THE NUCLEAR INDUSTRY AND FUTURE GRAPHITE NEEDS –
Pebble Bed Reactors and Potential Graphite Demand

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Stormcrow

What is Stormcrow?

- Well, we had a business plan when we started…
- Stormcrow is a critical materials consulting firm
  - We study the critical materials space, and try to pick coming areas of interest
- We do work for junior resource companies
  - Where applicable, provide paid-for research to the investment community
  - Where not yet applicable, we help to make junior companies strong enough to merit research coverage
- We do work for investment funds
  - At present, are looking into particular stories or larger areas of interest for two resource funds
- We also work for multinationals
  - Are fortunate enough to have two interesting projects in this vein, at present
- We are licensing as an exempt market dealer, and are investigating interest in establishing a critical materials investment fund

The Future of Graphite

- Everyone agrees that automotive batteries are graphite's future
- Clearly, there is almost no chance that another anode material will subvert graphite in the lithium battery space in the near term
  - Graphite is too inexpensive, too well studied and too well understood to be quickly replaced
- However, the penetration of electric vehicles is likely to continue to be slow
  - The public still has issues with electric "fuel", Tesla notwithstanding
- There are other areas for future graphite demand that have potential, over similar time frames
  - We need cleaner, baseload electrical power generation
  - One of the best options in this regard is nuclear
  - But we need SAFE nuclear
- Enter the modular pebble bed reactor…

A New, Old Story

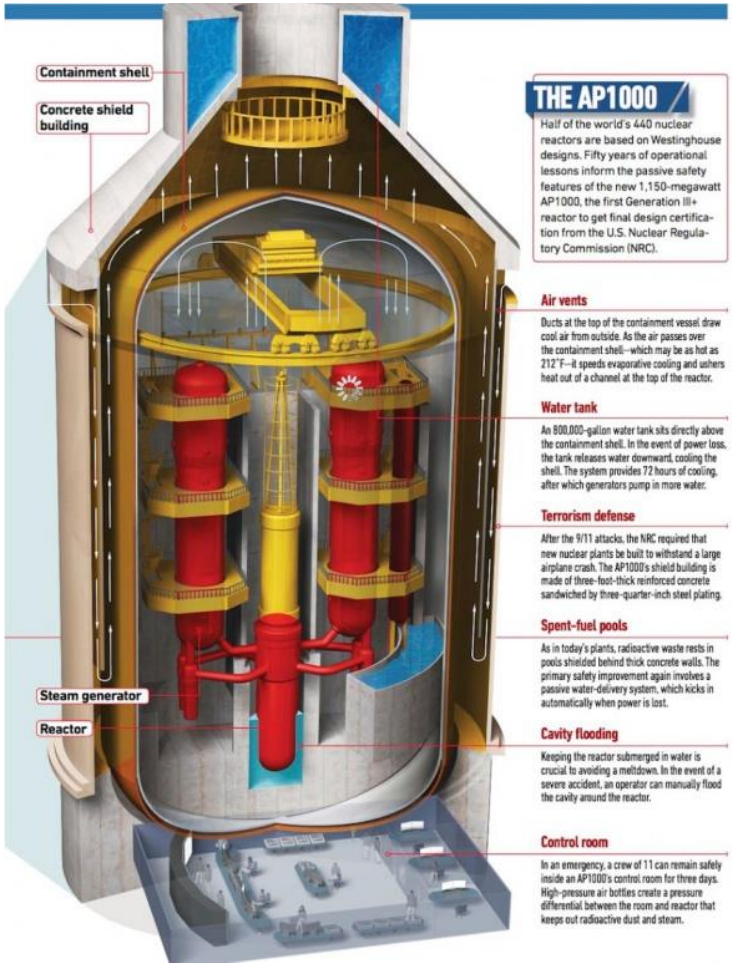
- The pebble bed modular reactor (PBMR) design has been pursued for decades, because it is simple and inherently safe
  - We will detail why in the next few slides
- Not only is the PBMR safer, it is also more efficient than most other reactor designs
  - Cooled by hot gas, the PBMR can have an efficiency of 50% because it runs hotter
  - Reactors cooled by pressurized water can't run as hot, have efficiencies of 30-40%
- PBMRs are cheaper to operate
  - Refueling a conventional reactor requires a costly shutdown, and you can't generate electricity when shut down
  - PBMRs refuel on the fly, by adding pebbles at the top and removing them from the bottom

Nuclear Reactors 101

- Reactors are not that difficult to understand
  - ^{235}U is the active fuel in a reactor
  - Most of the uranium in nuclear fuel is less useful ^{238}U
  - Nuclear fuel might be concentrated as high as 8% ^{235}U (natural is 0.7%)
  - Slow neutrons can be absorbed by ^{235}U, split the nucleus and emit more neutrons
  - The trick is that the neutrons have to be SLOW
  - To slow the neutrons, they need to bounce off and collide with atoms and nuclei that won't absorb them while they are moving fast, so-called moderators
  - These moderator atoms need to be light, like H or O or C…
  - Put the right amount of fuel and the right amount of moderators around them, you get a self-sustaining chain reaction that makes heat
  - Pull out the heat, turn it into high-pressure steam, and use it to turn a generator
- Conventional designs use water as coolant, separate moderator systems, complex methods of positioning the fuel and multiple complex control systems to keep the reactor safe

