

Science, Technology, and Innovation Policy (STIP)
Forum Lecture Series

Reversing Climate Change with Molten State Technologies

Frank Shu



RIS

Research and Information System
for Developing Countries

विकासशील देशों की अनुसंधान एवं सूचना प्रणाली



ABOUT THE SPEAKER



Prof. Frank Shu is renowned for his pioneering contribution to astrophysics, particularly in understanding the spiral structure of galaxies and the formation of stars and planets from molecular clouds. He has worked at Berkeley and San Deigo and has served as President of the National Tshig Hua University in Taiwan. After taking up research in climate change, has worked on and strongly advocated technologies such as molten salt thorium reactor concept and the pyrolysis of biomass to reduce carbon emission. He is the recipient of many honors and awards, among which are the Shaw Prize for Astronomy, the Fellowship of the US National Academy of Sciences and the University Professorship of the University of California. He is founder of Astron Solutions Corporation and also first Academy-Springer Nature Chair Professor at the Indian Academy of Sciences.



RIS
Research and Information System
for Developing Countries
विकासशील देशों की अनुसंधान एवं सूचना प्रणाली



Vigyan Prasar



Indian
Academy
of Sciences

SPRINGER NATURE



Grand
Challenges
Programme

tAcT
THE ACADEMY TRUST

Science, Technology and Innovation Policy (STIP) Forum Lecture Series

REVERSING CLIMATE CHANGE WITH MOLTEN STATE TECHNOLOGIES

Frank Shu

December 2017

REVERSING CLIMATE CHANGE WITH MOLTEN STATE TECHNOLOGIES

Frank Shu

Introduction

I am very honoured to be in India! Historically, India played an important part in the past development of human civilization, and I believe that India can play a crucial role in meeting the great challenge of climate change that now threatens the future of civilization.

The central message I hope to convey tonight is that economic development is compatible with finding a solution to climate change. Moreover, India may be in the best position to do what needs doing, which has two components:

- To halt climate change, stop emitting CO₂.
- To reverse climate change, extract CO₂ out of the atmosphere by a safe, proven method.

To stop emitting CO₂ in the production of energy, an expansion of nuclear power from current levels may be necessary. The expansion has to occur Sustainably, Safely, and Securely, while maintaining a Superiority of the economics. I will argue that nuclear reactors using thorium as fuel have the best chance of achieving the four S's, with India leading the world in the development of the thorium fuel cycle.

To reverse climate change on a time scale of interest to living generations, technologies are needed that can provide negative carbon emissions. Evolution has engineered growing vegetation to perform negative carbon emission, and India has huge amounts of vegetation.

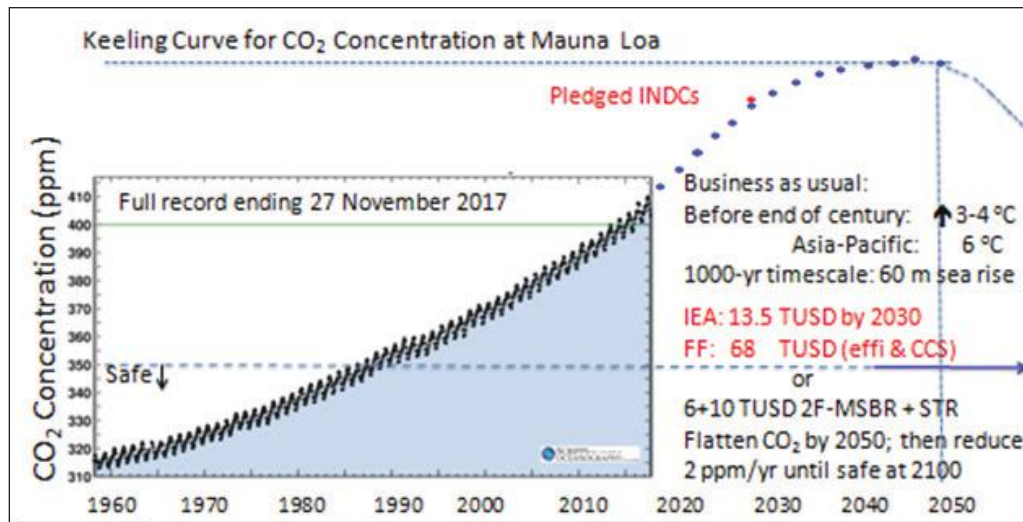
Climate mitigation goals and objectives

Figure 1 shows an outline of the central ideas underlying our overall discussion.

Many people believe that as a global average, the safe concentration of carbon dioxide is 350 parts per million (ppm) which we passed in 1988. It has since been climbing steadily. At the time of this lecture, it stood at 407 ppm. If signatories live up to the commitments of Intended Nationally Determined Contributions (INDCs) made in Paris, the CO₂ concentration should follow a trajectory that takes the mean curve to the red asterisk in Figure 1. To not exceed an eventual temperature rise in excess of 2 degrees Celsius (2 °C) above pre-industrial levels, the trajectory would have to turn over at about 450 ppm at mid-century. However, if we stay at 450 ppm, temperatures at the end of the 21st century may rise by 3 or 4 °C, exceeding the 2 °C that is considered acceptable and the 1.5 °C that is considered aspirational.

* Astrophysicist and Academy-Springer Nature Chair Professor. Email: shufrnk5@netscape.net
The usual disclaimers apply.

Figure 1: CO₂ Concentration (Parts Per Million) in Atmosphere Versus Time.



In Asia-Pacific, with business as usual (i.e. no attempts at mitigation), the mean temperature rise will probably be more like 6 °C. Just imagine the average temperature in summer being 6 °C higher than it is today. Vast parts of India would become literally uninhabitable.

If we look at time scales of thousands of years, then eventually all the ice at the poles, including Antarctica, would melt, and 60 metres of sea rise would occur. Clearly, we wish to avoid catastrophic inundation of all the coastal cities of India and the world.

The International Energy Association (IEA) has estimated the expenditure needed just to reach the first stage of this plan, namely to hit the target represented by that red asterisk in Figure 1. It will cost the governments of the world roughly US\$ 13.5 trillion. In addition, the fossil fuel industry would have to invest US\$ 68 trillion in efficiencies and carbon capture and sequestration to trap and store the CO₂ emitted by thermal power plants. Will they do it?

By contrast, I estimate that if one adopts the two molten salt technologies to be discussed in this talk, then it will only cost US\$ 6 trillion to build the fleet of needed nuclear reactors that gives zero-carbon emission for the entire energy needs of the world, plus another US\$ 10 trillion for the supertorrefaction technology that turns biomass into a carbonised form (charcoal) that brings the CO₂ concentration to a safe level of 350 ppm by the end of the century.

How does the scheme work in outline? The wiggly solid curve in Figure 1 shows the data of Keeling, father and son, at San Diego who measured carbon dioxide directly from the peak of Mauna Loa in Hawaii. In the very first year of measurements, the data showed that the CO₂ level wiggles up in the fall when plants (in the Northern hemisphere) begin to die and decay, putting the carbon in them back into the atmosphere as CO₂ as bacteria digest the dying vegetation. In the spring as new plants grow, the CO₂ concentration wiggles down. The difference between up and down is about 8 ppm. In addition to the annual variation, there is a steady drift upwards from burning fossil fuels. So if one can stop this steady upward climb with energy technology that has zero CO₂ emissions (such as nuclear power), then, in principle, by year 2050 can flatten the mean curve at 450 ppm, or 100 ppm above the 350 ppm considered to be safe (Hansen *et al.* 2008). If one could further carbonise all the vegetation that dies before it decays, then one would only have “wobble down,” because “wobble up” that follows

in the fall would be interrupted if one puts vegetation that has died into a carbonised form that does not decay. An unrefrigerated bag of garbage decays in days, but without refrigeration a bag of charcoal can last thousands of years without decaying. At 8 ppm per year of negative emissions, reducing mean CO₂ concentration by 100 ppm would take 12 ½ years.

