction and installation associated with the traditional HTGR design.

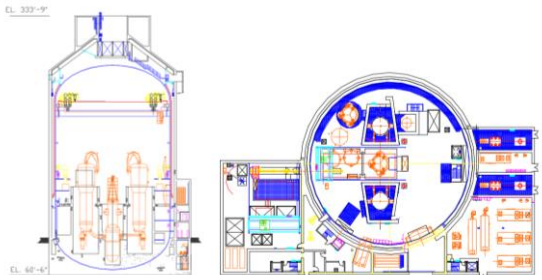

Fig. 2. Layout of AP-1000 [13]

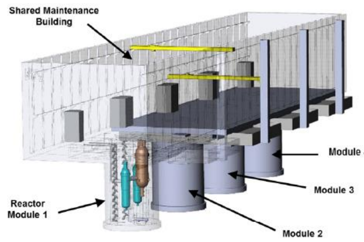

Fig. 3. Framatome SC-HTGR building [14]

TABLE V. PLANT SPECIFICATIONS AND ESTIMATED VOLUMES

	PWR12	AP1000	traditional HTGR	MIGHTR
Units	1	1	4	4
Thermal Power (MW)	3417	3415	2500	1400
Electrical Power (MWe)	1144	1100	1100	616
Containment Vol. (m^3)	95898	103378	-	-
Reactor Bldg. Vol. (m^3)	-	-	125000	54000
Aux. Bldg. Vol. (m^3)	172069	56234	375000	27000
SC1 Bldg. Vol. (m^3)	172069	56234	500000	81000

III. Horizontal Integrated Reactor

Based on just the building volume comparisons, the traditional HTGR plant design is unlikely to be cost competitive with an AP1000 or a traditional four-loop PWR. However, gas-cooled reactors represent the state-of-the-art in safety performance and fulfill a mission of high temperature heat that water-cooled reactors are unable to provide, but current gas reactor designs are too large and thus too expensive to be built. To solve this problem, we propose the Modular Integrated Gas High Temperature Reactor (MIGHTR). The primary feature of our design was a laser focus on reducing the size and scale of civil structures, since these dominate the costs of nuclear construction. The reactor core and steam generator were integrated into one body and flanged together. The system lies horizontally and on rails as opposed to upright to simplify installation. The resulting compact horizontal gas reactor was conceived using designed-to-build and structures-first approach.

In MIGHTR, the reactor core and the steam generator have been rearranged to be horizontal and axially aligned. This novel layout allows for a much smaller confinement building. The core and materials selection are based on the already-conducted NGNP design and it uses NRC in-licensing-process TRISO particles requiring minimal R&D. The primary system consists on several modules flanged to each other that are guided on rails, facilitating assembly and maintenance operations. The rails eliminate the need for overhead cranes during construction or during operation. The functions typically performed by the cranes are carried out by railed robots on the ground. Eliminating the overhead crane increases the building power density. The in-vessel-fuel-handling-machine flanges to the cover during refueling to create a sealed coolant flow path for decay heat removal. The Main Railed Robot (MRR) bolts and unbolts flanges, and it moves components along the rails throughout the reactor building. The cask handling robot (CHR) transfers fuel casks from the in-vessel-fuel-handling-machine to the Local Fuel Storage (LFS). A rail system takes fuel casks from the LFS out of the reactor building. The Reactor Cavity Cooling System (RCCS) consists of a set of tanks, pipes and panels that cool the reactor cavity during operation. In loss of flow or loss of coolant accidents, the RCCS prevents the concrete from exceeding allowable temperatures and cools the reactor vessel via radiation keeping internal fuel temperatures below the 1600°C limit for TRISO. This system operates as an ultimate heat sink for over seven days after a station black-out or loss of other cooling means without need for human intervention.

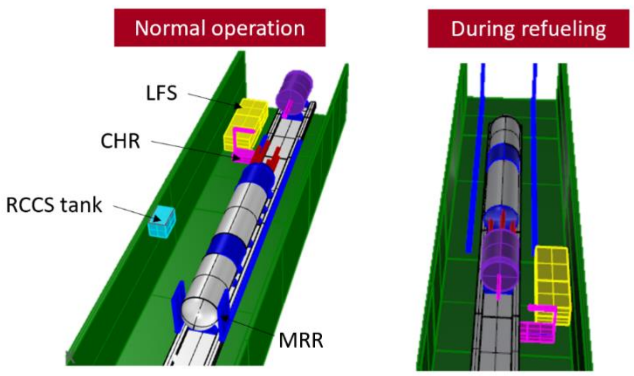

Fig. 4. MIGHT-R reactor builing layout with auxilary systems.

This alternative layout facilitates a dramatic size reduction in the reactor building. Eliminating the overhead crane space and aligning the core and steam generator significantly reduced wasted space inside the building. For a 350 MWth, 150 MWe unit, the reactor building is 15x15x60m. The reduction in height in the reactor building with respect to other reactors facilitates construction and embedment. The shorter the building is the easier it will be to construct, and construction consumes less time and structural robustness demand. The auxilary building for a four-unit MIGHTR plant lies perpendicular to the plant as shown in Figure 6 for a single unit MIGHTR. Its dimensions are 15x20x15m. A four-unit MIGHTR plant would share an auxilary building with dimensions 90x20x15m.

