Leveraging Commercial Nuclear Reactors to Power Space Exploration

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This study is aimed at exploring the adaptation of commercial nuclear reactors as an alternative to NASA's current high-power fission reactor systems, particularly with respect to applications on the surface of Mars. The study concludes that while the Kilopower architecture is brilliantly poised to provide affordable, near-term power in the 1-10 kilowatts electric (kWe) range, the financial barrier to higher power scaling of such systems is significant. This financial barrier adds risk to the development of greater than 10kWe systems and is likely to result in the failure to successfully scale the technology to higher powers for space exploration applications. To investigate the feasibility of commercial reactor adaptation, the study first explores which general reactor concepts would be the most likely to succeed in space applications. The study's analysis of current reactor concepts concludes that solid core reactors scored the best, although molten salt reactors also show potential for applications in space. A case study of AlphaTech's ARC Reactor concept demonstrates that a commercial reactor concept has potential to be adapted for NASA's purposes without sacrificing primary [illegible] density. Preliminary specific power estimates of the reactor concept demonstrate potential to bring energy orders of magnitude greater than the Kilopower concept to space exploration while also mitigating financial barriers. This study concludes that commercial reactor development merits further investigation as an alternative to NASA's development for reactors greater than 10kWe.

I. INTRODUCTION

NASA has had a goal of a crewed mission to Mars since the 1960s[1]. Current architecture for this manned mission recommends In Situ Resource Utilization (IRSU) on the surface of Mars and even the Moon to produce fuel needed for travel to and from Mars.[2] The power needed to convert the atmosphere and regolith into fuel was initially estimated at 80 kWe, although recent studies show that actual power requirements for a 500 day mission with a crew of six on Mars require at least 36 kWe of energy.[3] Producing consistent electricity on Mars and the Moon is challenging in some respects because the long lunar night and dust storms on Mars' surface make solar energy less feasible.[4] This has driven NASA to investigate a fission power source for the mission.

Fission power sources have also been investigated by NASA since the 1960s. In fact, the only successful development and launch of a space reactor happened in 1965 with the SNAP-10A reactor.[5] Since then, [illegible] expended to develop space reactors, but the technical, political, and financial barriers to development have led to their ultimate failure, until the Kilopower concept was developed, a solid core reactor designed to fulfill NASA's energy needs in the 1-10kWe range.[6] This comparatively simple reactor concept was designed to leverage existing facilities and technology. These attributes allowed the reactor to be nuclear tested under a budget of less than $20 million, which is less than 20 times the budget of its progenitor, the SP-100.[7] The 1-10 kWe potential electric output of the current Kilopower concept opens many doors for space exploration, including deep space exploration, as well as manned Moon and Mars landings.[6] Scaling the reactor concept to higher powers than its current 1-10 kWe range has also been considered, including the resulting Westinghouse eVinci concept, which scales the energy output to greater than 1 megawatt electric (MWe).[8] Intuitively, power systems greater than 10 kWe could open even more doors for space exploration, including nuclear electric propulsion and permanent lunar and Mars bases.[9]

II. ANALYSIS

A. Commercial Reactors for Application in the 1-10 kWe Range

The Kilopower system is well poised to fill the 1-10 kWe gap in power availability in the near term. This technology was developed much faster and cheaper than its predecessors, taking 5 years and under 20 million for near prototypic testing.[5,10] Similar testing done on the SP-100 reactor from 1983 until the project was canceled in 1994 cost about $500 million in 1994 dollars, which is $870 million in 2020 dollars.[7] Although there is no certain cost of further flight testing the reactor, a 2005 estimate for the cost to flight test a reactor was $100 million to $1 billion.[9] The contrast between the SP-100 and Kilopower testing costs gives some assurance that the 1-10 kWe concept should fall in the lower ranges of that estimate, which would likely be financially feasible. The cost of adaptation and flight testing of any commercial reactor design would certainly be more financially and technically expensive than the Kilopower system in the 1-10 kWe range, since any commercial reactor in use would merit the same technology readiness level Kilopower has already achieved.