Conventional Design

- Actually, this is beyond conventional
- The new Westinghouse AP1000
  - First Gen III+ design approved by the US NRC
  - 1,150 MWe design
  - Scale and design keeps cost down
- Incorporates passive safety features
  - This includes cooling water reserve
- However, core design is conventional
  - Basic pressurized water reactor (PWR)
  - AP1000 is a conventional light water reactor
  - Moderator is good, old H_2O
  - Coolant is good, old H_2O
  - Coolant and moderator are still separate

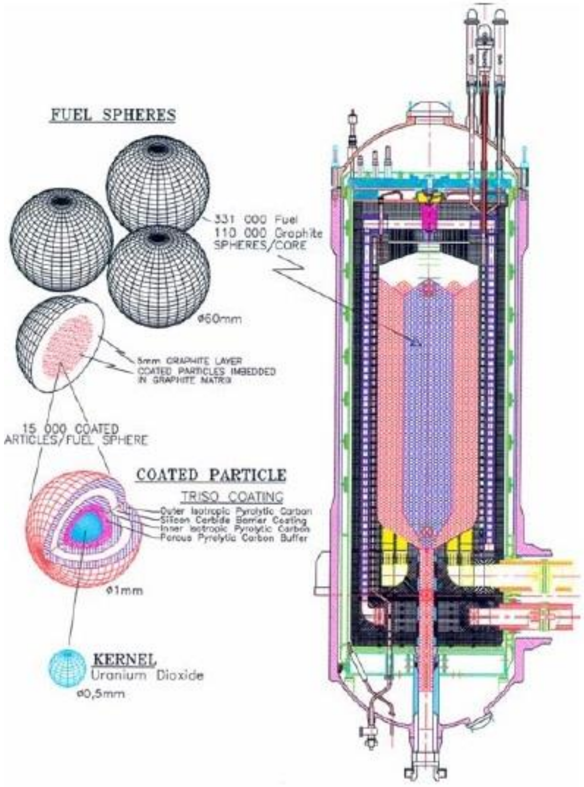


When Conventional Design Fails

- Failure generally occurs with a loss of coolant accident (LOCA)
- Coolant is lost, reactor continues to bleed heat out of fuel
- Very hot metal in contact with water releases H gas
- Eventually, air mixing with the H gas and a spark generates an explosion

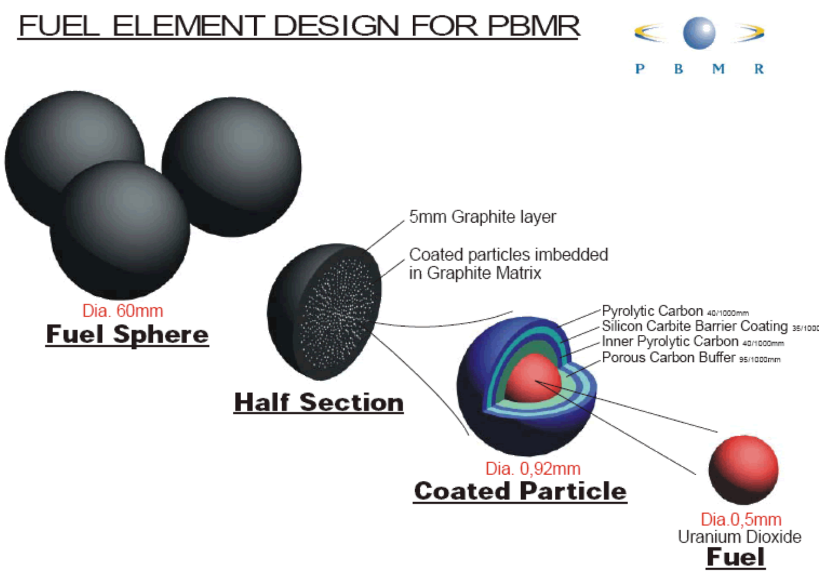
A Bucket of Balls

- PBMRs are considered Gen IV reactors
  - Designed to be inherently, passively safe
- Fuel pebbles stack up
- Moderator part of pebbles
- Coolant is light gas, usually He
- Pebbles get hot, gas carries heat away, water to steam and energy
- If coolant stops flowing, no danger
  - ^{238}U in fuel absorbs neutrons as temperature rises to 1,600 °C
  - Pebbles expand and move apart
  - Pebbles need only be able to sustain high temperature
  - Reactor can sit without coolant indefinitely



Fueling Around

- The PBMR utilizes a large number of so-called pebbles:
  - Fuel pebbles use a graphite matrix hosting a large quantity of ceramic-coated fuel pellets
  - Reflector pebbles are pure graphite, used to reflect neutrons back into the fuel
- The reactor core is surounded by a graphite neutron liner
  - Same idea, the neutron liner makes the fuel more efficient
  - This 110 MWe reactor module will use a large amount of graphite



