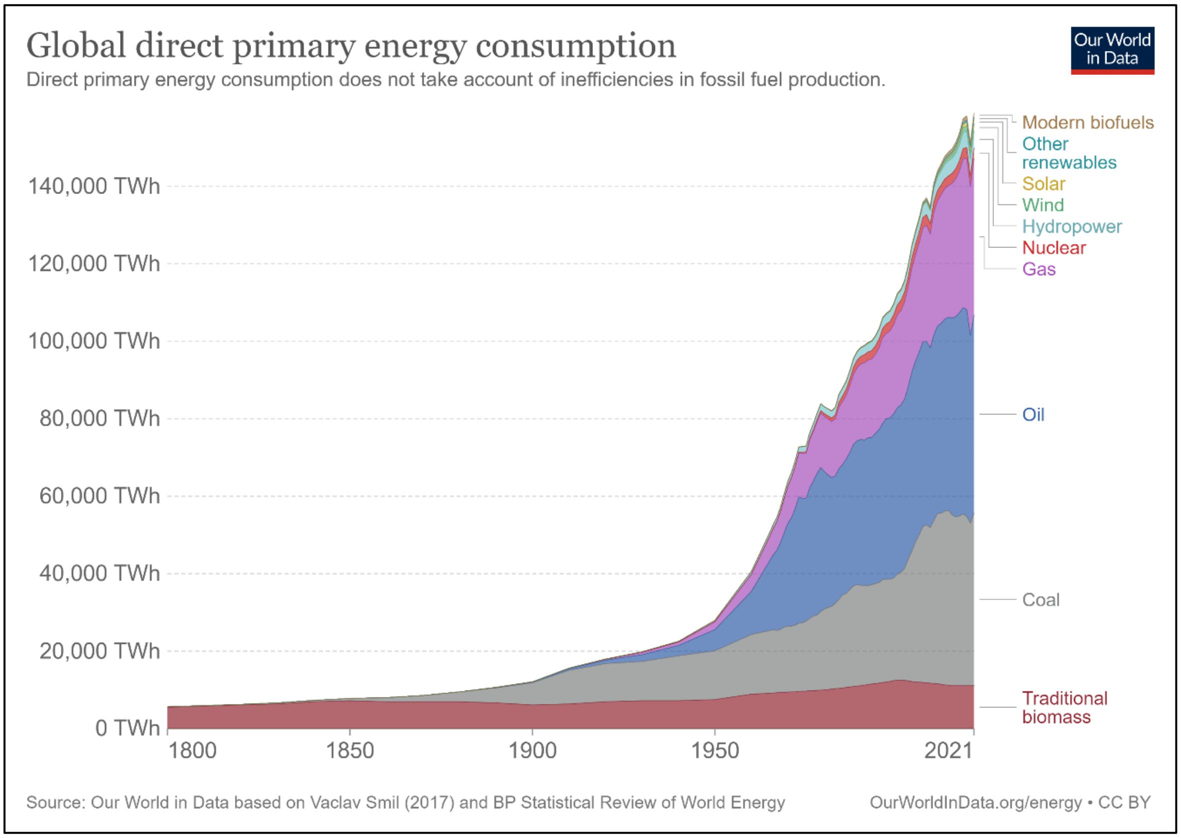
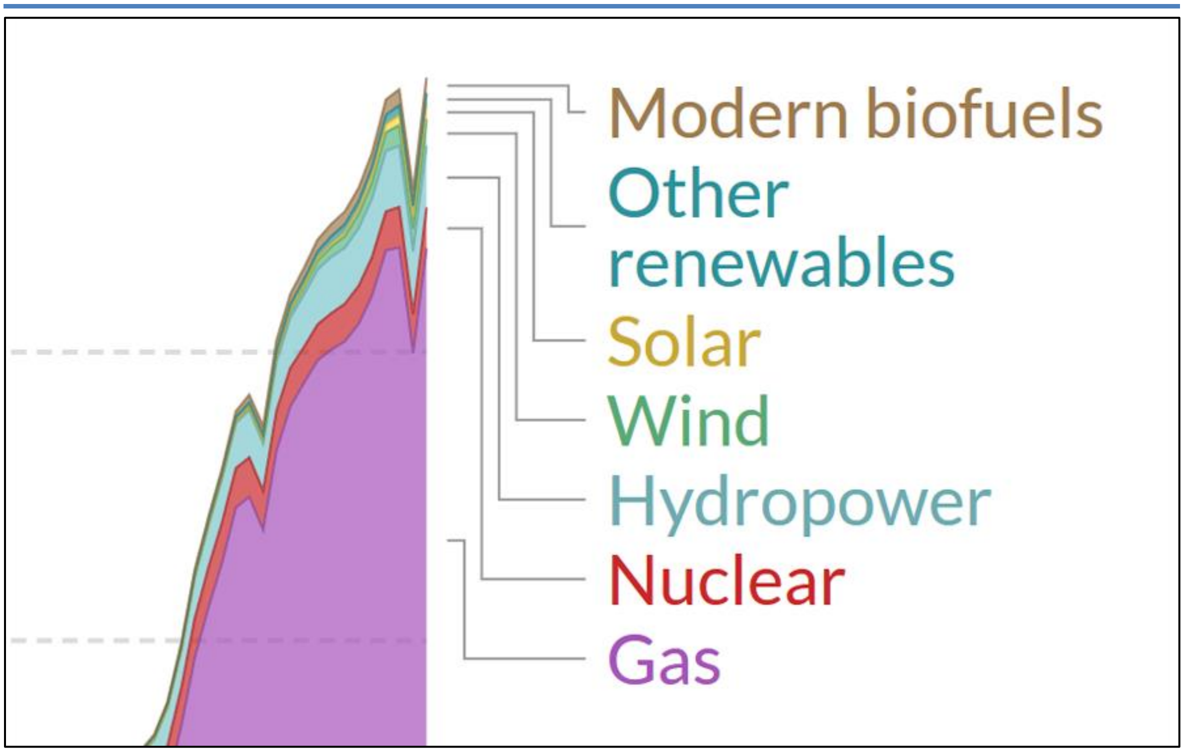
Solving the 2020s Energy Crisis





Narration Script

V1.0 DECEMBER 29, 2022

<u>Episode 4: What's wrong with Nuclear Energy?</u>

I'm Erik Townsend. In earlier episodes of this docuseries, I explained the critical role energy plays in determining our quality of life and the pace of advancement of the human race. Next, I explained why a global energy crisis is imminent, and can no longer be avoided. Then, in the episode before this one, I explained that I'm only aware of two realistic solutions to this crisis, and went on to explain the first of those two options in detail: deep supercritical geothermal energy.