B. Commercial Reactors for Application to Power Mars ISRU and Crew Habitat

1. Technical Benefits and Challenges of Applying Current Kilopower Technology to Mars Manned Mission Architecture

As previously stated, NASA's goal for a manned Mars mission requires more than the 1-10kWe range the Kilopower concept offers. Adapting a commercial reactor could be an alternative to scaling the Kilopower system to the requisite 36 kWe power level or transporting four, 10 kWe Kilopower reactors to Mars' surface. NASA recently conducted a study on the benefits and costs of a single 40 kWe reactor, versus four, 10 kWe Kilopower reactors for Mars surface power applications.[3] According to this study done by Rucker et al., application of four, 10 kWe Kilopower systems on Mars has technical advantages, including the ability to test the system viability on Mars or the Moon with a single, smaller and less massive reactor, lower cable mass, and easier surface transportability.[3] Rucker et al. also mentions challenges to scaling the power up with this methodology: additional surface delivery trips, increased operational complexity, and potentially lower overall system reliability to the challenges with such a trip. An important detail when considering the effect of these challenges is that all the connections made from the power system to the ISRU unit need to be made robotically, before the crew arrives. A United States Air Force study also cited by Rucker et al. determined that these connections are the leading cause of aerospace reliability problems. These challenges suggest that it may be desirable for the current Mars manned mission architecture to scale the Kilopower reactor to 40 kWe.[2]

Scaling this reactor also has technical challenges, including the bonding of the heat pipe heat rejection system to the core, potential concerns about the solid UMo of the core creeping at high temperatures, and the solid fuel swelling as temperatures increased. The fuel swelling is the primary reason attributed to the scaling limit of 10 kWe, although NASA is confident that this can be mitigated by a new fuel pin design. This new design would however require additional testing.[6]

2. Financial Barrier to Scaling the Kilopower Concept to Greater Than 10 kWe

One potential advantage to commercial development and adaption is the mitigation of the financial barrier to developing and testing a prototype. As previously mentioned, the Kilopower reactor concept was brilliantly designed to be tested under a minimal budget, including using existing reactor testing facilities. These tests used critical assembly equipment that was over 75 years old, FLATTOP and COMET.[11] These old critical testing facilities would not be able to critical test a larger, scaled Kilopower reactor.[6] It is difficult to estimate the cost of new facilities to accommodate the testing of a potential 40 kWe Kilopower concept, but some data points come from the FY 2020 NNSA budget reports.[12] These reports show that the NNSA plans on spending $188 million on Naval Nuclear Laboratory facilites, compared to $23 million in the combined costs of all other research facilities. Perhaps a better evidence that the cost of upgrading the facilities is substantial is that the 75 year old COMET and FLATTOP critical assembly units are still in use after years of NASA fission power testing and development.

The financial cost of the additional research and development for a scaled reactor is also a concern. It should first be noted that higher power Kilopower systems already have a proof of concept, and the technology is relatively simple compared to previous designs. This must nevertheless be balanced with the cost of overcoming the technical challenges mentioned earlier. This balance makes estimating the financial cost of scaling Kilopower to higher powers difficult. One potentially useful datapoint is the SP-100 reactor, which, as previously mentioned, cost $870 million in 2020 dollars. Budget reports from the NNSA are also yield another potential datapoint.[12,13] According to these reports, $2.7 billion is appropriated to naval reactor research and development per novel reactor built in the last 20 years. An MIT publication also mentions that commercial nuclear energy spends an average of $10-15 billion in research and development for each nuclear reactor design.[14] These figures provide reasonable evidence that the financial cost of scaling Kilopower, including upgrading facilities and flight testing, would likely cost closer to NASA's $1 billion estimate. For comparison, NASA's projected FY 2020 budget for Exploration Research & Technology is $178.6M, a category not exclusive to developing space fission reactors.[15]

