Aluminum: An Alternative Energy Storage Device for a Coal-Based Society

John M. Flynn*
21A.S01: Anthro-Engineering - With a Focus on Decarbonizing Ulaanbaatar
(Dated: December 17, 2022)

I. BACKGROUND

This semester-long pilot class sprung from an ad-hoc engineering collaboration between MIT (Massachusetts Institute of Technology) and NUM (National University of Mongolia) hoping to address pollution in Ulaanbaatar's ger districts. The focus previously was on engineering, but it became clear that the problem needed to be viewed through an anthropological lens as well. The class had 4 main sections. First, students were introduced to some of the essentials of relevant anthropological literature. Second, Mongolia and other relatable communities were studied. Third, systems thinking and design paradigms were presented to give students new frameworks to think with. Lastly was the ideation and preparation for fieldwork phase, where students read a book on Mongolia, took language lessons, and presented their own research & ideas, the last of which culminated in this paper.

II. THE ULAANBAATAR SITUATION

Ulaanbaatar has a pollution problem that has been labelled as "a growing bio-political crisis.[1]" This stems from a combination of CHG Plants inside the city, heavy vehicle congestion, and the burning of coal for heating by ger residents. Rapid migration to the city has accentuated problems, with population doubling in 20 years (from 828k to 1.64m since 2002) [2]. The city was only designed for half a million people [3]. The third reason - the ger districts - is considered to be the most contributive and is the target for an intervention.

Ulaanbaatar, Mongolia's capital city, consists of a central urban landscape containing modern apartments and houses, and sprawling ger districts. It is estimated about 60% of the population live in the ger districts (a number oft quoted still today from a 2008 study). These ger districts consist of hashaa - fenced areas surrounding one or more housing units. Almost all hashaa have at least one ger, but many contain other forms of housing as well. Extended family comes and goes on these plots. Massive migration to the city in the forms of these living arrangements has been facilitated by a government policy of granting all citizens the right to small plots of land. Migration is also driven by the classical promise of a better life, taking shape as an imaginary in many forms.

* jmflynn@mit.edu

The electric grid reaches the majority via formal or informal methods (about 90% according to guesses by professors in this class), however there are frequent outages, and the supply is not sufficient for electric heating in the ger districts, nor is the infrastructure there to support heating. Gers were designed to be movable, so there is minimal utility support. Many have an outhouse, and a dog in their yards as well.

The central problem is pollution due to coal burning for heating in the gers and residential houses in the ger district. This is typically done by a central furnace which is also used for cooking. This is a very wasteful process. Many of the stoves are old. Low quality coal was used. These last two issues have tried to be addressed. There are more problems still. There is not much temperature regulation on the stoves, so that is done by opening the door out to the freezing cold air, letting much extra heat escape. When times get tough, people are known to burn wood, dung, and other things out of desperation, all of which are also hazardous. By some reports, the amount of wood burning is almost as significant as coal burning by mass [4] [*Note this source is DNCQ*]. This local carbon burning creates bad air quality both in and outside the ger which has led Ulaanbaatar to be dubbed as the world's most polluted capital city in the winter months: 133 times the WHO recommendation of particulates [3]. This pollution has had a noticeable drastic effect on youth health, and it is still too soon to see the full affects it will have on those that spend a lifetime subjected to it.

Making matters worse, the government has staked its future on coal. Much of the economy is in coal, and there are no serious plans to get off of it. The population is also losing trust in the government's capability and the idea of democracy as a whole. Public and Private debts loom large [5]. Migration is only increasing.

One can imagine solutions for some things. Build new powerplants further out of the city (although the lossy pipes are already a problem, losing 17% in transmission [3], 3x that of Helsinki, Finland), and eventually switch to renewables. Widen and improve the roads, so they are not as congested. Switch to electric vehicles. Have a stronger public transportation network to reduce car usage. Improve the insulation of the city buildings. Unfortunately, many of these are far away, and even so, *the major player, the ger district, needs to be addressed to mitigate this public health crisis.*

Given this context, what can be done to reduce the pollution of the ger districts, while offering the greatest positive externalities with emphasis on the people of Ulaanbaatar? In other words, what would a good

Anthro-Engineering Intervention look like?