I've intentionally waited until now to tell you that the very best option before us is the one I know some of you already vehemently oppose. That's right, I'm talking about nuclear energy. But please don't jump to the conclusion that I'm a fan of the current generation of uranium-fueled pressurized light water reactors like the ones that melted down at Fukushima Daiichi. Quite to the contrary, I think the nuclear power industry has some significant problems to overcome, and my concerns go well beyond the usual objections about meltdowns, nuclear waste disposal, and weapons proliferation.

So I'll start with a short tutorial on how nuclear electricity generation works, and then focus most of this episode on what's *wrong* with the current generation of nuclear power plants. The overarching theme is that there's really nothing inherently unsafe or wrong with nuclear power. The problem is that governments tightly control and regulate the nuclear power industry, and until very recently, they did an atrocious job of protecting the interests of *We The People* from corruption, greed, and horrendous policy errors caused by political favoritism. I'll expose some of those violations of public trust in this episode.

Unless we can achieve some really big breakthroughs in deep supercritical geothermal energy technology, and achieve them very quickly, there simply isn't any alternative to nuclear that can generate clean electricity on the scale we're going to need to solve this crisis. Nuclear energy most assuredly *can* scale up to produce 180k TWh of new clean, safe energy by 2050, but doing so will require a complete reversal of public policy. And then it will take at least a full decade to build all the nuclear power plants we're going to need.

Nuclear power is already the cleanest and safest source of baseload energy by any objective measure. But similar to aviation, although the accidents are extremely few and far between, they always make front page news. Far more people are killed by drunk drivers every single year than the total number of passengers killed in airline accidents in all of aviation history. But the crash site photos after an airline mishap are so graphic and gut-wrenching that we never forget them. Drunk driving fatalities seldom make the nightly news.

By any objective measure, the number of accidents, deaths, and diseases, including cancer, is far lower per gigawatt-hour of energy produced from Nuclear than from any other baseload energy source. But the extremely rare events where something goes badly wrong in a nuclear power plant are so sensational that we never forget them.

Many nuclear advocates will tell you that's reason enough to stop worrying about safety and get behind nuclear energy. Sorry, but personally, I still have reservations. They're right that nuclear power is already safer than any other form of power generation, but the accidents at Chernobyl, Three Mile Island, and Fukushima all could and should have been prevented. Those accidents didn't happen because nuclear power is inherently dangerous or unsafe. They all happened because human beings did astonishingly stupid things that resulted in horrific outcomes.

Regulators have created a mountain of bureaucracy and red tape around all things nuclear that pushes the price of nuclear energy much higher than it needs to be, but all that regulation failed to prevent accidents that were easily preventable. We don't need *more* regulation of nuclear energy. We need smarter, more *effective* regulation in place of bureaucracy and red tape which is currently standing in the way of both progress and *safety*.

Much better and safer reactors were designed, tested, and proven decades ago. They produce much less waste, and it only needs to be stored for a few hundred years as opposed to one hundred thousand years for the waste produced by current-generation nuclear reactors.

I promised in the first episode to tell you the truth about the full extent of the challenges we face. So before moving on to the latest nuclear technology, let's take a look at what's wrong with current nuclear power plants. There are several different reactor designs, but for sake of brevity I'm going to focus on the most common type used in nuclear power plants in service today and currently under construction: The Pressurized Light-Water Reactor fueled by uranium.

A nuclear reactor works by harnessing the heat energy released from a sustained nuclear fission chain reaction. The core of the reactor contains fuel rods made of low-enriched uranium. For our purposes, all you really need to know about the nuclear physics involved is that there are a bunch of neutrons flying around, and they're moving too fast. To make the nuclear fission reaction sustainable, it's necessary to slow those neutrons down. This is accomplished by filling the reactor core with water. The water serves two main purposes. The first is to slow down the neutrons flying around between the fuel rods. The water is called the *moderator*, because it *moderates* the speed of the neutrons.

The second purpose the water serves is to absorb the heat energy being released by the nuclear fission reaction occurring between the fuel rods. That means the water gets really hot, really quickly. So it has to be continuously circulated out of the core into a heat exchanger, where the heat can be removed and used to produce steam to turn a turbine and generate electricity. Nuclear reactors are so good at heating water quickly that most of the problems arise only when that heat can't be removed quickly enough.

To shut down the nuclear fission reaction, control rods are inserted into the core. The purpose of the control rods is to absorb the neutrons flying around inside the core, which are essential to sustaining the nuclear fission reaction. With the control rods fully inserted, the nuclear fission reaction will completely stop. 94% of the heat being generated in the fuel rods will stop instantly when the control rods are inserted and the nuclear fission chain reaction stops. But the remaining 6% of the heat generated by the fuel rods is known as decay heat, and it doesn't just switch off instantly like a light switch. It takes quite a while after the control rods are inserted before the fuel rods stop producing decay heat, so it's critically important to keep removing heat from the coolant water to prevent the core from overheating.