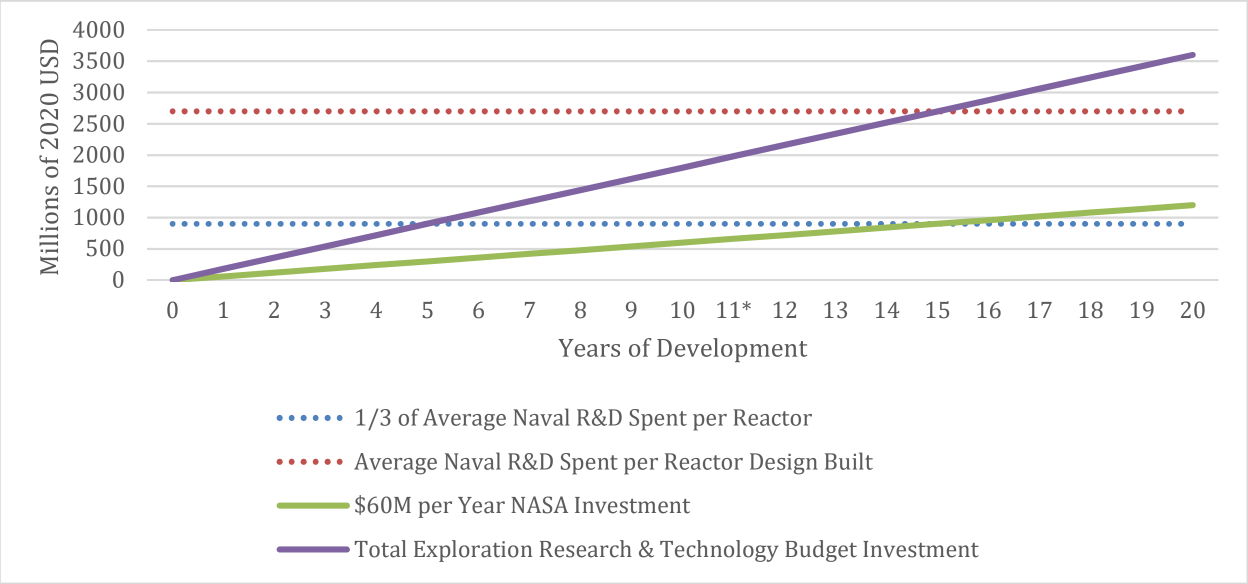
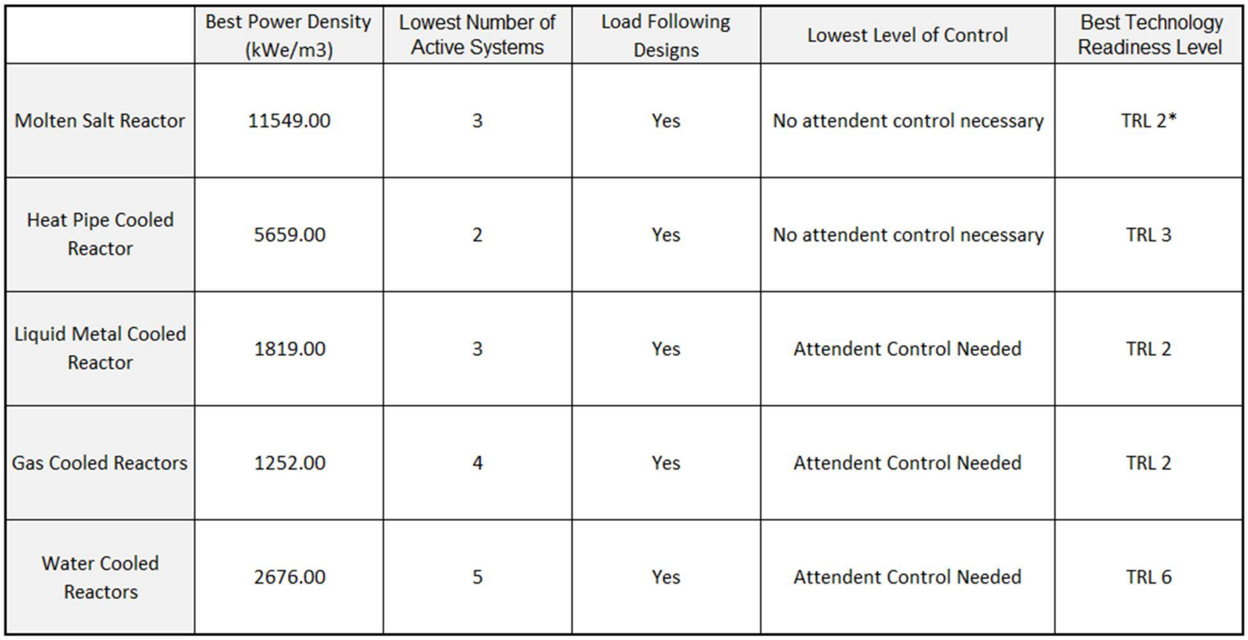


Fig. 1. Potential NASA Investment in Kilopower Scaling Over Time
The SP-100 program was canceled after year 11 of development