Graphite in the Fuel Pebbles

- Now comes the boring part (or exciting if you like basic math)
- MIT tells us that their core design contains:
  - 331,000 x 60 mm diameter graphite matrix pebbles with fuel pellets embedded in them
  - Fuel pellets are 0.9 mm diameter, about 15,000 per pebble
- Volume of each pebble is 113.1 cm^3
- Volume of one fuel pellet is only 0.000408 cm^3
- There are 15,000 fuel pellets in each pebble, so remaining graphite volume is still 107.0 cm^3
- For 331,000 pebbles, the graphite load is 35,410 liters
- Based on graphite density of 2.266 g/cm^3, the total is 80.2 tonnes
- The reactor requires 350 new pebbles every day, a total of 84.6 kg of graphite per day

Graphite in the Core Reflector

- The reactor core in the MIT design is only 3.5 meters across
- It appears from patents that the reflector core is about at least two meters across
- We are also told that the graphite pebbles are the same size as fuel pebbles
- A single 60 mm diameter graphite pebble should have mass of 256.3 grams
- MIT says that there are 110,000 reflector pebbles at the center of the core
- Load mass is thus 28.2 tonnes
- There is probably no ongoing need for replacements, not at a level requiring calculation, anyway

Graphite in the Outer Reflector

- Surrounding the entire reactor core is a graphite neutron reflector
- By sending lost neutrons back into the reactor, the reactor is made efficient
- Since 1 meter works in the middle, we assume the reactor is surrounded by a 1 meter thick graphite layer
- The cylindrical reactor core is 10 meters high, 3.5 meters across
- Thus, volume of the annular shield is 141,372 liters
- Total mass of the annular shield is 320 tonnes
- The top and bottom caps can each be considered discs, 5.5 meters in diameter and 1 meter thick
- Volume of each cap is 23,759 liters, a mass of 53 tonnes
- Total mass of the outer reflector is 426 tonnes
- No ongoing need for replacement here, either

The Heavy Lifting

- In summary, then, in case no one was taking notes:
  - The reactor is a 110 MWe design
  - It needs 80 tonnes of graphite (as uranium-flecked pebbles) in the fuel load
  - It needs 28 tonnes of graphite (as pure pebbles) in the core neutron reflector
  - It needs 426 tonnes of graphite (solid) in the outer reflector shield
- Likely a small ongoing annual need for graphite for refueling
  - We calculate roughly 31 tonnes per year
- If someone wanted to build a 1.1 GW nuclear plant, then they need 10 of these modules, with total initial graphite demand of 5,340 tonnes

The Obligatory Blue Sky Slide

- As we must…
- China plans 40 GWe nuclear installation by 2020
- Further 30 GWe by 2030
- They have the most advanced PBMR research program in the world, led by their best technical school
- If ALL of this were PBMR, then 70 GWe would require:
  - 340,000 tonnes of graphite for the initial build
  - An additional 20,000 tonnes per year for refueling
- This is for China, alone
  - India, South Africa, the US and others are investigating PBMR at various levels
- But here's the fun part….
  - ALL this graphite MUST be nuclear grade
  - Nuclear-grade graphite MUST be extremely pure
  - Nuclear grade graphite is worth a lot more than sieved flotation concentrate

Nuclear Grade Graphite

- Every bit of matter can absorb thermal neutrons, the slow neutrons that keep a nuclear reactor going
- Some contaminants, like boron (B) are good at it
  - Some reactors contain fail-safe systems that use boron or gadolinium as a “poison”
- Graphite/carbon doesn’t do much of that at all
- If there are contaminants at any meaningful level in the graphite, it won’t work, especially in a pebble bed
- To be characterized as nuclear grade, graphite needs to have an equivalent boron content (EBC) of less than 5 ppm; in real life, less than 2 ppm is desirable
- Nuclear grade graphite sells for well in excess of $10,000 per tonne
- So the value of graphite in a 1.1 GW PBMR is at least $52.3 million
  - Interestingly, UO_2 fuel in this same reactor would be currently valued at $3.1 million
- That won’t break the budget on a $1 billion reactor project, but it won’t help

The Punchline

- Unfortunately, that 5 ppm EBC limit, but more like 2 ppm, means that the overall winner for PBMR use is probably synthetic graphite
- Synthetic graphite is just purer than natural graphite
- Or at least that was true for many years
- There are only two junior companies that have claimed that their graphite reaches nuclear grade after chemical processing:
  - Zenyatta Ventures (ZEN-TSX) – EBC = 0.919 ppm (09/02/2014)
  - Canada Carbon (CCB-TSXV) – EBC < 0.824 ppm (11/18/2014)
- But, I know of only ONE company that can produce EBC<5 ppm from flotation, alone:
  - Canada Carbon (CCB-TSXV) – EBC < 2.4 ppm, all fractions +200 mesh
- If you can make nuclear grade graphite from flotation alone, revenue might be $10,000 per tonne, cost might be $700?

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