That's why coolant circulation pumps are essential to reactor safety. If the circulation pumps stop working, the water in the core can overheat and boil off. If that happens, even though the nuclear fission chain reaction has already stopped, the fuel rods are still making so much decay heat that they can melt and burn through the bottom of the core chamber. That's the so-called *nuclear melt-down* scenario you hear so much about in Hollywood movies.

And that's exactly what happened at Fukushima Daiichi. When the earthquake hit, seismic sensors were triggered, and the reactors shut down automatically. All that was necessary to prevent disaster was to keep the circulation pumps running to cool the fuel rods in the core, and everything would have been fine.

Once the reactors shut down, the electricity produced by the nuclear plant was offline, but the pumps could run on electricity from the power grid. And just in case the power grid failed, which it did, there were diesel backup generators installed specifically to cover this exact scenario. The backup generators were supposed to provide electricity to run the circulation pumps even after the electricity from the power grid was cut off. But when the Tsunami hit, everything was flooded including the backup generators. The circulation pumps shut down, the cores overheated and eventually melted down, and the rest is history.

I want you to remember one very important detail about how this type of nuclear reactor works: The moderator used to slow the neutrons down, which also serves as the coolant used to remove heat from the core, is *ordinary water*. In the nuclear industry, it's called *light water* to distinguish it from a special kind of water known as *heavy water,* which I'll explain in the next episode. The vast majority of nuclear reactors in commercial use for producing electricity are moderated and cooled by light water. And as we'll see, that leads to quite a few problems.

The light water inside the core circulates through a heat exchanger so that heat produced by nuclear fission chain reaction can be used to boil a separate source of water into steam that drives a turbine to generate electricity. The amount of energy the reactor can produce, and thus the amount of electricity it can generate, depends primarily on how hot the water in the core can get.

Ordinary light water boils at 100C. In theory, you could operate a nuclear reactor with water which never gets hotter than 100C. But if your goal is to run an electric power plant, that's not nearly hot enough. To get the most out of the nuclear fission reaction and produce enough electricity to power the grid, you need to get the water up to several hundred degrees Celsius.

At normal atmospheric pressure, water can't get that hot. It boils to steam at 100C. The solution that's used by most light water reactor designs is to pressurize the water in the reactor core. Just as a pressure cooker makes it possible to heat food in liquid form to more than 100C without boiling, a pressurized core allows the coolant water to be heated to several hundred degrees Celsius, allowing much more energy from the nuclear fission reaction to be harnessed to generate electricity. This requires pressurizing the core to about 150 times atmospheric pressure, or about 2,200psi in a typical pressurized light water reactor design.

But as any engineer in almost any field will tell you, any time you build any machine that operates under such high pressure, there's always a risk that a failure will occur, and all that pressure will suddenly be released. If that happens to water that's been heated to several hundred degrees Celsius, the water will flash to steam instantly. And that's the whole reason that such large containment buildings are needed for relatively small nuclear reactor cores. If something breaks and the water in the core depressurizes, it will instantly flash to radioactive steam. One of the primary purposes of the containment building is to prevent the radioactive steam from escaping into the atmosphere.

I know, that sounds pretty scary, right? Hold on, it gets worse. The risk of the water in the core flashing to radioactive steam if the core depressurizes is just one of the inherent shortcomings of using light water as the coolant. To understand the next one, we need to recall the chemical formula for water, which everyone knows: H_2O. In other words, every water molecule consists of two hydrogen atoms and one Oxygen atom.

Hydrogen is the extremely flammable gas that the Hindenburg was filled with, and Oxygen is the stuff that makes everything burn faster and hotter. The combination of pure hydrogen and pure oxygen is an explosive mixture you could literally make a bomb with. Yet water, which is made of hydrogen and oxygen atoms, is what we use to put fires *out* with! Please ask yourself how this is even possible.

The answer is that the hydrogen and oxygen atoms in every molecule of water are bound together so strongly they can't be separated without consuming a huge amount of energy. It's what scientists call a *covalent bond*, and it holds those hydrogen and oxygen atoms together in a way that makes them perfectly safe. In almost any normal, everyday situation, there's no risk whatsoever that water could separate into the incredibly dangerous combination of pure hydrogen gas and pure oxygen gas, because it takes so much energy to break the covalent bonds holding the water molecules together that nothing short of the neutron bombardment from a sustained nuclear fission reaction could ever break them apart.

NEWS FLASH! Guess what's going on inside a nuclear reactor core? You guessed it: A sustained nuclear fission reaction which could, if things go wrong, break the covalent bonds in the light water causing it to separate into the incredibly dangerous combination of pure hydrogen gas and pure oxygen gas, which could explode and blow the roof off!

And to be clear, I'm not using the phrase "*blow the roof off*" figuratively. That's exactly what happened at Fukushima Daiichi. Here's the video of a hydrogen explosion literally blowing the roof off the containment building after the circulation pumps failed, and the reactor core melted down, separating some of the coolant water from the core into an explosive mix of hydrogen and oxygen.

Are you getting the picture now why I'm not the biggest fan of light water as a nuclear reactor core coolant when better choices have been available for decades? The alternative coolants don't separate into explosive gases if the core melts down, and they have other benefits too.

What if I told you that another coolant called molten salt has already been tested and proven to work in a nuclear reactor with no need for any pressurization whatsoever? And what if I told you that it could operate at temperatures up to 700C, removing heat from the nuclear fission chain reaction even better than pressurized light water, and without any risk of depressurizing or flashing to steam, because nothing needs to be pressurized to start with?

I'll bet you're thinking this molten salt stuff must be the latest and greatest 21st century invention, since it clearly seems like a much smarter way to build a reactor. Surely, we wouldn't be using light water as the coolant in our commercial reactor fleet if we'd known about this molten salt stuff back in the 1970s, when we started building the reactors in service today, right?