Figure 1 is a simple demonstration that shows that high costs of reactor development consistent with that of other reactors with roughly similar electrical output and constraints would put the project at risk of cancelation. It shows that if NASA were to invest all $178.6 million of the current Exploration Research & Technology budget in scaling Kilopower, it would take nearly 15 years to match the Navy's research and development expenditure per reactor. Even if the actual cost of realizing a space ready 40 kWe Kilopower reactor was a third of the Navy's average expenditure per reactor, the cost would likely be too high under current NASA budget constraints. Although the scaled Kilopower reactor features relatively a simple design and already has a proof of concept, the cost of mitigating the technical challenges mentioned are likely to be prohibitively high. This risk could be mitigated by adapting commercial technology for NASA's needs, given that there is a commercial reactor concept that could be adapted to fulfill the rigorous requirements of space exploration.

C. Assessment of Commercial Small Modular Reactor Design Suitability for Space Power System Adaptation

There are many modern Small Modular Reactor (SMR) concepts being developed by commercial and government entities around the world. One of the questions this study seeks to address is which category of commercial reactor technology, if any, would be best suited for adaptation for space power systems. To address this question, concept designs were sorted based on technology categories as determined by the 2018 SMR Book, a collection of 55 SMR designs gathered by the International Atomic Energy Agency (IAEA).[16] A table evaluating the power density, number of active systems, ability to load follow, lowest level of control, and technology readiness of each reactor was created for each reactor category. Then Figure 2 was created by evaluating each reactor category table for the best metric, so each row in Figure 2 represents a conglomerate of the best attributes of reactors from that reactor category. While the 2018 SMR Book had easy to access information about the volume, power output, and instrumentation and control systems of each reactor, gathering data about the lowest number of active systems was somewhat ambiguous. To truly identify how many moving part systems would require the analysis of each reactor schematic. Often, because of the pre-conceptual or proprietary nature of the designs, this was impossible. Instead, number of active systems was determined by counting the number of pumped or motor-controlled systems mentioned in each reactor briefing. This typically included active reactivity control mechanisms, power conversion systems, and primary and secondary reactor coolant loops. NASA's technology readiness level, however, was very relevant to this application. Higher numbers indicate better performance. For comparison, the Kilopower reactor concept has merited TRL 5, and would have two active systems: its active reactivity control mechanism and power conversion system.[17] Because this wasn't a rigorous study of each design, the data collected should be interpreted to show trends rather than to provide definitive information on the technologies investigated.



	Best Power Density (kWe/m3)	Lowest Number of Active Systems	Load Following Designs	Lowest Level of Control	Best Technology Readiness Level
Molten Salt Reactor	11549.00	3	Yes	No attendent control necessary	TRL 2*
Heat Pipe Cooled Reactor	5659.00	2	Yes	No attendent control necessary	TRL 3
Liquid Metal Cooled Reactor	1819.00	3	Yes	Attendent Control Needed	TRL 2
Gas Cooled Reactors	1252.00	4	Yes	Attendent Control Needed	TRL 2
Water Cooled Reactors	2676.00	5	Yes	Attendent Control Needed	TRL 6

Fig. 2. Best Achieved Space Fission Reactor Adaptation Metrics.
ThorCon claimed the 1960s MSRE experiment as a prototype, however, the conceptual design was deemed significantly different than the MSRE.

Perhaps the most important metric in Figure 1 table is the lowest level of control. Any reactor technology that requires online monitoring is probably unsuited for space fission system adaptation, which makes water cooled, gas cooled, and liquid metal cooled commercial reactor concepts less suited for NASA applications. The remaining alternatives, heat pipe cooled, and molten salt reactors show high power density designs and load following capability, as well as a relatively low number of active systems, but low technology readiness seems to plague both designs. This shows that technology readiness may be one of the greatest barriers to adapting commercial nuclear reactors for space exploration.