Thus, in principle, if one were really ambitious, one could solve climate change in 12 ½ years. Of course, it is almost impossible to find every blade of grass that died and carbonise it. What can one do realistically? Well, 10 percent is possible if undeveloped countries in the world stop burning wood and carbonise it instead. In agreement with some experts (Smeets *et al*, 2007), I think 25 percent is reasonable, especially if we reclaim desertified lands (see below). Converting 25 percent of the dying vegetation on land into biocarbon means that one is getting negative emissions at a rate of 2 ppm per year. At 2 ppm/year of negative emissions, one would need 50 years to bring the CO₂ concentration from 450 ppm at 2050 to 350 ppm at 2100, where it is safe. This goal is basically the outline and hope of today's talk.

Thorium fuel cycle

In a far-sighted 1954 presentation at a conference held in Delhi attended by Prime Minister Nehru, Dr. Homi Bhabha mapped out what India's goal should be in terms of utilising fission nuclear energy. In particular, he pointed out that the thorium fuel cycle could satisfy all of India's needs for 400 years. Beyond 400 years one might have to progress to thermonuclear fusion, or perhaps something so novel that we have not yet discovered it in science.

In the first stage of what was a three-stage plan, one would use light-water and heavy-water reactors to produce what is usually called nuclear waste. Dr. Bhabha pointed out that spent nuclear fuel is not a waste, but a resource. This conclusion is a common theme in sustainability science. We must abandon a linear economic model that begins with resource input and ends in product output including the downstream passage of waste. Instead, we should draw flow charts that recycle waste back into a resource. The "waste" from the spent nuclear fuel of enriched and natural uranium reactors includes plutonium made as a by-product of burning uranium fuel. Plutonium has extra neutrons that can convert materials like thorium into more fissionable fuel forms if one uses the so-called thorium fuel cycle.

Dr. Bhabha foresaw a problem: India lacks sufficient amounts of the fissile uranium-235 to produce the needed levels of plutonium. In other words, just using light- and heavy-water reactors, India would not have enough nuclear waste to start the required fleet of thorium reactors. A second stage would be needed: a fleet of fast reactors that, using fast fission neutrons, could produce large amounts of plutonium from the fertile uranium-238 that exists as 99.3 percent of natural uranium, which contains only 0.7% in the form of fissile uranium-235.

With an intermediate fleet of fast reactors producing sufficient amounts of plutonium, it would be possible for India to achieve the third stage of building reactors that run on the thorium fuel cycle (see Banerjee & Gupta 2017 for a review).

Modification of the Homi Bhabha vision for energy independence and sustainability

When I talked with the scientific staff at the Bhabha Atomic Research Centre (BARC) as part of this lecture tour of India, I asked them to consider skipping the second stage of the Bhabha plan, and go directly from the first stage to the third stage by using molten salt breeder reactors (MSBRs) that need much less plutonium to convert the fleet to a thorium fuel cycle. MSBRs use epithermal neutrons rather than fast neutrons to make, not only enough fissionable fuel to sustain the host reactor, but extra fuel

to expand an existing fleet.

The people at BARC are very interested in this possibility, and I hope we can follow up on the suggestion. I am not going to give you much of the details concerning the concept of two-fluid molten-salt breeder-reactors (2F-MSBRs) except to say that molten salt carries both the fuel uranium-233 and the breedstock thorium (see Fig. 2). The fuel and breedstock are kept separated for technical reasons. Thus, in a 2F-MSBR, the breedstock is dissolved in a blanket salt that cools the fuel dissolved in a fuel salt, with the blanket salt capturing neutrons generated by fission reactions in the fuel that are in excess of what is needed to sustain a chain reaction. This capture process turns the thorium breedstock into new fuel that is easily extractable from the molten blanket salt to use as fuel in the host reactor, as well as have some extra left over to fuel additional reactors.

The scheme has a factor of 400 advantage, resulting in effective energy independence and sustainability. In a light- or heavy-water reactor, ultimately you can only extract about 1 percent of the nuclear energy in natural uranium (0.7 percent in the form of uranium-235 plus 0.3 percent coming from the conversion of uranium-238 into plutonium). In contrast, with the thorium fuel cycle, you can extract close to 100 percent of the nuclear power in thorium (U-233 releases in fission almost the same energy per kg as U-235). Thorium is about four times more abundant in the crust of the earth than natural uranium. Being relatively uranium-poor, India has only enough uranium-235 to supply about 1 year of its full energy needs, but its thorium can provide, as noted by Dr. Bhabha, India's energy needs for 400 years.

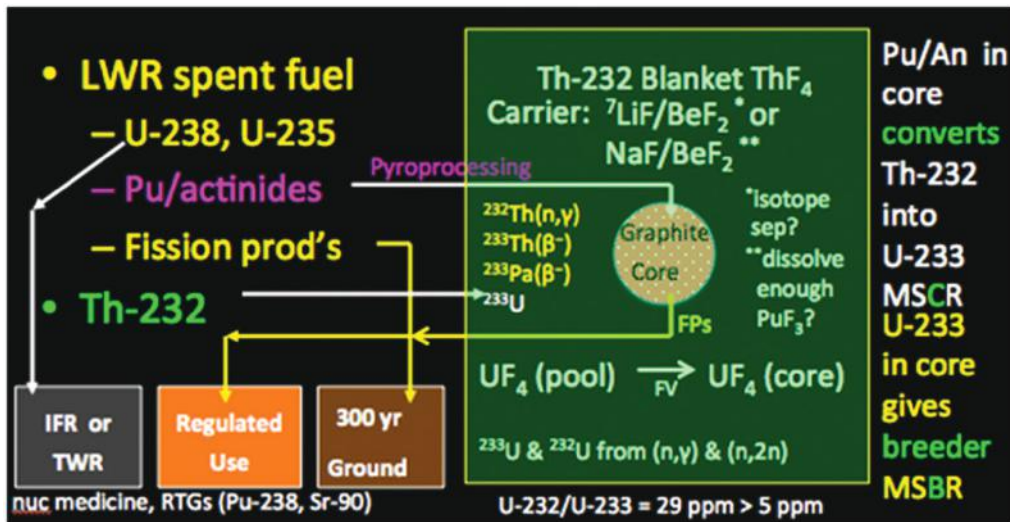


Figure 2: Schematic Diagram for Two-fluid Molten Salt Breeder Reactor.

Once on the thorium fuel-cycle, the only true waste comes from the fission products. If one only has to worry about the radioactivity of fission products, one only needs to bury that material for 300 years, and it would decay to the levels of radioactivity provided by background rocks. In contrast, plutonium treated as a waste product requires hundreds of thousands of years to decay to background. Does India have the technology where one can keep things safe for 300 years? The answer is yes, India had that technology 5000 years ago. You recover artifacts all the time that have been buried for 300 or more years.

Superiority of economics

A common criticism of new nuclear power plants is that they are expensive to build and operate. How

does one make molten salt breeder reactors Superior in their economics? Here, we have a direct connection with solar thermal. Solar thermal, as Dr. Kumar mentioned, uses the sun to heat molten salt. At night one does not have the sun, but one has hot salt. With the salt as a source of heat, one can use a turbine to convert the excess thermal energy above ambient constraints into electricity. The usual method begins by using the heat to vaporize water into steam and letting the expanding steam flow to turn a turbine. A much better way is a new kind of turbine invented by General Electric using supercritical carbon dioxide.

What is supercritical carbon dioxide? Carbon dioxide, of course, is what one gets if one combusts a fuel like natural gas or coal with oxygen in the air. As a product besides water, one gets CO_2 that is a gas. With supercritical carbon dioxide, the CO_2 is at a high enough temperature, above 400°C , and at a high enough pressure, hundreds times atmospheric pressure, so that one loses the distinction between gases and liquids. In other words, supercritical carbon dioxide can expand like a gas, creating a flowing fluid, but instead of being rarified, the fluid has almost a density of a liquid. So imagine the power of a turbine on a jet plane which expels fluid a hundred times denser than air. That is the new technology.

Figure 3 shows a sunrotor turbine that GE has built; they hope to have a full working system by 2019, so it is not just a pie in the sky. Other groups are also working on such turbines. For scale, Figure 3 shows a yardstick. The turbine is something that one can hold in one's hands. The inlet and the outlet have a circumference that can be almost encircled by human hands. Despite being much smaller, the sunrotor can generate more electric power, 10 megawatts electric (10 MWe), than can be generated by the turbine of most airplanes because air is much less dense than a liquid, especially if the airplane flies in the stratosphere.