Sorry, wrong answer. Molten Salt cooled nuclear reactors were designed, built, tested, and proven to work in the mid-1960s, and I don't just mean on a drawing board. The Molten Salt Reactor experiment at the Oak Ridge National Laboratory built and *operated* molten salt-cooled nuclear reactors in the mid-1960s, and they worked beautifully, completely eliminating the need for a water coolant susceptible to hydrogen separation, and eliminating the need to pressurize the reactor core.

But wait, it gets better. The molten salt reactor project at Oak Ridge also perfected a new reactor design that completely eliminated meltdown risk, by dissolving the fuel in the molten salt coolant so that there are no fuel rods.

In the liquid-fueled molten salt reactor designed at Oak Ridge, the nuclear fission reaction stops all by itself when the circulation pumps stop, so there's no need for control rods. In other words, they didn't *just* figure out how to eliminate the need to pressurize the reactor core, eliminating the risk of light water flashing to steam in case of depressurization, or worse yet, separating into an explosive mixture of hydrogen and oxygen. They *also* figured out an incredibly innovative way to completely eliminate any possibility of a fuel rod meltdown occurring in the first place, because they eliminated the fuel rods! Had the molten salt reactor been adopted as the industry standard when it was first proven in the 1960s, these safety innovations could have prevented the Chernobyl, Three Mile Island, and Fukushima accidents.

But there was one very serious problem with the molten salt reactor, which led to its demise in 1971. Molten salt moderated nuclear reactors were developed in Tennessee, but President Nixon was a Californian. There was a competing experiment in California called the liquid metal fast breeder reactor. The liquid metal fast breeder reactor didn't offer *any* of the safety benefits I just described. But the liquid metal fast breeder reactor project was in the President's home state. The Molten Salt Reactor experiment in Tennessee, which was doing groundbreaking work on reactor safety, was cancelled, in large part because President Nixon and the power brokers running the Atomic Energy Commission at the time wanted the money spent in California instead.

I'm sure you probably think I sound like a crazed conspiracy theorist to make such an outlandish claim, but you don't have to take my word for it. If you're familiar with the Watergate scandal, you already know that President Nixon had an odd habit of tape recording himself at what would later turn out to be the most inopportune times. So let's listen in now to President Nixon's June 1971 phone call with congressman Craig Hosmer, also from California.

(PLAY RECORDING 12:06 – 13:36 in https://www.youtube.com/watch?v=bbyr7jZOlII&t=731s&ab_channel=GoogleTechTalks)

President Nixon made it quite clear in that call that Team California was "ruthless" and "playing it close to the vest", and they were ultimately successful at keeping all the research money in their own state. The safety of our civilian nuclear power industry would pay the price for that political favoritism for the next five decades. And still counting…

Breeder reactors will be a critically important part of our future, and I'll explain what they are and why they're important in the next episode. But let's return to the Molten Salt reactor story now.

By 1971, the scientists in Oak Ridge Tennessee who had already proven the benefits of molten salt as a coolant in a working reactor were hard at work designing a molten salt *breeder* reactor that had numerous safety advantages over the Californian breeder reactor design.

The Californians working on the fast breeder reactor had gone way over budget on their version of the breeder reactor, but at least that money was being spent in the President's home state. By September 7, 1972, testimony in a congressional hearing made it clear that cost overruns on the California fast breeder reactor project would cost the taxpayers at least $700mm, which was a lot of money in 1972. That's more than five billion in today's dollars.

The molten salt reactor experiment in Oak Ridge Tennessee was run by Alvin Weinberg, who was unsuccessfully trying to call attention to the profound advances in reactor **safety** that had just been achieved in the molten salt project. Weinberg's team had eliminated the risk of depressurization, steam flashing, and hydrogen explosions by eliminating the light water coolant. And they completely eliminated meltdown risk by dissolving the fuel in the molten salt coolant, eliminating fuel rods completely.

The liquid metal fast breeder reactor project in California was being run by Milton Shaw, who had a reputation for being ruthless in achieving his goals. The other man in a position of power and influence was Chet Holifield, who President Nixon mentioned briefly in the call we just heard. Holifield was a congressman from… you guessed it—California.

Alvin Weinberg, father of the molten salt reactor design would later write in his 1994 autobiography, "Congressman Chet Holifield was clearly exasperated with me, and he finally blurted out, 'Alvin, if you are concerned about the **safety** of reactors, then I think it may be time for you to leave nuclear energy." Weinberg wrote that he was speechless. It was instantly clear that the powers-that-be were not interested in Weinberg's focus on making nuclear reactor **safety** the top priority. Especially if the nuclear reactors in Tennessee were safer than those in California.

Alvin Weinberg, the father of the molten salt reactor design, was fired. The molten salt reactor experiment at Oak Ridge was cancelled completely in 1973, and Weinberg's reactor designs, which by the late 1960s had *proven* that the risks of fuel rod meltdowns and hydrogen explosions could be completely eliminated, were all but forgotten.

In the decades that followed, reactors at Chernobyl, Three Mile Island, Fukushima, and several others would melt down in accidents that Weinberg's reactor designs could have prevented. The Three Mile Island incident was a partial core meltdown accident due to loss-of-coolant, which never could have happened with Weinberg's molten salt designs. Then in 2011, hydrogen explosions that Weinberg's reactor designs could have prevented literally blew the roofs off the containment buildings at Fukushima Daiichi.

Please ask yourself: is the problem really that nuclear energy is inherently unsafe, or is the problem that our government hasn't done an ideal job of putting priority on what's most important to *We the People*? I think it's the latter.

Weinberg's emphasis on designing *safer* nuclear reactors back in the 1960s was sacrificed for the sake things far more important to the people running the Atomic Energy Commission than eliminating the risk of reactor meltdowns or preventing hydrogen explosions like the ones that blew the roofs off in Fukushima. They cared much more about which state federal research money would be spent in, and they didn't want competition upstaging their pet project, the liquid metal fast breeder reactor, which was being developed in Southern California.