III. REFERENCE INTERVENTION

A few years ago, an idea was conceived, and some foundational design work has been done. This is the idea of the Molten Salt Heat Brick (MSHB).

Molten Salts have found use in many applications. These include [6]:

- as a heat transfer fluid, especially for heat treating alloys, and in fission reactors
- as a solvent, especially for Aluminum Oxide reduction in the Hall-Heroult process
- for thermal slow-release storage, especially for concentrated solar
- for pyroprocessing nuclear fuel
- for surface modifications, such as carburizing steel
- as a thermal battery, promising because of the low leakage (maintain potential energy for 50+ years)
- for high-temperature heating applications, since the boiling point is very high

The key insight was to wonder: could Molten Salt have an application for consumer heating? Until now we have seen it extensively used for industrial heat transfer, but not so much for households. Why? Most likely because they are typically operated at very high temperature and may be seen as dangerous. Also, using a liquid fuel source requires building infrastructure to contain it, solid fuels are simpler. More importantly, if the energy storage is in the heat, rather than chemical bonds, the storage time is finite and requires extreme insulation.

MIT's NSE department together with NEET-CSS have developed a prototype for consumer Molten Salt Heating![7] The created a steel casing around a nitrate salt, which they call a Salt Brick. This can be heated up above the melting point to turn it into a Molten Salt Heat Brick (MSHB). The idea is it can be heated using waste heat from existing coal power plants, or in the future be heated in dedicated facilities running on renewables.

The salt brick is better than other materials for its high boiling point and high specific heat. This hot brick is then encased in an insulating material (Rockwool). The total MSHB-insulation systm is about 25lbs. It is to be loaded into trucks and get carried to distribution centers near residents. Either there would be delivery from there to the home, or if users preferred more privacy, they could use a delivery cart to wheel it back and forth to the house. They could load this into the stove using a lifting mechanism on the cart. If there was direct delivery, the current idea is to either have a worker do full transport to the stove, or have the brick deposited in a mailbox system, and the cart is used within the hashaa.

The MSHB currently heats a 20C room by about 10C for around 12 hours, but the goal is to make it last 24 hours and use daily delivery and return. Lastly of note, the outer insulation can be cracked for temperature control. Appropriate engineering and optimization of this is still to be done.

The NEET report [7] estimates heating needs based on electric heater use, coming out to 1000kw/month or 120MJ/day per household. They claim residents use a 35lb bag every day, coming to $1.13/day or $200/year assuming 6months usage. Their materials cost for the prototype was $333.23, but they expect the brick could be sold for $100 in Mongolia with scale. Either way, this is a great deal because the lifetime should be 20 years, and the government may provide subsidies. Additionally, credit is widely used in UB, so financing plans would likely be abundant. (It is interesting to consider whether small subsidies would be helpful or harmful - it may be better to leave the government out of public perception of the artifact, and allow them to regard the brick and loans for it as a way of managing the gap, and keeping many futures open) [5]

IV. PROS AND CONS OF THE MSHB

In this section I will list some of the most important benefits and weaknesses of the MSHB. These include engineering and Anthropological aspects. They are ordered by estimated importance.

First the positives:

- No local emissions. Reduces particulates in the gers.
- Easy to use, besides potentially heavy lifting.
- Minimally disruptive to the current ger design
- The MSHB system is analogous to coal in a lot of ways. Job transfer could ease the burden of lost coal jobs. However, coal stakeholders could also be placated by maintaining coal in the medium-term as an export.
- Allows for heat control (potentially). This would further increase the efficiency of the system because currently gers waste a lot of energy because opening the door is the response to coal getting too hot. Additionally, sensitive enough heat control could allow for cooking.
- High heat capacity gives us large heat storage potential.
- Chance to appear innovative. Both leveraging the people's belief in their own greatness, the government's desire to reestablish legitimacy, and both of their desires to impress foreigners. Also, trying innovative solutions may open the door for further

innovation. Lastly, this also can give them the image of renewable energy leaders, which could spur further investment in that area.