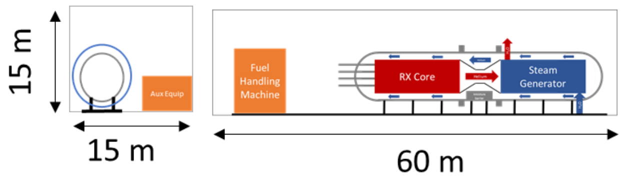

Fig. 5. MIGHT-R reactor building layout with auxilary systems

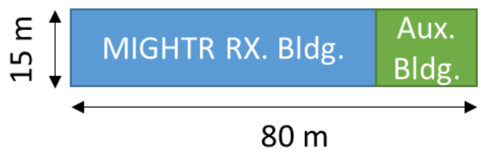

Fig. 6. MIGHTR- reactor building layout with auxilary systems

IV. Results and Discussion

A. *Cost estimation with PWR12 as the base unit*

In 1987 USD, EEDB reported two total plant costs: one for the median experience plant, and one for the better experience plant. The two reported numbers were intended to relay the substantial cost escalations experienced in the US nuclear industry in the 1980s. The total cost for the median experience plant was $2.53B and the better experience plant was $1.46B. We used the cost escalation of Ganda et al. [15] which included both a standard inflation and a nuclear price escalation index.

In 2017 USD, the PWR12 median experience cost was $7.26B or $6,345/kWe. This cost broke down into the relative cost accounts of Table II to create the PWR12 column of Table VI. Then, using the power scaling assumptions of Table IV and the plant specifications of Table V, we estimated the total overnight costs for the AP1000, traditional HTGR, and MIGHTR. These results are in Table VI. Using the “median experience” basis was more similar to a first-of-a-kind (FOAK) estimate, so we analyzed the traditional HTGR and MIGHTR as single unit plants. In this case, the MIGHTR cost estimate was 40% lower per MWe than the traditional HTGR.

Then, using the “better experience” cost basis, we make a cost estimate more similar to an nth-of-a-kind (NOAK) estimate. As before, we escalated the $1.46B to $4.18B overnight cost or $3,650/kWe using the method of Ganda. Table VII presents the NOAK cost breakdowns. In the NOAK case, MIGHTR and traditional HTGR became four unit plants.

At NOAK, the MIGHTR was still 30% less per kWe than the traditional HTGR and it was essentially equivalent to the PWR12.

B. Economic Assessment

In this section, we assess the volume-price scaling model by applying it to several reactors. The model was sufficiently accurate for high level comparisons for LWRs. The model aligned within the bounds of cost estimates for HTGRs from Idaho National Laboratory (INL)

The MIT Future of Nuclear study quoted the overnight cost range for AP1000 reactors recently completed, proposed or under construction in the US at between $6,400/kWe and $8,600/kWe (2017 USD) [16]. This range coincides with Vogtle 3&4 and V.C. Summer, units 2&3 quotes. This range could be deemed the actual range for FOAK AP1000, where our FOAK estimation for AP1000 fits rather well. Table VI shows a FOAK cost of $6,671/kWe for AP1000.

TABLE VI. OVERNIGHT COST ACCOUNTS MODEL RESULTS FOAK OR MEDIAN EXPERIENCE (2017 $, BILLIONS)

Account	PWR12	AP1000	traditional HTGR-1	MIGHTR-1
21-Structures & Improvements	$2.16	$ 2.58	$0.81	$0.12
SC1. Bldg.	$1.12	$ 0.35	$0.81	$0.12
Cont. Bldg.	$1.03	$2.23	$-	$-
22-Reactor Plant Equipment	$2.57	$2.57	$0.83	$0.54
23-Turbine Plant Equipment	$1.21	$1.17	$0.37	$0.24
24-Electrical Plant Equipment	$0.55	$0.54	$0.23	$0.17
25-Misc. Plant Equipment	$0.50	$0.20	$0.31	$0.03
26-Condensing Heat Rejection	$0.28	$0.28	$0.06	$0.04
Total cost ($B)	$7.26	$7.34	$2.61	$1.13
Specific cost ($/kWe)	$6,345	$6,671	$9,900	$7,346

TABLE VII. OVERNIGHT COST ACCOUNTS MODEL RESULTS NOAK OR BEST EXPERIENCE (2017 $, BILLIONS)

Account	PWR12	AP1000	traditional HTGR-4	MIGHTR -4
21-Structures & Improvements	$1.24	$1.49	$1.87	$0.30
SC1. Bldg.	$0.65	$0.20	$1.87	$0.30
Cont. Bldg.	$0.59	$1.28	$-	$-
22-Reactor Plant Equipment	$1.48	$1.48	$1.58	$0.99
23-Turbine Plant Equipment	$0.70	$0.67	$0.89	$0.56
24-Electrical Plant Equipment	$0.32	$0.31	$0.31	$0.22
25-Misc. Plant Equipment	$0.29	$0.11	$0.53	$0.07
26-Condensing Heat Rejection	$0.16	$0.16	$0.11	$0.07
Total cost ($B)	$4.18	$4.22	$5.30	$2.21
Specific cost ($/kWe)	$3,650	$3,838	$4,814	$3,585