Figure 3: The sunrotor turbine built by General Electric.

How does the sunrotor compare with a wind turbine? Well, wind turbines of ten-megawatt electric capability have not yet been built. The largest erected is over 100 stories high and has 3 to 5 MWe capacity. So something like the sunrotor can obviously beat a wind turbine. The electricity from a sunrotor is steady. It doesn't depend on the sun shining; it just depends on having hot salt. That hot salt can come from solar thermal when the sun did shine, but it could also be the hot blanket salt of a nuclear reactor. Thus, this technology is going to be cheaper than wind, and wind is now almost competitive with fossil fuels, so it is going to be cheaper than fossil fuels. A best guess is that dispatchable electricity generated by molten salt reactors will require only half the capital cost of natural-gas power plants. And the nuclear fuel required to power a molten salt breeder reactor will be much less costly than the fluctuating price needed to fuel natural-gas power plants. That is the hope. Given that natural-gas power plants still emit CO_2 (although less than coal-fired power plants), it would be foolish

not to use molten salt breeder reactors if they can be made completely safe from worries about the accidental large-scale release of radioactivity into the natural environment.

Safety by two aspects of physics

Everybody knows about Fukushima having terrible problems because it was overwhelmed by a tsunami. With the electricity to the nuclear plant disrupted when the tsunami knocked down the grid, the main backup electricity disappeared when seawater flooded the diesel generators stored below ground level. Safe operation devolved to using chemical batteries to open and close valves that vented steam created by the boiling of cooling water in contact with the shutdown fuel rods. Anybody who has a laptop computer knows that chemical batteries only last a few hours. After that the operators were defenceless. They had what is called a station blackout, and the fuel rods kept getting hotter. The reactor had shut down properly, but the fuel rods still had decay heat from the fission products, and that decay heat became enough to melt the fuel rods. The steam that touched the melting fuel rods dissociated into hydrogen and oxygen. Once dissociated, the hydrogen needed venting, and the operators couldn't release it any more because they couldn't open and close the valves. So eventually the hydrogen accumulating in the building exploded, with the chemical explosion wrecking the reactor building and releasing massive amounts of radioactivity into the environment.

Now it has always puzzled me why nuclear power plants rely on chemical batteries as the backup of last resort. Why don't they use nuclear batteries? What are nuclear batteries? Nuclear batteries are devices that have a decay-heat source keeping an inner wall hot relative to a cold outer wall. When one puts in special kinds of materials between the two walls, the walls can act like the terminals of a battery to turn flowing heat into flowing electricity. The same principle – the Seebeck effect – governs how a thermocouple works. The connecting material could lead telluride, which is 10 percent efficient converting flowing heat into flowing electricity, or silicon germanium, which is 20 percent efficient, or ultimately graphene, if it lives up to its theoretical promise, 50 percent efficient. Such efficiencies are more than enough to run pumps that provide the cooling of fuel salt (the equivalent of fuel rods in molten salt reactors) by the blanket salt (the equivalent of cooling water in molten salt reactors). In contrast to chemical batteries, nuclear batteries, called RTGs (radioisotope thermoelectric generators) in the spacecraft business, have operating lifetimes that measure decades, not hours. Therefore, if one must rely on batteries, it is best to use nuclear batteries, and not chemical ones. In the nuclear power-plant application, if nuclear decay heat becomes too small to power nuclear batteries, then the decay-heat is no threat to any equipment. Thus, it is impossible to have a station blackout that destroys the power plant if one uses this strategy. It should be the first line of defence in the bastion of safety represented by a 2F-MSBR.

What happens if something really traumatic occurs, such as a loss of coolant accident (LOCA)? A pool of molten blanket salt cools the fuel salt in the reactor core. After the core has been shut down, the chain reaction has stopped, but one still has to remove the decay heat by circulating blanket salt through the core. What happens if a leak develops in the pool, and one loses the blanket salt? In that case, a LOCA, there is a second line of defence invented for molten salt reactors by the Oak Ridge National Lab (ORNL) nearly sixty years ago. ORNL proposed the construction of freeze plugs below the pump bowls of the fuel salt. Melting the freeze plugs would let the fuel salt drain to dump tanks in which passive cooling equipment could protect the fuel salt from the decay heat released by the fission products. The pioneering experimental reactor (MSRE) that ORNL built had very low power, so it was relatively easy to fabricate a working freeze plug and dump tank.

Once one goes to the high power environment of a commercial reactor, one has to work harder

to ensure passive safety. Melting the freeze plug is not a worry because if it doesn't melt, just wait a while, and the decay heat will continue to raise the temperature until the freeze plug melts. At that point the fuel salt will drain by gravity. Although one can worry about pumps not working because the electricity has stopped, one doesn't need to worry about hot things melting frozen things. And one doesn't need to worry about gravity failing. So the fuel salt will just drop to spherical tanks containing large stores of buffer salt that increase the volume and mass of salt whose temperature needs to be raised by the decay heat. The increase stretches out the time over which events unfold, and time is of the essence during a nuclear accident. With a large enough system, the dump tank has sufficient surface area that blackbody radiation from the surface can carry away the released heat. The law of blackbody radiation is among the most secure knowledge in physics; it will not fail!

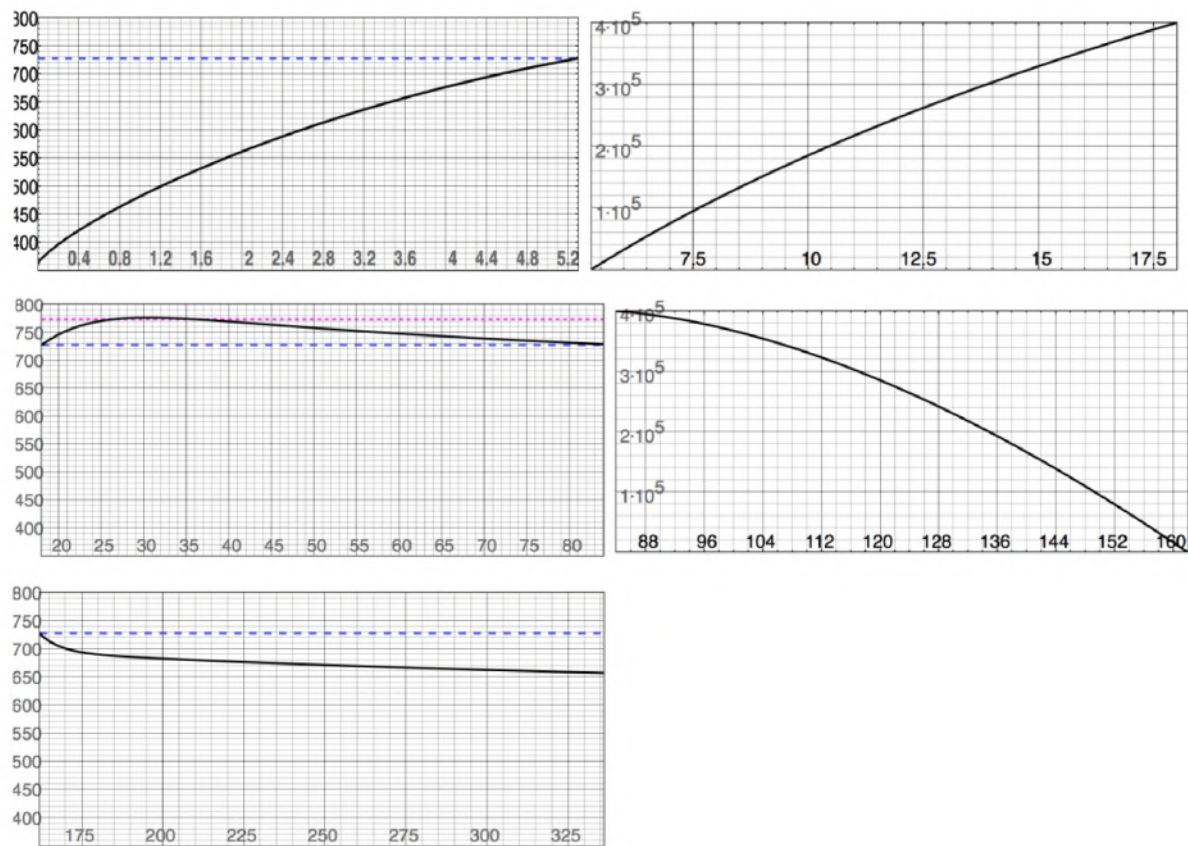
By non-proliferation treaty obligations, we are not allowed to do reactor experiments of this sort in Taiwan, but we can perform theoretical calculations. Figure 3 depicts the results for a 2F-MSBR with fission products cleaned to $\frac{1}{4}$ of the value that would apply to a conventional reactor operated at the same steady-state power level of thermal power = 4.631 billion watts (4.631 GWt). At time $t = 0$, a LOCA event causes the fuel salt to heat to 900 °C that triggers the melting of the freeze plug and the dumping of the entire inventory of fuel salt into four spherical tanks of outer diameter 2.56 m and inner diameter 2.50 m made of the alloy TZM. Inside each dump tank is 100 tonnes of powdered buffer salt at an ambient temperature of 25 °C with which the liquid fuel salt mixes and solidifies at $t = 0$.