Milton Shaw and Chet Holifield were, in President Nixon's own words, "ruthless", and "playing it close to the vest". How thoughtful of them to record Craig Hosmer's phone call with President Nixon, so there can be no question as to what the real priorities of the AEC were back in late

1971 when Alvin Weinberg was fired, and the stage was set for the Oak Ridge Molten Salt Reactor experiment to be completely cancelled 18 months later.

The groundbreaking work on nuclear reactor safety done at the Oak Ridge National Laboratory in the 1960s would almost certainly have been forgotten forever, if not for the efforts of Kirk Sorensen, a NASA Engineer who discovered the Molten Salt Reactor Project's research papers when he was trying to figure out how NASA might colonize the moon. A human colony on the moon would require power to operate, and Sorensen was at first fascinated by the possibility that a Thorium-fueled molten salt nuclear reactor based on the Oak Ridge designs might provide the energy needed to power a moon colony.

Sorensen later realized that the work done at Oak Ridge in the 1960s could revolutionize how energy is produced right here on Earth. He would eventually leave NASA to become an outspoken proponent of Thorium-fueled molten salt reactors, and the founder of a company aspiring to build and commercialize them.

All the research papers from the Oak Ridge experiments somehow found their way to a storage room in a rural children's museum a few miles from the Oak Ridge laboratory, where they were scheduled to be destroyed! Sorensen launched a one-man effort to save the records from Oak Ridge, and managed to raise enough money to scan all the research documents just before they would otherwise have been lost forever.

To this day, Kirk Sorensen is a leading advocate of Thorium-fueled nuclear power, and his website energyfromthorium.com is well worth checking out if you want to learn more about the work done at Oak Ridge and the promise Thorium offers as an alternative to Uranium. I'll also address that topic in the next and final episode of this docuseries.

Putting all of this in context, many of the things that can go wrong in a nuclear power plant are a result of using light water as the coolant and moderator in the reactor core. Better alternatives have been known for more than 50 years, but the vast majority of nuclear reactors in commercial operation around the globe are still light water-moderated and cooled, as are the new reactors being built today.

Back in 2012, when I first became aware of Kirk Sorensen's desire to commercialize the Oak Ridge designs, I reached out to the most knowledgeable and successful energy investors I know, seeking their advice. I asked them, "Is this Sorensen guy for real? Is this molten salt reactor idea really as compelling as he makes it out to be? Should I consider an angel investment in the company he was launching at the time?"

My mentors all gave me the same answer. First, they said *yes*, both molten salt and thorium fueled reactors are just as exciting as Sorensen makes them out to be. But then, in the very next breath, they told me I would be crazy to throw money away investing in them in 2012. They went on to explain that nuclear energy is the most regulated industry in existence. The government makes the rules, and they alone decide what technology will be commercialized.

They said it was a real shame that the advanced designs pioneered by the Oak Ridge Molten Salt Reactor experiment of the mid-1960s were never commercialized. But then they explained that it would never happen unless the government were in the driver's seat, making it happen. My mentors told me that to lobby congress to approve an advanced reactor design, never mind a new fuel like Thorium, would be so expensive it would never happen.

The solutions to the problems of core meltdown, steam flashing of pressurized water cores, and hydrogen explosions, are anything but new. Most of the operational safety and waste disposal problems the nuclear power industry has experienced to date could have been prevented by the advanced reactor designs Weinberg's team at Oak Ridge perfected in the 1960s. But that work was almost completely forgotten quite literally because it happened in the wrong state.

Now things are finally starting to turn around for the better, at least on a small scale. On April 12, 2021, the United States Department of Energy, Office of Nuclear Energy, issued a flyer titled "Three Advanced Reactor Systems to Watch by 2030". The three designs they describe in that paper are the Sodium-Cooled Fast Reactor, the Very High Temperature Reactor, and the Molten Salt Reactor.

That's right, the last one on their list is the very same molten salt reactor design which was built, tested, and proven by Alvin Weinberg's team at Oak Ridge in the 1960s, just before Weinberg was *fired* by California congressman Chet Holifield and Atomic Energy Commission honcho Milton Shaw for making the outrageous statement that **safety** should be the top priority in reactor design.

Now, more than half a century later, the U.S. Department of Energy has finally declared in an official communication that the so-called "new technology" we should be keeping an eye on is exactly what Weinberg's team perfected in the 1960s. It's about time!

An old saying in Washington goes "Never let a crisis go to waste", because it's in times of crisis that the most progress can be made pushing through government bureaucracy and making important things happen. So, as I became convinced in late 2021 that a global energy crisis was unavoidable for the reasons explained in the 2nd episode of this docuseries, I decided to revisit the question of investing in advanced nuclear technology.

I learned that there are already several startups working right now on molten salt reactors, Thorium fueled reactors, and several other exciting advanced nuclear technologies. Almost all these startups are the pet projects of billionaires who have so much money they don't mind taking an irrational investment risk building a reactor that governments might never even allow to be turned on, because its design is miles ahead of anything the regulators are equipped to regulate. These guys are so passionate about inventing technology that could save the world from the coming global energy crisis that they're willing to take irrational investment risks to try and make it happen.

For example, Microsoft Founder Bill Gates has bank-rolled an advanced nuclear project called the Natrium reactor. Several other startups are building molten salt cooled and even Thorium fueled nuclear reactors, knowing full well that there isn't a country on earth that will allow them to be turned on, because no regulatory precedent exists for operating that kind of commercial reactor.

My strong suspicion is that the billionaires bankrolling these pet projects in advanced nuclear technology see exactly the same writing on the wall that I see: A global energy crisis beyond almost anyone's comprehension is coming, and coming soon. When it happens, being the guy who already built the advanced reactor that could save the world if only the government would allow it to be turned on, is an awfully good look. Consider how governments fast-tracked COVID vaccines and threw outlandish sums of money at the companies that had plausible ideas for vaccine development in the hysteria of the pandemic.