Then the negatives:

- Requires Daily Delivery. This is unfortunate for many reasons. First, coal is nice because you can stock up. Daily delivery is intrusive. But the bigger problem is lack of reserves. If the MSHB is expected to provide all your heating needs, what happens when the system fails for a day? Failure = Death. In the current formulation, some fuel reserve will need to be maintained. One positive might come out of this: community building through the routine delivery.

- Distribution infrastructure needs to be more complex then that of coal. MSHB is time sensitive because it starts cooling the moment it leaves the oven. Specialized equipment is needed, whereas with coal it is just lifting heavy objects.

- Accidents in transport (which frequently happen with coal), or in the household, will be more troublesome and even dangerous (due to heat).

- Governmental involvement. Could be a positive or a negative. The logistical complexities, potentially high price tag, fact that government already regulates coal, and community aspect of delivery and adoption, makes it likely government will be involved.

- How much scale is needed to justify the initial investment, and can that be achieved considering the roads?

- Still reliant on coal in the short term. It may slow down renewable development if they realize they have a solution to their crisis that doesn't force them to move away from their economic gem (coal). I put this at the bottom because this could also be viewed as a positive: having a rapid transition away from coal may meet with much resistance.

It is important to keep in mind not just the engineering formulation of the problem, but the hidden boundary conditions imposed on us by the values, aspirations, and social situation that the engineering problem is embedded in. With this, here are a few boundary conditions it is good to keep in mind.

- The government has a heavy stake in coal. It brings them revenue, gives political power, connects them with other countries through trade, and allegedly some of them profit illegally - there are coal interest groups.

- Employment of people by the coal industry. What will happen to them?

- People don't have much faith in the government. The govt has displayed incompetence, inconsistency, and ulterior motives several times.

- Roads are crowded and not well maintained.

- Ger households consist of individuals of many different types: young, old, disabled, sick.

- -40 degree temperatures means the system must work 100%

- Messing with the historical ger design could meet with some resistence, but once the ger is no longer being used as a nomadic structure it loses much of its value, so it is possible some people would be open to changing some aspects of the ger.

- Most households (90%) - but not all - have electricity access, and it is intermittent for some.

Synthesising this, I do believe in the strength of the salt brick as a human-centric intervention. There are many specifics to answer, such as how to partner with the government to access waste heat, but the high-level idea seems strong. Adoption would start on a small scale, and slowly expand through the districts. This will be a great thing for those using it, as well as serving as a beacon of hope. However, I don't imagine it achieving 100% market capture, and it also looks like it will spread slowly - maybe taking 5-15 years to be supplying a full khoroo. Additionally, the salt brick still leaves two key problems: Cooking, and Reserves. Cooking is currently supplemented with an electric stove, but they use a dirty grid. To best decarbonize, there must be many avenues of 'progress'.

Besides the literal impact it will make on the air quality, the largest impact of the MSHB may be to allow Mongolians to perceive themselves in a different way. The real gap between a hopeless situation and an improved life is often much smaller than it is envisioned in our brains. Some spark to set us in the right direction is sometimes all that is needed. Once people begin to see MSHB adoption improving the lives of some people, this will encourage them to adopt it, or look for other ways of sidestepping their emissions. It will inspire entrepreneurial minds to think of more solutions, with evidence that something can work despite the odds. It will inspire the government to re-uptake renewable projects with more belief and cohesiveness. It will reignite foreign capital investment and humanitarian non-profit funds.

With the salt brick looking like a real possibility - containing several anthro-engineering challenges yet to overcome - I will focus on supplementary interventions that can push Ulaanbaatar even further in the right direction.

V. PROPOSED INTERVENTION

In this world that is transitioning to molten salt for heating, reserve energy is crucial. Also, some districts will take longer to adopt the MSHB, and some not at all. I see two main options for reserves: Expansion of the electric grid (or heating pipes) combined with increased renewable generation, or having a secondary fuel. The former has been extensively discussed by Shaler Campbell (another member of the 21A.S01 class). For secondary fuels, there are many ideas. Staying on coal and wood is the default. More efficient coal and stoves has already been tried, this can be done in conjunction with a redesign of exhaust circulation. Connecting an air heat pump was suggested by Shaler. Maybe dung or other animal products can be processed to make a safe biofuel.