Figure 3a shows the subsequent temperature history of the salt mixture as a function of the time t measured in hours. Beyond $t = 0$, the salt mixture steadily rises in temperature T as the fission products release their decay heat, until $t = 5.3$ hours when T reaches the melting point of the mixture at 454 °C = 727 K. Between $t = 5.3$ hours and $t = 17.6$ hours, the release of decay heat goes into the latent heat, 400,000 J per kg of salt, needed to convert the solid into a liquid, while T remains at 454 °C = 727 K. However, Figure 3b shows that at $t = 17.6$ hours, the change in specific enthalpy H has risen 400,000 J per kg of salt, which completes the melting of the salt mixture. Figure 3c then shows that the continued release of decay heat raises the temperature from 454 °C = 727 K at $t = 17.6$ hours to a maximum of about 775 K = 498 °C at $t = 28$ hours, when the release of decay heat has dropped to a level that can be compensated by losses of blackbody radiation from the dump tank's surface proportional to T^4 . Indeed, we sized the dump tank so that the maximum temperature stays below the 500 °C believed capable of damaging reinforced concrete. At $t = 84$ hours (3.5 days after core dump), the salt mixture drops below the melting temperature 454 °C = 727 K and begins to freeze again. Figure 3d gives the specific enthalpy under isothermal evolution at $T = 454$ °C = 727 K, with the salt mixture becoming completely frozen again at about $t = 164$ hours (nearly a week after core dump). Beyond $t = 164$ hours, Figure 3e shows that the temperature of the frozen salt inside the dump tank declines very slowly with time, characteristic of a balance between the slow late-time radioactive decay of the fission products and the loss-rate of energy by blackbody radiation from the surface of the dump tank.

Freezing of the fuel salt into a solid state means that the radioactive fission products have been immobilized; they cannot flow out of the power plant to contaminate the local environment. The situation is stable and under control. When the emergency is over, the operators can put an opaque covering over each dump tank to prevent further losses of blackbody radiation. After another week or so, the radioactive decay of the fission products will have added enough unlost heat to remelt the salt mixture, and the molten salt can drain to a hot cell to be processed to restart the reactor. Because Fukushima did not have this kind of safety device, it is now almost seven years after the 2011 accident, and they are still in clean-up mode. With a 2F-MSBR, after two weeks they would be back online.

Safety by intrinsic physics not by engineered defence in depth

Notice that there are no operator decisions to trigger the safety mechanisms that prevent a 2F-MSBR from having catastrophic mishaps. Whenever one has humans or robots with artificial intelligence in the loop, they can make a mistake. Physics has its own immutable laws that do not require intelligent operators to make it function. Thus, a nuclear power plant designed for intrinsic safety by physics is *walkaway safe*. Contrast the walkaway-safe strategy with today's nuclear engineering approach which is called defence in depth. What is defence in depth? Defence in depth means that if one absolutely must have a piece of equipment work – when astronauts go to space or when companies run a nuclear reactor – regulatory agencies will require the building of multiple copies of crucial pieces of equipment. Instead of 1, one has to build 3 or 4. If number 1 conks out, number 2 kicks in; if number 2 conks out, number 3 kicks in; if number 3 conks out, number 4 kicks in. And if number 4 conks out, well, you have a nuclear accident, or you lose astronauts. Unfortunately, defence in depth can only decrease the probability of an accident, not take the probability of an occurrence to zero. Because people are unhappy with even low probabilities of a nuclear accident, increasing expectations for safety can make the enterprise very expensive.



Figures 3a, 3b, 3c, 3d, 3f: Left column: T versus t ; Right column H versus t . Temperature T is in degrees Kelvin; specific enthalpy H is in J/kg; and time t is in hours after core dump.

When intrinsic physics governs the design, it becomes impossible to have a nuclear accident via routes that involve the design physics. This explains why we fabricate dump tanks in the form of spheres. Suppose a terrorist comes and shoots a bazooka at a spherical dump tank. A sphere has the least radiating area for the volume of any three-dimensional object. So when molten salt spills out, it

will have more radiating area than a sphere of the same volume. The spilt salt, which is transparent to infrared and visible radiation, will cool even faster than given by the calculations for spherical dump tanks. The spilling of the salt mixture into the room that holds the dump tanks may destroy the concrete of that room, or even the whole power plant, but the fuel mixed with buffer salt will freeze solid before going anywhere far. This feature is the beauty of a molten salt reactor. It is designed so that if an accident occurs, the fuel salt will go to an immobile state which cannot flow into the environment. It is absolutely safe, which prevents escalating costs from undermining a construction project.

Security against weapons proliferation

We have now covered three of the four S's of nuclear requirements: Sustainability, Safety, and Superiority of economics. My discussion of the fourth S, Security against weapons proliferation, will be brief. For technical reasons involving the physics of neutron transformation of fertile materials like thorium, the thorium fuel cycle in 2F-MSBRs automatically produces U-233 fuel contaminated by U-232. The U-232 makes the U-233 difficult to weaponize. Let me now transition to my other major topic: supertorrefaction.

Supertorrefaction

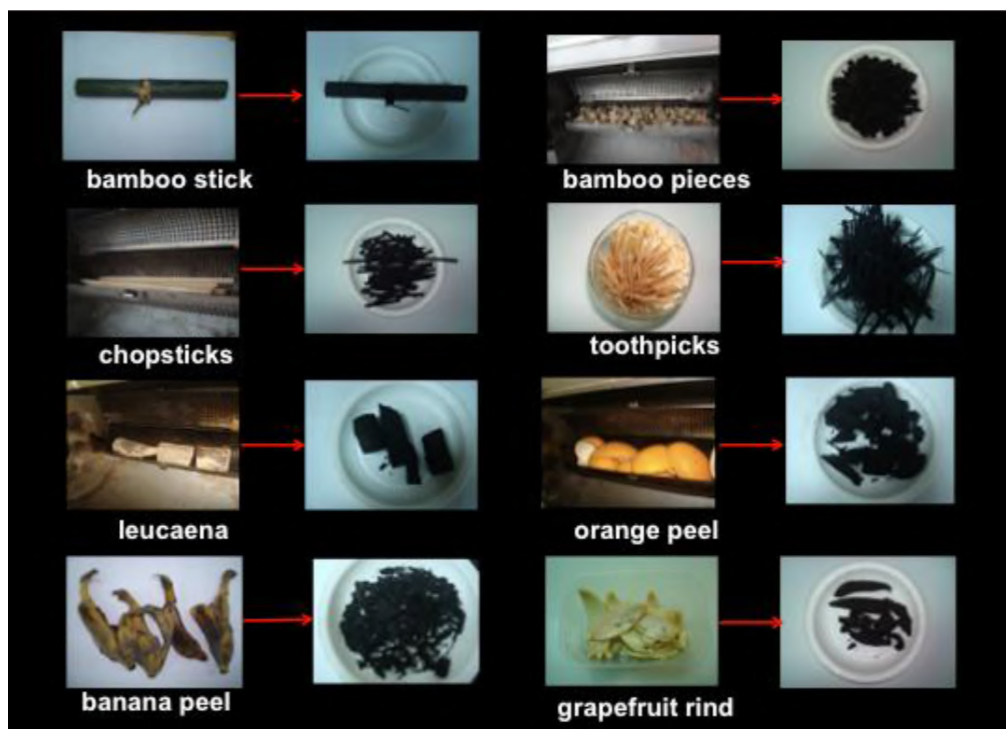
Supertorrefaction is a process that immerses any form of biomass under molten salts to rapidly carbonise the organic matter under intense heat. The carbonisation of biomass is among the oldest technologies in the world. If you look at prehistoric cave paintings, what are they drawn in? They are drawn in charcoal. When a wood fire lacks enough oxygen to sustain complete combustion, one is left with charcoal. In fact, anything that has organic matter in it can be carbonised by driving out the volatile components in the absence of oxygen. Immersion of biomass under molten salt excludes the air above the surface of the liquid salt, and the heat from the hot salt quickly penetrates the biomass and drives out the volatile components of the biomass, leaving behind a solid residue that is largely elemental carbon.