D. Case Study of AlphaTech's ARC Reactor

The greatest question to be answered by this study is if there are any single reactor designs being developed commercially that fulfill the many requirements of a feasible space power system. To evaluate this question, a case study is done with AlphaTech's ARC Reactor. Brigham Young University's reactor design research group has had regular contact with AlphaTech, a local nuclear energy company. AlphaTech is designing a molten salt reactor with simplicity and safety in mind for potential Department of Defense and other remote power applications.[19] The primary feature of the reactor is its physics-driven passive safety systems, which, like the Kilopower reactor, provides 'walk away safety' and doesn't require online monitoring. MCNP validation of the reactor demonstrates both its criticality and negative void and temperature coefficients, such that any increase in temperature would decrease the heat flux of the reactor. The reactor's simplicity and safety are designed to decrease NRC certification and testing costs, which are expected to be a significant barrier. The reactor core footprint is an 18 inch by 18 inch cylinder, which is of similar size and shape to the 10 kWe Kilopower concept. The basic reactor design is a cylinder housing molten salt, dissolved fuel, moderator, and a mechanism to activate and deactivate the reactor. Preliminary, conservative mass estimates for the reactor core and housing come out to 2400 kg. These mass estimates were derived from density given of the proprietary molten salt and fuel mixture, and a 3 inch solid molybdenum containment wall. According to AlphaTech, the proprietary containment would be less massive than the 3 inch molybdenum containment.[18] The ARC Reactor is expected to produce a thermal output of 3 MWt, with an electrical output of 1 MWe. A conservative estimate from AlphaTech for the mass of a 1 MWe ARC Reactor system including the necessary power conversion systems and radiation shielding is 35 US Tons, or about 31.7 metric tons. However, AlphaTech is confident that optimization of shielding of the 1 MWe reactor will lead to a total system mass of 25 US Tons or about 22.7 metric tons, less than the maximum payload of a Delta IV Heavy.[20] Both of these mass estimates include radiation shielding for a commercial reactor which would be greater than the necessary shielding for a similar system on Mars. This gives the 1 MWe reactor specific powers of 32 kg/kWe and 23 kg/kWe for the conservative and optimized reactor systems, respectively. Another potential benefit is that scaling the reactor down to the kilowatt range would not require a change in the geometry of the reactor, allowing for easier validation for a wide range of power levels. Additionally, AlphaTech is investigating integration of the same heat pipe technology Kilopower used to transfer heat from the reactor to the power conversion systems. This would reduce the number of systems with moving parts to only the power conversion system, as the reactor requires no active reactivity control. To compare the mass of Kilopower systems to potential modified ARC Reactor systems, a linear scale up from the average specific power (kg/kWe) of Kilopower's 10 kWe power conversion systems, radiator, and balance of power system was added to the base ARC Reactor mass.[6] These are also conservative estimates, since the mass of power conversion systems and radiation shielding scale less than linearly to higher powers, as demonstrated in scaling of 1 kWe Kilopower systems. One result of these conservative estimates is a 40 kWe scaled ARC Reactor with a mass of 8700 kg, within 10% the mass of the similarly fueled 8064 kg 4x10 kWe low enriched uranium (LEU) Kilopower configuration. A more compact highly enriched uranium (HEU) configuration of the Kilopower concept is also presented Figures 3,4,and 5.

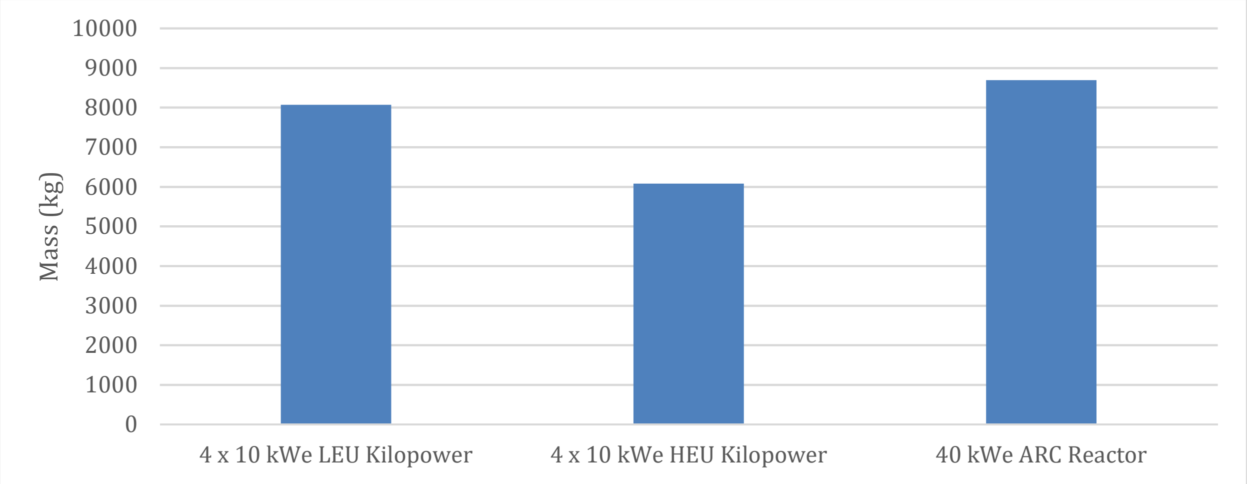


Fig. 3. Mars Surface Fission Power System Mass Comparison.