INL estimated the cost of the Framatome SC-HTGR plant in 2012 [16]. In the analysis, a 1-unit demonstration plant would absorb most of the design and R&D costs, so called NGNP. Later, commercial units would be built following the FOAK-NOAK cost logic. The 1-unit FOAK would have an overnight cost of $2.7B (2017 USD), and Table VI shows a 1-unit traditional HTGR FOAK overnight cost of $2.61B (2017 USD). While our forecasted figure is practically on target, our economic model does not include a demonstration plant, hence many of the design and licensing activities afforded by the demonstrator (NGNP) plant, would need to be assumed by the FOAK we postulate. This aspect would result in a costlier FOAK than the one predicted by INL and by our model. Yet, our estimate for the traditional HTGR shows reasonable agreement with the INL estimation in predicting the FOAK overnight cost for the SC-HTGR.

INL estimated the NOAK overnight cost of a 4-unit SC-HTGR. The 4-unit NOAK would have an overnight cost of $5.5B (2017 USD), and Table VII shows a 4-unit NOAK overnight cost of $5.3B (2017 USD) for the traditional HTGR. Our model shows excellent agreement with the INL estimation in predicting the NOAK overnight cost from the SC-HTGR. Given that the SC-HTGR has not been built, there is not absolute standard. Yet, both our model and the INL analysis suggest at the least the possibility of substantially higher costs for HTGRs than for PWRs.

C. Discussion

Our model predicts a NOAK overnight cost of $3,585/kWe for the 4-unit MIGHTR plant. This overnight cost is very competitive in many markets. There are three additional attractive features from the MIGHTR not included in our model. First, we are exploring a modified confinement building to perform all the functions of the auxiliary building, thus eliminating the auxiliary building. Second, our model does not include the fact that a shorter building is easier and faster to construct. The lower height of the buildngs together with the interal layout based on several railed systems makes construction and assembly highly modularizable. Third, the high core outlet temperature makes the MIGHTR, unlike LWRs, suitable for coupling with advanced ultra-supercritical rankine power cycles. Advanced ultra-supercritical steam cycles have thermal efficiencies of almost 48%, and therefore, they would lower the plant specific cost by a further 10%.. These features do further increase the cost competitiveness of the MIGHTR, making it highly attractive.

Further, limited R&D requirements together with the low financial risk associated to the construction of a 1-unit plant relieve from the necessity of a demonstration plant for the MIGHTR. Instead, a 1-unit plant will be built. The low financial risk stems from the modular and building charateristics as well as low overnight cost we forecast a FOAK single unit will have $1.13B.

V. CONCLUSIONS

There is a correlation between the building volumes, thermal power, and number of units on site to the overnight cost of a nuclear power plant. We generated a cost forecasting model based on this correlation. The model decouples from the type of nuclear technology: light water reactors or high temperature gas reactors. The correlation we generated in this work is not exact, but it demonstrated that a trend exists, and it can inform engineering design decisions to lead to more cost effective nuclear power plants. Comparisons of our cost estimates with the overnight costs produced by INL and quoted for US AP1000s reinforces that the model tends in the right direction. Both, the cost estimates from INL for the SC-HTGR and those predicted by our model for the traditional HTGR, indicate challenging cost and market conditions when competing with LWRs, not to mention combined cycle natural gas.

With the purpose to make HTGR technology cost competitive to lead a deep decarbonization in the electricity and process heat markets worldwide, the paper presented the MIGHTR. The MIGHTR is a highly ready, designed-to-build gas reactor. The distinctive features of the MIGHTR bring about an outstanding cost reduction with respect to other HTGR technologies and an NOAK $3,585/kWe overnight cost. The construction simplicity reduces the expected construction time and the cost of capital. The overnight cost predicted by our model for the MIGHTR is competitive in many electricity markets. One can extrapolate our cost estimates for the electricity market to process heat markets and see how competitive it is in process heat markets.

The NGNP program already invested hundreds of millions of dollars in resarch and development for HTGR technology, which the MIGHTR leverages to become a climate change mitigation tool. In the next ten years, 25 GW of nuclear capacity will retire in the US, UK, and Canada. If it is replaced entirely with combined cycle natural gas plants, CO_2 emissions will increase 100 million metric tons per year. Affordable HTGR technology can meet these retiring capcity needs in the near term. Further, HTGRs can replace high temperature fossil fuel heat in industrial processes. The MIT Future of Nuclear study identified 134 GWth of industrial heat applications in the US that nuclear power can meet, and switching these heat sources to nuclear from natural gas would save over 300 million metric tons a year [12].

The MIGHTR was the product of design-to-cost thinking, and in the nuclear industry cost means primarily civil and structural engineering. Innovative thinking in civil and structural systems for nuclear reactors has high impact potential for near term climate change mitigation.

VI. ACKNOWLEDGEMENTS

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