Consider a stick of bamboo. Plants like bamboo are made of three broad categories of organic matter: cellulose, hemicellulose, and lignin. At temperatures higher than 220 °C, the volatile components in cellulose, hemicellulose, and lignin can be driven out, leaving behind a solid residue that is mostly – 80 percent or more by weight – made of elemental carbon. Elemental carbon is not digestible by most microorganisms; thus, the resulting charcoal will not rot for thousands of years or more. The starting biomass can be in small pieces, or it can be in the form of chopsticks, or toothpicks; they can all be quickly turned into charcoal by immersion under hot molten salt, with the charcoal largely preserving its original shape if it started with a lot of strong, fibrous, lignin. As well as bamboo, leucaena, which is a foreign woody plant species that has invaded, India, Taiwan, and much of Southeast Asia, can be turned into good charcoal. By carbonisation via supertorrefaction, such invasive plants can become a resource for rural areas instead of something that farmers try to kill by pouring kerosene on it.

Figure 4 shows that even waste biomass in the form of orange peels or banana peels or grapefruit rind can be turned into charcoal, but the resulting charcoal crumbles easily if the feedstock material did not start with a lot of lignin. If structural integrity of the resulting charcoal is unimportant, one can carbonise anything that is organic by the process of supertorrefaction. Biomass that would otherwise rot and put carbon dioxide or methane into the atmosphere then becomes a resource for making charcoal that does not rot or stink.

In structural detail, land plants consist of cells with walls composed primarily of cellulose that are

strengthened by lignin fibers. Pathways exist that bring nutrients solubilized in water from the outside world into the cells. On the left, Figure 5 shows a schematic drawing of the cells of a grass plant and the lignin that strengthens and protects microfibrils that contain cellulose and hemicellulose valuable to the plant. On the right, Figure 5 shows a scanning electron microscope (SEM) image of the carbonised cell walls and microfibrils when leucaena (subalis in Hindi) has been immersed for 1 minute under molten salt at a temperature of 550 °C. The cell walls and pathways are largely preserved in the carbonization process, but the interior contents of the cells get volatilized and escape from the salt as volatile organic compounds (VOCs). The VOCs (mostly water) have economic value, but I will not



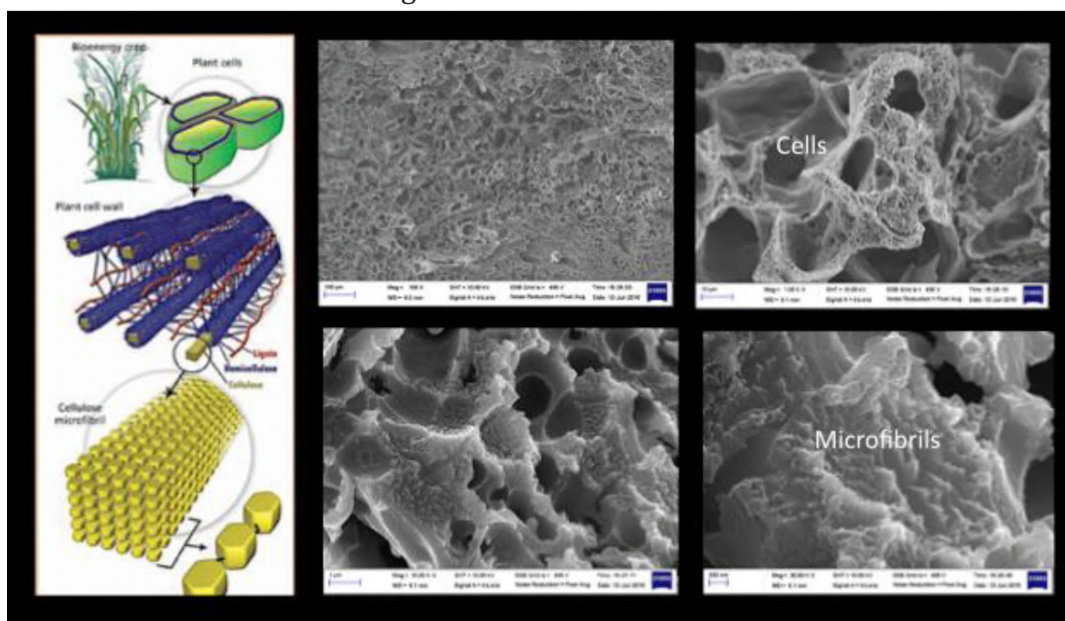
discuss their handling in this lecture which focuses on the solid residue, the char or charcoal.

Figure 4: Any form of organic matter can be carbonised in the absence of oxygen.

The charcoal has a microstructure consisting of connected pores (carbonised cell walls) that are open to small molecules in the outside world. As measured by the Brunauer-Emmett-Teller (BET) technique using CO_2 as the adsorbing gas, the resulting specific surface area of the charcoal shown in Figure 5, is 530 meter squared per gram, implying the presence of pores smaller than cell walls. In one minute we can produce activated biocarbons that have porosity competitive in accessible specific area to the best materials used for filtration or chemical catalysis that take traditional techniques days to weeks to manufacture. The high-grade charcoal made at elevated temperatures in molten salts with special thermochemical properties are too valuable to burn as fuel. When the resulting product has a BET- CO_2 value larger than 500 m^2/g , we categorize the product as “activated biocarbon.” We assign medium-grade charcoals made under intermediate conditions, with BET- CO_2 values in the low hundreds of m^2/g to the product category of “biochar.” Biochar can be used as a soil enhancer for ag-

ricultural applications. Finally, we term the low-grade charcoals made at relatively low temperatures, say, 300 °C, with resulting BET-CO₂ values typically in the tens of m²/g, product as “biocoal.” Biocoal is a carbon-neutral substitute for coal.

Figure 5: Left: a schematic drawing of the cellular structure and associated microfibrils of a grass



plant. Right: SEM images of similar structures in activated biocarbon made by immersing leucaena under molten salt at 550 °C for 1 minute. The horizontal bar at the bottom left of each image gives the linear scale of the picture: top-left 100 μm; top-right 10 μm; bottom-left 1 μm; bottom-right 200 nm.

Designer char and throughput

By varying the input biomass, the processing temperature, the residence time, and the chemical nature of the molten salt (e.g. if it is oxidizing or reducing), as well as by adding perhaps pre-treatment or post-treatment steps, we can produce charcoal with different attributes (e.g. different pH values, different proportions of residual elements, different BET-CO₂ or BET-N₂ values). We can, therefore, fine-tune a char product to a customer’s specifications, as well as provide standardized chars with generic properties (e.g., activated biocarbon, biochar, or biocoal). Moreover, for the same equipment size, the throughput in tonnes of biomass processed per hour for manufacturing the chars by supertorrefaction can be hundreds to thousands times faster than conventional techniques making similar products but using gases such as steam or flue gas as the heat-transfer agent. The advantage is due to molten salts as ionic liquids being much denser than gases at near-ambient pressures. It is, of course, possible to speed up conventional approaches by using gases at much higher pressures (e.g., by bringing them to a supercritical state), but generally speaking, it is much more expensive to build apparatuses that operate at high pressures rather than apparatuses that operate at near-ambient pressures.