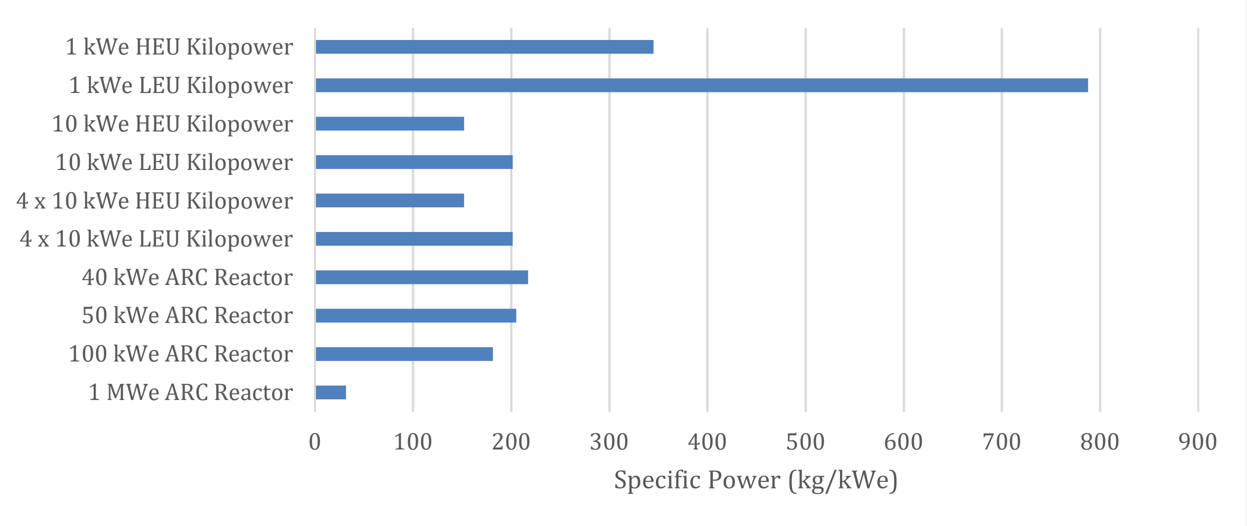


Fig. 4. Specific Power of Reactor Concepts.