All of these will be great to explore, but nothing holds more promise for massive potential, while not disturbing existing infrastructure significantly, like the emerging technology of recyclable fuels based off solid-metal combustion [8]. The products of these reactions are an oxidized metal that can be transported back to the powerplant and reduced again. This is in contrast to fossil fuel products (CO_2, CH_4) that are released into the atmosphere and lost + they have an impact on the climate. This paper [8] suggests Iron oxidation holds the most promise as a recyclable fuel because it "has a high energy density, completely burns out during heterogeneous combustion, and yields larger metal oxide particles than do fossil fuels. In addition, Fe absorbs heat that is later released because of the heterogeneous reaction of the solid particles." It also seems to make other metal oxidation reactions more effective when added as composite. I will be focusing not on Fe but another example of this class of technologies - **Aluminum Heat+Hydrogen Storage** - due to time constraints, prior knowledge, and because this has seen recent breakthroughs.

Aluminum (Al) as an energy storage device has long been a dream for researchers: it has high energy density, high abundance, and high stability.

By volume and by weight, the oxidation of pure aluminum releases more heat than coal. It is also good as a 'hydrogen gas storage device,' since the classical heat production reaction

$$2Al(s) + 6H_2O(l) \implies 2Al(OH)_3(s) + 3H_2(g) + \text{heat}$$

also produces hydrogen gas. Hydrogen gas is useful in many energy applications, and notoriously difficult to store and transport. Using aluminum to 'store' H_2 results in 10x the density of H_2 stored when compared to storing it in the compressed gas phase [9]. Several startups from MIT are already in motion taking advantage of this. One, Found Energy, is using this very reaction as way to fuel hydrogen-powered ships with Al-combustion on the ship itself, since the water part of the reaction is free [10]. Another, Hydrova, is working on tackling the problem of turning waste from the Aluminum industry into usable Al that can form Hydrogen Gas [11]. In the lab at MIT, an 'Emergency Power Pack' has been created weighing 734 grams outputting 30W for up to 10 hours using this reaction and the catalyst discussed below [12]. This technology is rapidly advancing upon us.

This leads us into the abundance of Aluminum. Al is the most abundant metal in the Earth's crust at 8.1%. Additionally, Australia and China are the first and third producers worldwide, and Australia is also the #2 reserve holder [13]. Australia and China trade extensively with one another, and China is Mongolia's main trade partner. This points to strong access to aluminum for UB.

The stability of Aluminum is due to its high oxidation potential, causing any pure Al-block to quickly become coated with an aluminum oxide outer layer, which is nonreactive (the reason Al soda cans don't react with the drink inside). This outer layer, while good for ensuring handling is safe, also makes it difficult to access the pure Al when it is time to combust it. Some catalyst is necessary to prevent continual outer layer oxidation from occurring.

Many things have been tried to achieve this catalyst effect, nothing has emerged as a clear answer yet. However, a recent breakthrough at MIT has been successful in the laboratory doing just this [9]! Their method is to use a gallium-indium eutectic mixture, which seeps through the cracks in the Al and 'blocks' oxygen from reacting with the surface. They call the application of the eutectic mixture 'activating the aluminum'. Once the Al is activated, you drop it in water and H_2 will be generated instantly, and heat released. The added bonus - the catalyst doesn't interact chemically - so both the eutectic and the aluminum oxide can be recycled, meaning the only consumed item is water turning into H_2 gas. The difficulty of this recycling process is not clear from the article and needs to be investigated further.

Although aluminum is abundant, we can access it mostly through the oxidized Al_2O_3 form *alumina*, whether be by mining or from recycled waste Al. This is usually purified by the Hall-Heroult process. In this, the alumina is dissolved in another substance to lower its melting point, and then electrolysis with carbon (from coke) electrodes separates alumina into pure Al and organic byproducts, notably CO and CO_2. This is the real catch. Unless an alternative method of turning alumina into aluminum is found, CO_2 emissions are guaranteed. Additionally, to achieve melting of the alumina solution, temperatures of 1000C must be used, which will require lots of energy - in the short term I'd imagine coal would be used for this. Perhaps these Hall-Heroult powerplants should be fitted with carbon capture.