We built a pilot facility at National Tsing Hua University in Taiwan to demonstrate practical aspects of a complete system. In the foreground of Figure 6 is a line of basins of saline water with which we wash salty biochar. The salinity in the basins become progressively smaller until there is fresh water at the end closest to the viewer, with which we can bring the char salt level below what natural veg-

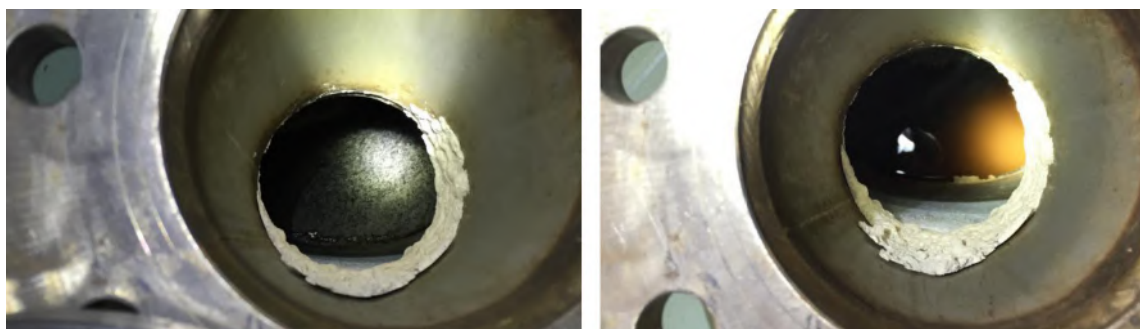
etation possesses, much less than it had exiting the cooker. Thus, when the time comes to sell or use the charcoal, it is not salty by natural standards.



Figure 6: Photograph of first pilot facility for supertorrefaction of biomass into biocoal built by the HX Team on a site of the National Tsing Hua University in Hsinchu, Taiwan.

Another problem that has to be solved is how to rid the molten salt of the charcoal fines continually created when moist biomass chips have miniature steam explosions upon being suddenly immersed in hot molten salt. Fines are defined as the charcoal particles that are too small to lift out of the cooker by whatever mechanism one employs to extract the charcoal pieces. We can clean up the salt by putting an oxidant into it. In Figure 7, we pour charcoal ground to a powder into a cooker that we call a charcoal fines oxidizer. If one kept pouring in charcoal fines to simulate what might happen in a production machine with increasing time to accumulate charcoal fines, the salt in the machine will turn into a sludge and become too viscous to operate. However, if one puts an oxidant into the salt, one can burn the fines preferentially relative to the larger pieces when they are both inside the salt. Burning does not occur in the sense of air nourishing a fire; chemical oxidation is the correct description. With chemical oxidation of the carbon-rich fines, the salt becomes clean after a few minutes. During the oxidation process, one can see the temperature of the molten rise as the oxidation reactions proceed to turn carbon into carbon monoxide or carbon dioxide. Adding an oxidant to the salt, makes the device self-heating. By burning a small percentage of the charcoal that is in the form of fines, one can supply the heat necessary to supertorrefy the larger amount of biomass pieces into charcoal. Such processes are self-sustaining without the addition of external sources of heat. They can use charcoal fines to make charcoal pieces analogous to how a breeder reactor can make more nuclear fuel than it needs to keep running.

Figure 7: View from the top of the reactor vessel of a charcoal fines oxidizer. The left panel shows half a kilogram of charcoal fines poured onto the surface of hot molten salt that contains an oxidizing agent. The right panel shows the same view after oxidation of the charcoal fines. Notice that the



molten salt is transparent to visible light, so one can see through the molten salt to the bottom of an illuminated tank. Molten salt that has splashed to the cool metal surface above the molten salt has frozen as a solid into a white opaque solid.

When we perform the oxidation reactions beneath the surface of the molten salt, there are no emission of fine particulates. Any carbonised particulate that would have come out with the flue gas if the oxidation were performed in air is trapped and converted into CO or CO₂ in the salt. The smoke that emerges from the chimney of the charcoal fines oxidizer is white in color (from condensing steam), not black with the soot particles that plague inadequately equipped coal-fired or biomass-fired power plants. In Figure 7, you can see the salt that splashed on cool metal from previous demonstration experiments. The salt has frozen onto the cool surfaces of the equipment and is white not black, proving that the small particles in the molten salt are completely removed by the oxidizing agent.

In an integrated system, one would like the oxidizing agent to be recoverable by contact with the free oxygen in air. We have worked out a number of ways of performing the oxidant recovery in a commercially viable manner, and established a company, Astron Solutions Corporation, that is now in the stage of building an automated system that will process biomass into charcoal plus wash the product charcoal on a single processing line at a rate of roughly 1 tonne of biomass per hour. The equipment occupies a space of an ordinary kitchen that includes a stove plus some basins for washing. All relevant pieces of equipment can be brought to the site of the “kitchen” by trucks and assembled on-site in a day or so.

Rather than truck large amounts of biomass great distances to a fixed centralized processing site, the plan is to transport small amounts of equipment by truck to remote distributed sites that access large amounts of renewable biomass. The dead or dying or nuisance biomass is of little native worth, but when the biomass is processed into smaller amounts of char, the char is of great worth. Activated biocarbon and biochar can sell for more than refined gasoline of the same weight. Two trained people per working shift are needed to load the biomass onto the line and unload the washed charcoal for storage or shipping to other sites. The char output of a single production line suffices to make poor rural areas prosper if they can produce valuable porous biocarbon from their local feedstock of renewable biomass.

India is good at building equipment, so India can easily enter different niches of this general line of business. The only knowledge not disclosed in our published patents that India perhaps lacks is what kind of salts one should use, what kind of metal alloys can withstand the corrosion inherent with operating molten salts at elevated temperatures, and how to wash to acceptably clean levels the biochar coming out of the supertorrefaction vessel (which we generically call a “cooker”) that is full of salt. Astron Solutions Corporation is a repository of such trade secrets. Astron can partner with interested entities in India and elsewhere to build a global supertorrefaction network.

Opportunities for innovation opened up by a disruptive technology

The top-left panel of Figure 8 shows that India already makes activated biocarbon from coconut shells by traditional techniques. India supplies half of the world’s activated carbon, but its manufacture typically takes two weeks, and involves equipment of a scale not affordable by poor rural communities.

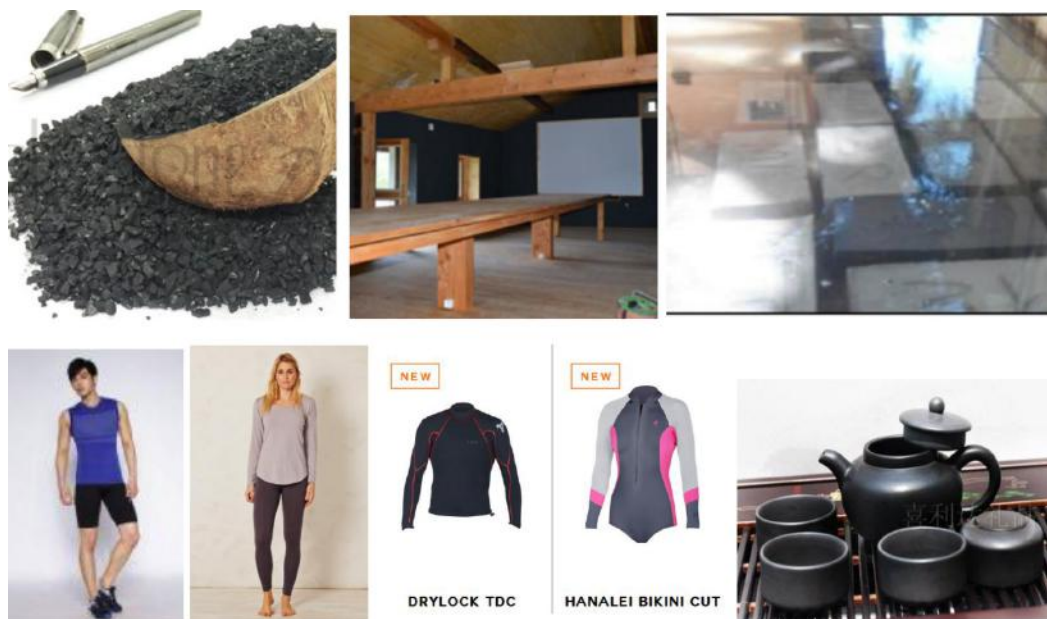
If Indian companies are interested, we can license them the rights to the supertorrefaction technology, or form business partnerships to produce different grades of charcoal products. We won’t charge partner companies too much; they can afford to distribute the benefits to rural areas. Our goal is not

to make a lot of money, but to help mitigate the potentially catastrophic effects of climate change. What took two weeks to do before can now be done in one minute. Think of the possible increases in productivity!