When you factor in the effects the coming global energy crisis will have on the attitude of regulators, suddenly, investing in those crazy advanced reactor startups which are building reactors no country on Earth will permit operation of *today* doesn't sound nearly as irrational as it did when I first received the advice *not* to invest in this stuff over a decade ago. It wasn't time yet back then, but now it's another story.

Let's return now to the type of nuclear reactors that governments around the world already know how to regulate: Pressurized light water moderated reactors fueled by uranium, such as those built by Westinghouse, the company that designed and built most of today's operating fleet of commercial nuclear power plants.

An issue of great concern to the anti-nuclear lobby is Nuclear Weapons Proliferation. One of the biggest myths we need to debunk is the idea that the Uranium fuel that powers nuclear reactors could somehow be used to make a nuclear bomb. It just plain doesn't work that way. To make a nuclear bomb, Uranium must be enriched to at least 90% U-235, the specific isotope of Uranium which is fissionable. Natural Uranium mined from the ground contains only 0.7% U-235. To make fuel for nuclear reactors, Uranium is typically enriched to between 3% and 5% U-235. That low-enriched Uranium has no value in making a bomb, so this perceived risk is pure fiction.

That's not to say there are no bona fide weapons proliferation risks. To make the fuel for nuclear reactors, Uranium is enriched by converting it into gaseous form and spinning it very fast in centrifuges which concentrate the U-235. Although the centrifuge facilities that are used to make nuclear reactor fuel are typically not capable of making high enriched uranium needed for nuclear weapons, an argument can be made that once a country has the centrifuges needed for making nuclear reactor fuel, it's possible to add more centrifuges and use them to produce weapons-grade Uranium.

That's a legitimate concern, but please notice that the centrifuges aren't needed to operate nuclear reactors. They're only needed to make the fuel rods required to operate nuclear reactors. This means that if you're concerned about weapons proliferation, it really doesn't make sense to concern yourself with which countries are allowed to *operate* nuclear reactors. The important question is where the fuel is made, and who is in control of that process. Most of the weapons proliferation concerns can be overcome by restricting where nuclear reactor fuel can be produced, rather than restricting where nuclear reactors can be operated to generate electricity. Breeder reactors also play a key role this story, and I'll come back to that topic in the next episode.

The next big objection to nuclear power is nuclear waste disposal. There's nearly a quarter million metric tons of high-level nuclear waste in storage worldwide. High-level nuclear waste consists almost entirely of spent nuclear fuel that was already used in nuclear powerplants over the last 60 years. The reason so many people understandably freak out about nuclear waste is that some of the material stays radio-active for 100,000 years or longer. That's an awfully long time, but that statistic is misleading.

The radioactive decay of spent nuclear fuel waste declines rapidly after just a few years. After it's been stored for just 50 years, 99% of the dangerous radioactive decay has already occurred. There are still materials in that spent fuel with half-lives upwards of 100,000 years, but the radiation is so small that it barely exceeds safe background radiation levels.

Now to be clear, I personally don't like the idea of *any* radioactive waste needing to be stored for 100,000 years, and I think the nuclear industry has in the past been too dismissive of this concern. But to keep it in perspective, the *dangerous* radiation really is done and over with after the first 50 years. And even during those first 50 years, high level nuclear waste isn't nearly as dangerous as most people think.

To make this point, the Dutch government built a single building which serves as both a nuclear waste storage facility, and a children's science museum. Look at the big round circles on the floor in this picture. That's the floor of the children's museum, and those big round circles are the tops of the cannisters in which spent fuel waste from their nuclear reactor is stored. The children are welcome to sit on top of the nuclear waste cannisters just to prove to themselves and their parents that spent nuclear fuel waste isn't really the stuff of horror movies.

When spent fuel comes out of a light water moderated reactor, 95% of that spent fuel material is perfectly good natural uranium that can and should be recycled rather than left sitting in dry cask storage for 100,000 years. The process for recycling the spent nuclear fuel has already been proven and commercialized. So just going to the trouble of recycling spent nuclear fuel could reduce the amount of nuclear waste produced by today's nuclear industry by 95%.

But wait, the story gets even better from here. The remaining 5% is some pretty nasty stuff, called trans-uranics. Is it really better if we have to store *concentrated* nuclear waste for 100,000 years instead of storing a much larger volume of current-generation nuclear waste for the same period? There's some benefit to reducing the volume of waste material in storage, but that hardly solves the overall problem.

But **waste burning** breeder reactors do solve that problem, and they solve it in a beautiful way: They can actually burn the nuclear waste that's already been produced by the last 60+ years of operating light water moderated reactors, and use that waste as fuel! That's right, we already have the technology to take the nuclear waste we thought we were going to have to store for thousands of years, recycle it, then re-use the 95% of it which is perfectly good natural uranium, and then burn the rest as fuel in waste burning breeder reactors.

That means it's possible to have a nuclear renaissance that not only doesn't add any more nuclear waste to the quarter million tons already in storage. We can actually burn the waste we already have as fuel, and thus eliminate the need to store it long-term!

Remember, the reactor that Alvin Weinberg was working on when he was fired in 1971 was a molten salt **breeder** reactor. So the technology needed to solve the nuclear waste problem was actually developed and almost completed in the United States half a century ago. It just happened in the *wrong* United State, and that's why it was abandoned.

And there's still a catch: there's still no regulatory precedent for commercializing waste burning breeder reactors, so the guys who already know how to build them are currently working for those advanced nuclear startups that tend to be the pet projects of billionaires, waiting fingers-crossed for the day when governments get with the program. I'll tell you about one such company that's leading the charge on waste-burning breeder reactors in the next and final episode of this docuseries.

Until very recently, the government's performance in managing the nuclear power industry has been nothing short of abysmal. And I contend that's the real problem. Nuclear energy was never inherently unsafe. The problems began when our government fired Alvin Weinberg for the offense of making **safety** his team's top priority.