In summary, the proposal is as follows. Alumina is acquired, through trade, internal mining, and recycling of scrap. Eventually, no new alumina will be needed since there will be recycling of the existing material. Powerplants built to perform the Hall-Heroult process purify Al, at the cost of raw coal consumption and $CO and CO_2$ emissions. Al can then be shipped to points of sale. The distribution process can proceed near identically to coal.

Users have purchased a device that can load in Al, and then produce heat and power when water is added. This device has a hydrogen fuel cell, and a way of dissipating the heat in a favorable way. Additionally, it is loaded with the gallium-indium catalyst, which can be introduced into the aluminum sample with the push of a button. After burning is complete, another button seperates the waste alumina and the catalyst. The catalyst is stored in the device, and the alumina is deposited into the box you received the Al in, to be returned to a distribution center for a refund. Rather than refunds a punishment system could be implemented if Al supply was a large concern.

VI. TECHNICAL AND ANTHRO ANALYSIS

So in summary, we have an abundant material that is more energy dense than coal, which also gives us hydrogen as a byproduct which can be used for electricity, that is fully recyclable, and doesn't emit anything harmful onsite. What are the main problems?

One big issue that has been discussed is there is still embedded carbon in the reuse process. Hall-Heroult releases CO_2. How this compares to direct coal burning should be investigated. Additionally, there are some efforts underway to completely decarbonize the Al production process. A European research consortium called Reveal is attempting to do just this between 2022-2026 [14].

Another big question is that the eutectic mixture uses problematic elements. Indium is very expensive, although it has been theorized it may not be essential [9]. Gallium is not harmful in small amounts, but ingestion or inhaling can be very harmful. This is a key concern that must be looked into. Maybe a device could be built as suggested above where the gallium never needs to be handled directly, or exposed to the air. It will be important to understand what happens if things go wrong and is that safe. We must also keep in mind, though, while there is some risk handling things like gallium, and a hot molten salt brick - there is also risk in living with coal fumes in your face every single day.

The last major drawback is that this technology is still a long way from being normalized in the market. Aluminum is very electricity intensive to produce, and the technology for catalysis to use it as a fuel is relatively recent. To use this technology in the quick timeline that is hoped for in an intervention, all the risks of using cutting-edge technologies come along. There could be many unanticipated consequences.

On the bright side, should these issues be resolved, there are many reasons to believe adoption would occur. Al as a fuel is very analogous to coal - and it has been said if it weren't for the fact that coal was so polluting, and GHG emitting, it would be a perfect fuel for the Mongolian gers. This has all the benefits but with the additional 'cleanliness'. Minimal disruption would occur, all that is needed is to buy the new 'stove-power' system, and it could be put in the same spot as the classic furnace. This would admittedly likely be expensive, but this could be managed through loans that already abound in UB. Distribution would be similar to before. There has been some talk of burn-control of the Aluminum based on the size of the metal chunks, so an advanced device could maybe help with temperature regulation. The Aluminum fuel works as a reserve, and maintains that nomadic, independent feel, contrary to the MSHB. A last bonus to note is this can provide some electricity (effectively a battery) to that minority off the grid.

VII. POTENTIAL QUESTIONS FOR MONGOLIANS

In January 2023, a team from MIT will be travelling to UB for 11 days to do fieldwork. Here are a few questions that may be useful to investigate further, to aid in designing a potential Al-power system.

- Are you open to a new large purchase, or making a big investment for the future right now? (with regard to the Al-power device)
- If we describe the MSHB, how big of a problem do they see the lack of reserves being, and how would they propose to solve the problem.
- How are residents thinking about the future. Do they expect a solution in 2, 5, 10 years? How long are they willing to wait? Would they be satisfied with gradual change as long as it was clear they were moving in the right direction? Or do they feel desperate?
- It will be good to increase the sample size on cooking behaviors in all different types of homes and districts.
- It will also be good to learn more about the current coal distribution network - how it is transported, how people buy it - since we think Al will be analogous.