The panel at top-middle in Figure 8 is from Switzerland. The inventor incorporates crushed biochar into the plaster of room walls because the added porosity makes a good insulation material. This application is a novel change for the housing industry. The panel at top-right in Figure 8 is from an Indian engineering college in Chennai where they make bricks out of charcoal for the same insulation purpose in new construction.

In the panels at bottom-left of Figure 8, designers in the fashion industry embed activated carbon particles into men's and women's athletic clothing. Activated carbon absorbs the sweat and odours that come with exercise. The panel at bottom-middle shows that if one binds woven carbon fibers with recycled plastic, the fabrics become waterproof and can be made into wetsuits that keep scuba divers warm. The panel at bottom-right shows that the Japanese put activated carbon into their earthenware. Such tea sets sell well in Japan.

Figure 8: Different applications for porous carbon. Top left: activated carbon made from coconut shells (Pebblestone, Kolkata, India). Middle center: porous biochar incorporated as insulation in wall plaster (Schmidt, Switzerland). Top right: curing charcoal bricks in water (Venkatsen *and team.*, Panimar Engineering College, Chennai, India). Bottom left: sportswear for men and women made from cloth



embedded with activated carbon for the absorption of perspiration and odors (ysl-shapewear.com and shopmodena.com) Bottom middle: waterproof wetsuits made by recycled plastic to bind and seal fabrics made from carbon fibers (Drylock TDC, Hawaii) Bottom right: a Japanese tea set made by embedding earthenware with activated carbon to give freshly brewed tea a clean taste (Aliexpress.com).

The ideas in Figure 8 all use biocarbon in innovative ways that do not involve the burning of the charcoal. By using only renewable biomass as the feedstock to make the charcoal, a net sequestration of carbon occurs and yields a carbon-negative strategy that steadily decreases the global atmospheric

concentration of CO_2 , growing season by growing season. Carbon trading credits would distribute income fairly from carbon emitters to carbon sequesterers, generally helping biocarbon producers in poor rural communities at the expense of rich consumers in urban settings. Climate change and income disparity should both diminish.

Making biochar for environmental protection

Figure 9 depicts an environmental problem with which everyone in the audience is probably familiar. In fact, the air quality in Delhi has been poor the past few days because the farmers in neighboring districts like to have two cash crops a year, one from rice, the other from wheat. In between, they have two weeks to get rid of the rice straw stubble before planting for wheat. The quickest and cheapest option to get the task done is to burn the rice-straw stubbles in the field. Such open burning puts particulates into the air and results in harmful $\text{PM}_{2.5}$ pollution for those living in Delhi, downwind from the rice fields.

Unlike wheat straw whose silica content is not troublesome, rice straw has an unfortunately high amount of SiO_2 that makes unattractive the other options to burning it on-site. If one tries to use the rice straw as a feed for farm animals, the high silica content gives the animals indigestion. If one tries to bale rice straw for transport to a thermal power plant for use as a fuel, the slagging of the SiO_2 can clog and damage sensitive equipment parts. If one tries to chop the rice straw into small pieces before burying it to promote its rapid composting, the silica causes wear and tear in the equipment too costly for farmers to bear.

These obstacles are not unique to the Indian government's attempts to wean farmers away from the habit of open burning of rice straw. The same obstacles also prevail in the State of California where it has been illegal since 1991 for farmers to burn rice straw in the fields after rice harvest. Nevertheless, the recommended solution of incorporating the rice straw into the soil for composting has generated opposition from the farmers. As a result, even today, about 25 percent of the rice fields in California



receive “safe harbor” provisions that allow them to burn the rice straw on-site if they can show that disease harbored in the composting rice straw causes crop loss in later harvests.

Figure 9: Picture of a rice farmer burning rice stubble left in the field after rice grain harvest (photo credit: The Hindustan Times).

There is a possible solution if one puts rice straw in molten salt to be supertorrefied into low-grade biochar. The silica is trapped in the low-grade biochar to be put back into the rice fields as a soil amendment. Oxidation of the biochar fines in the supertorrefier puts its silica into the salt, but we know a salt system that minimizes such oxidation. We also have a viable way to get rid of the small amounts of silica that do end up in the salt.

Is there a difficulty? Yes, one has only two weeks to deal with the rice straw after local harvest. We suggest therefore that India should build enough of these machines to process biomass into high-end porous biocarbons for fifty weeks a year, and in the two-week interval between the harvesting of rice and the planting of wheat, India transports enough machines from the State or Territory fleet to handle the conversion of rice straw into low-grade biochar.

Some subsidy of the programme must occur to induce rice farmers to refrain from the old habit of simply burning the rice stubble in the open field, but credits for negative carbon emissions can transfer the bulk of the financial burden to the emitters of CO_2 . Indeed, if India were to embark on such an active programme of pollution reduction, it should win the gratitude of all who live downwind of rice fields that were previously set ablaze once a year.

In addition, the farmers are happy. Something that they used to consider a waste and a nuisance has become a resource to supplement their annual income. Not only can city dwellers in India pay them, their counterparts in Los Angeles should also subsidize farmers for helping to rid the atmosphere of excess carbon dioxide. Participants in carbon trading need to internalize the concept that atmospheric CO_2 does not observe national boundaries.

Biochar as a promotor of crop productivity

Figure 10 gives another incentive to bury biochar as an agricultural practice. In 2016 Hood-Nowotny of Austria published the results of experiments, conducted in tropical and temperate climates, of putting biochar into the ground where crops are grown for food. The specific example is crop land in Africa used for corn production. Because the soil is poor, the corn does not grow very high if one seeds unprepared soils with corn (left panel). But if one adds biochar, the corn stalks reach the height of the farmer (middle-left). Equally good results are obtained by adding fertilizer instead of biochar (middle right). If one adds both biochar and fertilizer, the corn stalks grow really tall (right). (Hood-Nowatney



2016) estimates that biochar can increase soil productivity by 75 percent in tropical and temperate climates. Perhaps possible is reclaiming desertified lands with biochar for agriculture that makes biochar on the side.

Figure 10: Adding biochar to carbon-depleted soils improves soil productivity (Hood-Nowotny 2016).

Managing soil carbon wisely is the new frontier for agricultural science. It has been estimated that poor practices have depleted the carbon in soils to the degree that the world has on average only 60 harvests left. India harvests twice a year. These facts imply, in a simple-minded way, that India can count on having food for only 30 more years. After that, malnutrition could become commonplace. The world is currently in a perilous place; not only is there too much carbon dioxide in the air, but there is not enough carbon in the ground.

A flourishing biochar industry would set an example of how to grow a sustainable circular economy. Start with renewable biomass; turn it into biochar which effectively removes CO₂ from the air. Put the biochar into the ground, which acts as a host for beneficial microbial activity that increases the soil carbon. The increased soil carbon increases crop productivity, which accelerates the production of biochar. The resulting economy then expands in a spiral. When the spiral reaches a desirable size, one applies the brake and transitions to a sustainable circular path. Business as usual with the unrestricted burning of fossil fuels forces us onto a contracting death spiral, which can only end badly for the inhabitants of this planet.