Some of my friends in the nuclear industry are completely dismissive of the waste disposal problem, because the true risk posed by nuclear waste is miniscule in comparison to how the public perceives it. They have their facts right, but I still disagree. I don't care how small the safety risk is; I don't want to be part of leaving behind *any* radioactive waste that future generations have to contend with for 100,000 years. But I'm also convinced that the technology to solve that problem was already invented by the time I was old enough to ride a bicycle, and I'm in my late 50s now. Maybe it's time we start using that technology which my parents tax dollars paid to develop back in the 1960s.

It's truly sad that it will probably take a global energy crisis punctuated by great human suffering for the government to finally get its act together and put to work the advanced nuclear technology that was invented when I was still in diapers. But at least we know from their 2021 pamphlet that the molten salt reactor is back on their radar screen. Hopefully Thorium fuel will be next.

I promised I wouldn't sugarcoat the problems with nuclear power, so we've already spent most of this episode on my critique of what needs to be improved. But let's step back now and put this picture in perspective.

Nuclear power is already the safest form of baseload power generation in existence. Despite the shortcomings of pressurized light water reactors and the political favoritism that prevented much safer molten salt reactors from being commercialized, the fact remains that nuclear is already far safer than any other option we have. Nuclear is the *only* option that can realistically scale up to supply 180k TWh of new clean energy by 2050, without relying on technological advances that haven't happened yet, as is the case with supercritical geothermal. The light water reactors of today still produce nuclear waste, but the path is now clear for how the waste burning breeder reactors of tomorrow will consume that waste as fuel.

It's essential to understand that there haven't been **any** serious accidents in the nuclear power industry except for those that were caused by human beings doing *really* stupid things they frankly should never have been allowed to do. In the case of Chernobyl, that reactor design would never have been permitted in the West to start with. Operators at the Chernobyl plant were trying to perform a safety test they had botched 3 times previously. They didn't bother to run their test plan past the reactor's designers or the nuclear regulator, despite that among other things, their test plan involved <u>intentionally disabling</u> the *emergency core cooling system* while the reactor was running. That's the system designed to protect the core from meltdown in event of a loss of coolant accident, so disabling it was reckless to say the very least.

The safety test was scheduled during the day shift, but it went badly awry, resulting in an unplanned near-total shutdown of the reactor. When they finally got the reactor running on only partial power, well below the threshold level their own written test plan called for, they still weren't sure why the reactor had almost completely shut down. But despite having no idea why the reactor wasn't behaving as expected, they decided to press on rather than abandoning the test.

Just after midnight, the reactor was being operated by a 25-yr old night shift technician with 3 months experience in his position. He made several serious mistakes that would ultimately result in catastrophic failure of the reactor. The accident was 100% the result of human error. There was nothing wrong with the reactor, and no significant malfunction occurred. The problem was with the humans operating the reactor, whose reckless test plans and egregious operational errors directly caused the disaster.

In the case of Three Mile Island, when a loss of coolant accident occurred, automated safety systems turned on the emergency coolant pumps to protect the reactor core from meltdown. Human operators responded by overriding the automatic safety systems, and turning the emergency coolant pumps back off!

After mis-interpreting the overall situation due to poor training, the operators had already convinced themselves there was no loss of coolant, but they were dead wrong. They decided the emergency cooling system, which had activated automatically to prevent a meltdown, wasn't needed. So they shut it off, and a partial core meltdown resulted. The meltdown could have been prevented had the operators not intervened to prevent the automated safety systems from doing the job they were designed to do.

In the case of Fukushima Daiichi, tsunami-related safety recommendations were made but then ignored not once but twice, first in 2000, and then again in 2008. Safety inspectors had informed the operator that the seawall wasn't high enough and recommended that it be extended to protect against a Tsunami, but no action was taken.

The diesel backup generators for the coolant system were originally located in the basement of the turbine building. Engineers from GE informed TEPCO, the operator of the plant, that this location was vulnerable to flooding and that the generators should be moved to higher ground. TEPCO responded by moving the generators to higher ground, while leaving all the electrical switching equipment for connecting the generators to the cooling pumps in the basement, where it was flooded by the Tsunami, rendering the generators on higher ground useless.

Regulators ultimately ruled that even with the extent of damage from the Tsunami, the entire nuclear disaster could easily have been prevented had safety recommendations been heeded. There was no unforeseeable freak of nature. The exact scenario of a tsunami hitting the plant and resulting flood damage disabling the emergency backup power for the coolant circulation pumps was fully understood and anticipated by safety inspectors who informed the plant operator in writing exactly what needed to be done to mitigate those exact risks, years before the accident occurred. Those written instructions were ignored not just once, but twice.

So history is clear: The problem is not that nuclear energy is inherently unsafe. The problem is that human beings prone to doing stupid things should not be allowed to operate nuclear reactors. The solution is automation, and that solution is well within our current technological capability. The latest Generation III pressurized light water reactors have far more sophisticated automation and fail-safe systems than the reactors that melted down in Three Mile Island and Fukushima. The state of the art in nuclear energy safety could still be improved a whole lot more, as I explained in great detail earlier in this episode. But it's already the safest form of power generation in existence, and we shouldn't hesitate to build more Generation III nuclear plants.

Going forward, we need to design fully automated reactors which don't rely on human operators at all, and which don't have big control rooms full of confusing instrumentation. The lesson we should learn is to design future reactors so that even Homer Simpson couldn't possibly cause a disaster by trying to interfere with automated systems that are better equipped to handle an emergency than human decision makers who have repeatedly failed to perform under pressure.

The final problem with nuclear power I want to address in this episode is the time horizon required to bring new nuclear power generation online at the scale we're going to need it. Sadly, large bespoke public works projects are something we're just not as good at as we once were. When the Golden Gate Bridge was completed in 1937, it took four years to build start-to-finish, and came in under budget at $35mm, which is just over $700mm in today's dollars.