VIII. CONCLUSIONS

Ulaanbaatar is in a very difficult situation. Rapid expansion and a historical reliance on coal has created a public health crisis. But things are not hopeless.

Injecting a fresh new idea, with the imaginaries attached, can be a more effective intervention than just bashing the same incremental strategies that the large development organizations and governments have been using for decades. The Molten Salt Heat Brick is a great idea that could bring about much positive change if the engineering and anthropological challenges are solved.

Aluminum Energy Storage is another great idea. It combines key benefits of coal but trades the onsite pollution for a more complicated device and operation.

My main thing to emphasize is it is not all about these particular technologies. A different metal-oxidation like Iron-Oxide may turn out to be the killer technology. Perhaps it will be something else entirely. The point is that there likely will be no silver bullet, and it is dangerous to bank on just one thing. Having many ideas to develop promotes competition and spurs more ideas.

If any of these 'novel-feeling' technologies can take root, even in just a small neighborhood, the seed has been planted. Because, eventually, the majority of the work should come from the Mongolians themselves. With just a little bit of hope, and a self-image as innovative and leaders in a new technology, their can be a snowball effect of further efforts - whether entrepreneurial, manufacturing, logistics work, business, finance, etc.

In the end, maybe even more important than the immediate critical pollution problem is for Mongolia to emerge with a more diversified economic environment. More innovation and sense of stability and hope will spur longer term enterprises. Improving education and growing businesses would provide many opportunities to provide value that isn't so easily subject to being preyed on by strong foreign nations.

It may all sound a bit colonial or neo-liberal mono-thought, but the more people's wants approach those of the classic modern city, the more difficult it is to stray from the central tenants that sustain them.

It is good to keep in mind that Mongolians overall are very open minded, open to change, open to trying new things. At the same time they tend to accept things the way they are, and adapt, rather than resisting. They are tough, and live in difficult conditions, but now they are starting to get frustrated, as evidenced by recent protests. It would be hard to imagine a place better suited to try out something crazy.

ACKNOWLEDGMENTS

John Flynn would like to thank his 4 instructors Manduhai Buyandelger, Lauren Bonilla, Rea Lavi, and Mike Short. They each contributed with their expertise to develop a cohesive class that taught me an incredible amount. I also am grateful to have had the opportunity to learn from the diverse group of brilliant students beside me.

[1] R. Plueckhahn, *Shaping Urban Futures in Mongolia* (UCL Press, 2020).
[2] *Ulaanbaatar Population 2022*, World Population Review (2022).
[3] A. Menard, *Young Mongols: Forging Democracy in the Wild, Wild East* (Penguin Books, 2020).
[4] S. L. R. Agnes Lobscheid, Gary Fitts and L. Dale, *Pilot Study of Fuel and Stove Use Behavior of Mongolian Ger Households* (2012).
[5] R. M. Empson, *Subjective Lives and Economic Transformation in Mongolia - Life in the Gap* (UCL Press, 2020).
[6] *Molten Salt* (Wikipedia, 2022).
[7] J. C. L. K.-P.-P. V. Tsolmon Bazarragchaa, Patricia Chan, *Decarbonoizing Ulaanbaatar*, NEET Capstone (22.S094) (2022).
[8] A. P. C. C.-T. Li Yueh-Heng, Stalline Pangestu, *Synergetic combustion behavior of aluminum and coal addition in hybrid iron-methane-air premixed flames*, National Cheng Kung University & Johns Hopkins University (2021).
[9] N. W. Stauffer, *Using aluminum and water to make clean hydrogen fuel — when and where it's needed*, MIT Energy Initiative (2021).
[10] *Found Energy Website*, Found Energy Co (2022).
[11] S. Kizner, *Minimizing aluminum waste, maximizing their potential: the story of Hydrova*, MIT Sandbox Innovation Fund Program (2022).
[12] M. MIT Lincoln Laboratory, Lexington, *Aluminum as a Fuel*, Tech Briefs - engineering solutions for design & manufacturing (2018).
[13] *Aluminium*, Royal Society of Chemistry (2022).
[14] *New ways of storing renewable energy - REVEAL project supported by Horizon Europe and the government of Switzerland*, Reveal (2022).