Biochar to reclaim polluted lands

Another unsustainable activity indulged by modern humans is the extractive mining of mineral resources. Mining for metals like silver gives tailings that contain a lot of toxic stuff like arsenic, lead, cadmium. Such was the situation for sixty years after the abandonment of the silver mine in Hope, Colorado. At the dump site for tailings, nothing could grow (left panel of Fig. 11). Worried about landslides into a nearby creek, the Aspen Center for Environmental Studies collaborated with the US Forestry Service to find a solution. They found a topical one in the pine trees being killed by pine beetle infestations aggravated by climate change in the American West. A truck hauled some of the dead pine wood to a manufacturer in Golden (near Denver), who used traditional methods to torrefy the wood into biochar. The biochar was then trucked to Hope, mixed with compost and grass seedlings, and sprayed by a high-speed conveyor onto the plot with the tailings. Photojournalist Troy Hooper, who took the picture on the left of Figure 11, returned a year later on August 2011 to shoot the picture on the right (Hooper 2011). What had been a toxic dump site was now green with growing grass, bring-

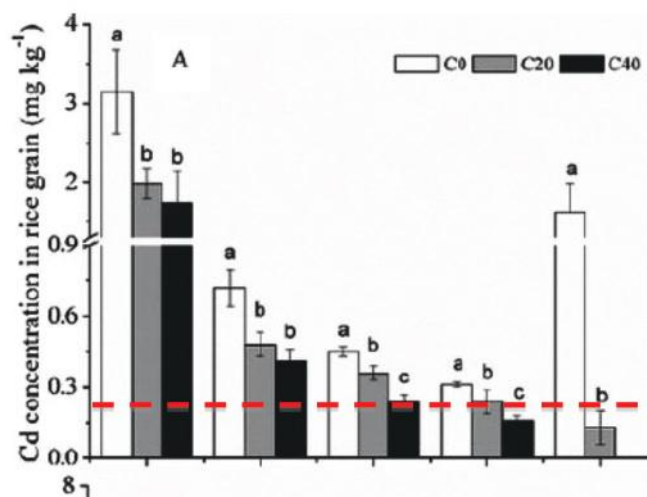


ing renewal and hope to the world from Hope, Colorado.

Figure 11: Left: site of tailings from abandoned silver mine in July 2010. Right: tailings site in August 2011 one year after the addition of 0.73 tonne of biochar mixed with compost and grass seedlings. (Photo credit: Troy Hooper, The Colorado Independent)

Evidently, when one puts down biochar, it soaks up the toxins. A similar remedy is available to humans who ingest poison. They are in danger of becoming very ill and are brought to the hospital. The doctors will typically feed the patients some charcoal granules to soak up the poison. A similar process is valid for plants that have their roots in bad soil. Biochar is very porous. When it rains, the water, carrying with them the water-soluble toxins, flows into the pores of the biochar. When the weather turns dry, the water evaporates as a vapor, leaving behind the toxins locked in the maze of pores that exist in the biochar.

Biochar can also help to reclaim lands tainted by industrial toxins. For example, the trace metal cadmium (Cd) is heavily used in the electronics industry (e.g., in nickel-cadmium batteries that power some cell phones). Cadmium contaminates many rice paddies in China. Rice grains from some provinces contain levels of Cd that exceed the EPA limits for safe consumption by humans. Control trials carried out by Bian *et al* (2014) tested the hypothesis that rice paddies tainted with cadmium respond positively to applications of biochar. These authors found that biochar applied at a rate of 20 to 40 tonnes per hectare reduced the Cd in rice grains harvested from tainted paddies by 20% to 90%. The improvement does not appear at once, but showed up three years after the biochar treatment. Except



for the two most heavily contaminated sites, treatment by 40 tonnes per hectare dropped the Cd in rice grains below the level considered dangerous for human consumption (red dashed line in Fig. 12).

Figure 12: The Cd concentration found in rice grains three years after treatment with 0 (white), 20 (grey) and 40 (black) tonnes of biochar per hectare applied to tainted paddies (adapted from Bian *et al*. 2013).

Mining for coal is perhaps the most invasive of all human extractive activities. The migration of the mercury contained in mined coal into the natural environment supplies the plot of a cautionary tale. Mercury compounds are notoriously volatile. Many types of coal, in particular lignite, contain inorganic mercury compounds. When a coal-fired power plant with unscrubbed smokestacks burns lignite, the

inorganic forms of mercury are volatilized and escape into the sky. Rain scrubs the inorganic mercury out of the sky, mostly to fall into the oceans. Some of the mercury is converted by anaerobic microorganisms to organic compounds of mercury, the most common form of which is called methyl-mercury. Methyl-mercury is soluble in water, and worse, when it is ingested by fish, it is chemically retained by the tissues of the fish because methyl-mercury mimics the chemistry of an essential amino acid. As a consequence, methyl-mercury concentrations bioamplify at each ladder step in the ocean's food chain. At the top of the food chain, the methyl-mercury levels in tuna can be a million times its concentration in the water. When people eat tuna as a part of their regular diet, they can develop neural dysfunction.

Recently, elevated levels of methyl-mercury have been found in rice grains harvested in East and South Asia. It is probably no coincidence that the cycle of growing rice has a phase when the fields are flooded with water where anoxic conditions can promote the growth of anaerobic microorganisms that can convert immobile inorganic forms of mercury emitted by coal-fired power plants to water-soluble methyl-mercury. Preliminary studies have shown some efficacy for removing methyl-mercury from rice paddies by adding biochar infused with sulfur compounds. To stop the vicious cycle at the source, however, East and South Asia should stop burning coal in unscrubbed coal-fired power plants. Replacing such power plants with nuclear power plants would make for a good start in both mitigating climate change and controlling the plague of the mercury poisoning of the biosphere.

Acknowledgments

I thank the members of the HX team for their contributions to the research on Two-Fluid Molten-Salt Breeder-Reactors and Supercritical CO₂: Po-Fu Cheng, Sam Chien, Ruben Krasnopolsky, Fen-Tair Luo, Frank Model, Ron Taam, Tashun Wei, Rebecca Zheng

I also thank Professor Rajaram Nityananda for making the initial arrangements that resulted in my making a most interesting and rewarding first trip to a hospitable and friendly India.

References

- Banerjee, S., Gupta, H. P. 2017. The evolution of the Indian nuclear power programme, *Prog. Nuc. Energy*, 110, 4-16
- Bian, R., Chen, D., Liu, X., Cui, L., Li, L., Pan, G., Xie, D., Zheng, J., Zhang, X., Zheng, J., Chang, A. 2014. Biochar soil amendment as a solution to prevent Cd-contaminated rice from China: Results from a cross-site field experiment, *Eco. Eng.*, 7, 31
- Hansen, J., Maki, Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos. 2008. Target atmospheric CO₂: Where should humanity aim? *Open Atmos. Sci. J.*, 2, 217-231.
- Hood-Nowatney, R. 2016. Biochar improves crop growth and climate, Project funded by Austrian Science Fund FWF
- Hooper, T. 2001. Hope mine cleanup demonstrates power of biochar, *The Colorado Independent*, Sept 9, 2011.
- Smets, E. M. W., Faaij, A. P., Lewandowski, I. M., Turkenburg, W. C. 2007. A bottom-up assessment and review of global bio-energy potentials to 2050, *Progress in Energy and Combustion Science*, 33, 56-106.

About STIP Forum

The Science Technology and Innovation Policy (STIP) Forum has been set up with the objective of promoting debate on various aspects of Science, Technology and Innovation Policy. The Forum would go beyond the disciplinary boundaries by taking into account the intersectionality of S&T and I. It aims to will also bridge the gap between the science and society for dissemination of scientific achievements as well as for generalising debate of societal aspirations and promoting responsible research and innovations. The monthly lecture series of public lectures has been launched to sensitize the public discourse on science, technology and innovation policy. Research and Information System for Developing Countries (RIS), The Energy Resources Institute (TERI), Centre for Science and Environment (CSE), Indo-French Centre for the Promotion of Advanced Research (CEFIPRA), Vigyan Prasar and India Habitat Centre (IHC) are collaborative institutes.



RIS

**Research and Information System
for Developing Countries**

विकासशील देशों की अनुसंधान एवं सूचना प्रणाली

Core IV-B, Fourth Floor, India Habitat Centre
Lodhi Road, New Delhi-110 003 India., Ph. 91-11-24682177-80
Fax: 91-11-24682173-74, Email: dgoffice@ris.org.in
Website: <http://www.ris.org.in>

Follow us on:



facebook

www.facebook.com/risindia



@RIS_NewDelhi



www.youtube.com/RISNewDelhi