A project is underway right now to add a suicide prevention net under the bridge. That's right, nothing more than a net strung up under the bridge to catch suicide jumpers. That project is now both over budget and late to finish. More than $400mm has already been spent. That's considerably more than half what it originally cost to build the *entire bridge*, even after adjusting for inflation. *Just to add a net under a bridge that's already built!* And the incomplete project to add the safety net has already taken more than the four years it took to build the *entire bridge*! We're just not as good at managing large construction projects and getting them done on time and on budget as we used to be.

In the nuclear industry, the same holds true today. Cost and schedule overruns at the Vogtle nuclear powerplant construction project in Georgia literally bankrupt Westinghouse in 2017. And even back in the 1970s, we had the same problem. The reason that nuclear power never delivered on the promise of making electricity cheaper than it ever was before is that every nuclear powerplant project ran massive cost overruns.

This is a really important point to understand: Nuclear power really is and always has been the cheapest way to generate baseload electricity, when you measure the cost of **operating** the nuclear power plant. The problem is that when you factor in the cost of **building** the powerplant including all those cost overruns, the fully loaded cost of electricity is far higher than the direct operational cost of producing it. That's the *only* reason electricity produced in nuclear power plants isn't much cheaper than it is today.

A personal friend of mine was a union construction worker who helped build the Seabrook nuclear power plant in New Hampshire in the 1970s, and the stories of corruption and malfeasance he told me would knock your socks off. He said the running joke among the union workers was that the day shift built the plant, and the night shift tore it down. Safety rules meant to protect the public made the construction contractors immune from penalty if they detected quality problems and had to re-do parts of the project. The contractors seized the opportunity to build the plant several times over, by intentionally allowing quality defects to occur, thus forcing reconstruction and horrendous cost overruns which only made the contractors richer.

My friend told me that ironically, clowning around on the jobsite was actually more common at the nuclear plant than on any other jobsite, because every union worker on the job **knew** that the first time they built *anything*, it was just going to be torn back down and rebuilt, so the contractors could gouge even more money by rebuilding it. And so long as they kept paying union wages, the workers never complained.

It's truly sad that our industrial capabilities have devolved to this level since WW II, but they have. And this leads me to the conclusion that large-scale nuclear power plants like Vogtle will always be plagued by cost and schedule overruns. I'm convinced that the only viable solution is to build nuclear reactors in factories, on assembly lines. What Honda did for the quality and rapid production of Automobiles needs to be done again, but this time to much more demanding nuclear safety quality standards.

The reason I've become focused on small modular nuclear reactors built on assembly lines is *not* because they're inherently better than much larger conventional nuclear power plants. I'm not convinced they are. The reason I'm convinced that small modular nuclear reactors are the way of the future is that I still have confidence we can manufacture them in factories on the scale we're going to need them. But sadly, I've lost faith in our ability to undertake large bespoke public works projects without screwing them up. The cost and schedule overruns at the Vogtle powerplant in Georgia which bankrupt Westinghouse in 2017 stand as evidence to my point.

I'm convinced that nuclear power can and should be the primary solution to the coming global energy crisis, unless a major breakthrough in supercritical deep geothermal energy changes the game. The reason I favor nuclear power is that it's the only option we have that can be scaled up to produce the 160k – 180k TWh of thermal energy we need to replace fossil fuels. But I want to be honest about the sadly unavoidable reality of nuclear power, which is that it will take well over a decade to roll out at the scale we're going to need it. That means the sooner we get serious about this energy transition and prioritize a nuclear renaissance, the better.

And it also means we're going to have to invest in keeping the oil & gas industry not just alive, but **growing,** for at least another decade.

It's true that rolling out nuclear will take more than a full decade, but the real conclusion to be drawn there is we should have started doing so at least a full decade *earlier*. We're late to get serious about this energy transition, and time is of the essence to put real plans in place that can deliver ***all*** the energy needed to replace fossil fuels.

The only option for adding more nuclear-powered electricity generation *right now* is to build more conventional nuclear plants using already-licensed light water moderated reactor designs like the Westinghouse AP1000. But the minimum time from commissioning a new powerplant construction project to delivering electricity into the grid is at least 7 years, and more likely 10+ years by the time all is said and done. Without significant new investment in oil exploration and production, petroleum prices will rise to economy-crippling levels long before enough new nuclear powerplants can be built to fully solve the problem.

It's easy for a futurist like myself to produce a docuseries like this one singing the praises of small modular nuclear reactors built on assembly lines, based on molten salt, Thorium fuel, fast breeder reactor technology, and other advances I'll discuss in the next episode. But as passionate as I might be about such things, the fact remains that there isn't a country on earth that's ready to permit the operation of a molten salt cooled reactor, never mind a Thorium-fueled commercial reactor. We desperately need to move past light water reactors and commercialize the even safer advanced nuclear technology that was invented when I was still just a toddler. But until we do, building more Generation III pressurized light water reactor powerplants is the best option we have.

Governments are notoriously slow to change until a crisis forces them to. Then they tend to act impulsively without much thought. My primary motive for producing this docuseries was to promote public understanding of these issues, so that when the mid-2020s energy crisis hits the stage, that crisis doesn’t go to waste. We need to *use* that crisis to push through a top-level policy directive to embrace nuclear energy as the *primary* strategy to achieve net zero objectives by 2050.

It's taken this entire episode just to explain what’s wrong with the current nuclear power industry. In the next and final episode of this docuseries, we’ll focus on solutions, introduce some really exciting advanced nuclear technology, and I’ll lay out a plan for solving the coming global energy crisis using a combination of nuclear power, existing renewable sources like wind and solar, geothermal energy, and yes, by extending the life of the oil & gas industry for at least another decade until we can phase in viable clean alternatives needed in order to eventually phase out fossil fuels completely.