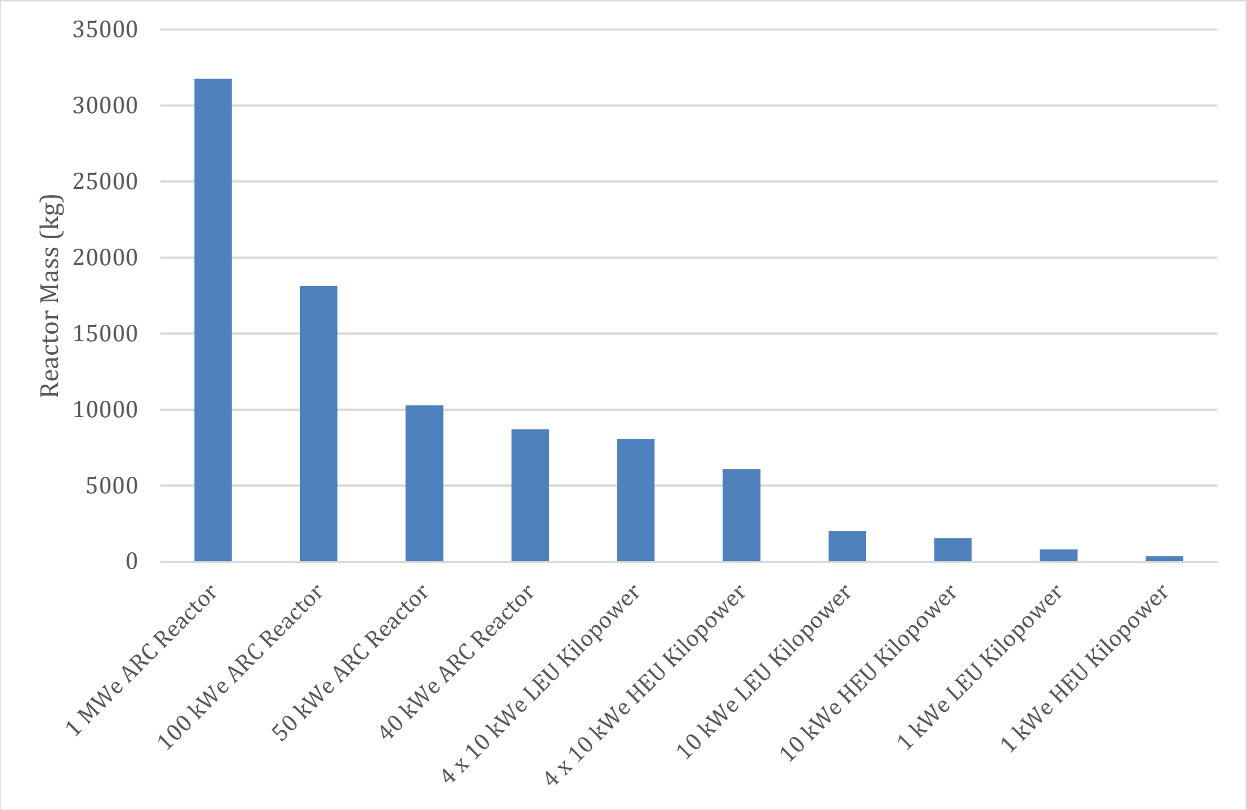


Fig. 5. Scaled ARC Reactor Mass Comparison.

1. Limitations and Implications of the Case Study

This case study has some obvious limitations. The ARC Reactor is a pre-conceptual design, the viability of the concept has yet to be physically tested and the complete design of the reactor is still fluid. First and foremost, this puts into question whether the final design will be compatible with the many constraints of space exploration. The information available may show potential, but there could be a disqualifying attribute of the final design. The proprietary nature of some of the enabling elements of the reactor design would also make it difficult for a NASA analysis to determine if the reactor can be adapted for NASA's purposes. The previous comments about the financial barrier to Kilopower's reactor development are just as valid to commercial development.[14] It is certainly unknown whether AlphaTech will be able to hurdle the financial barrier of relatively unknown magnitude.

The data, however, does serve as a type of proof of concept. It provides evidence that such a reactor could be adapted to satisfy NASA's requirements, if the reactor were successfully developed for commercially or other applications. With respect to the financial barrier, commercial ventures do have the advantage of being able to pull funds from both government vendors and the international market, which would make it less likely for reactor development to stall because of inadequate funding. Like the Kilopower concept, the ARC reactor's apparent simplicity also lends AlphaTech some credibility that the financial barrier it faces is not as significant as other reactor designs.

Assuming successful development of the reactor, NASA adaptation of the ARC reactor could potentially provide physical, validated prototypes not only for 40-80 kWe systems, but also for 100-1000 kWe systems. This has exciting potential for many space exploration applications. The added benefit is that with the mitigation of the financial barrier, NASA could concentrate its resources on developing the high-powered space exploration technology necessary for manned missions across the solar system.

III. CONCLUSION

This study concludes that NASA's adaptation of commercial nuclear reactors merits further investigation for power levels greater than 10 kWe. It is found that while NASA's current Kilopower system demonstrates relatively low financial and time costs, scaling the reactor is risk invasive and will likely fail to overcome the financial barrier to development. It is also discovered that commercial heat pipe reactors as well as molten salt reactors show potential for NASA applications with high specific power, low numbers of active systems, and no necessary attendant control. The case study of AlphaTech's ARC Reactor demonstrates that commercial reactor technology for reactors of the size, mass and reliability needed for NASA applications are in development. A mass estimate of an ARC Reactor adapted for Mars surface application is demonstrated to be comparable to NASA's current Kilopower standard. If the ARC Reactor or similar nuclear reactor were to be developed and put into use, adaptation of the reactor concept would save NASA hundreds of millions of dollars. Without substantial change in NASA's investment in high power fission systems, this may be the only feasible pathway to NASA's development of a fission power system greater than 10 kWe.

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