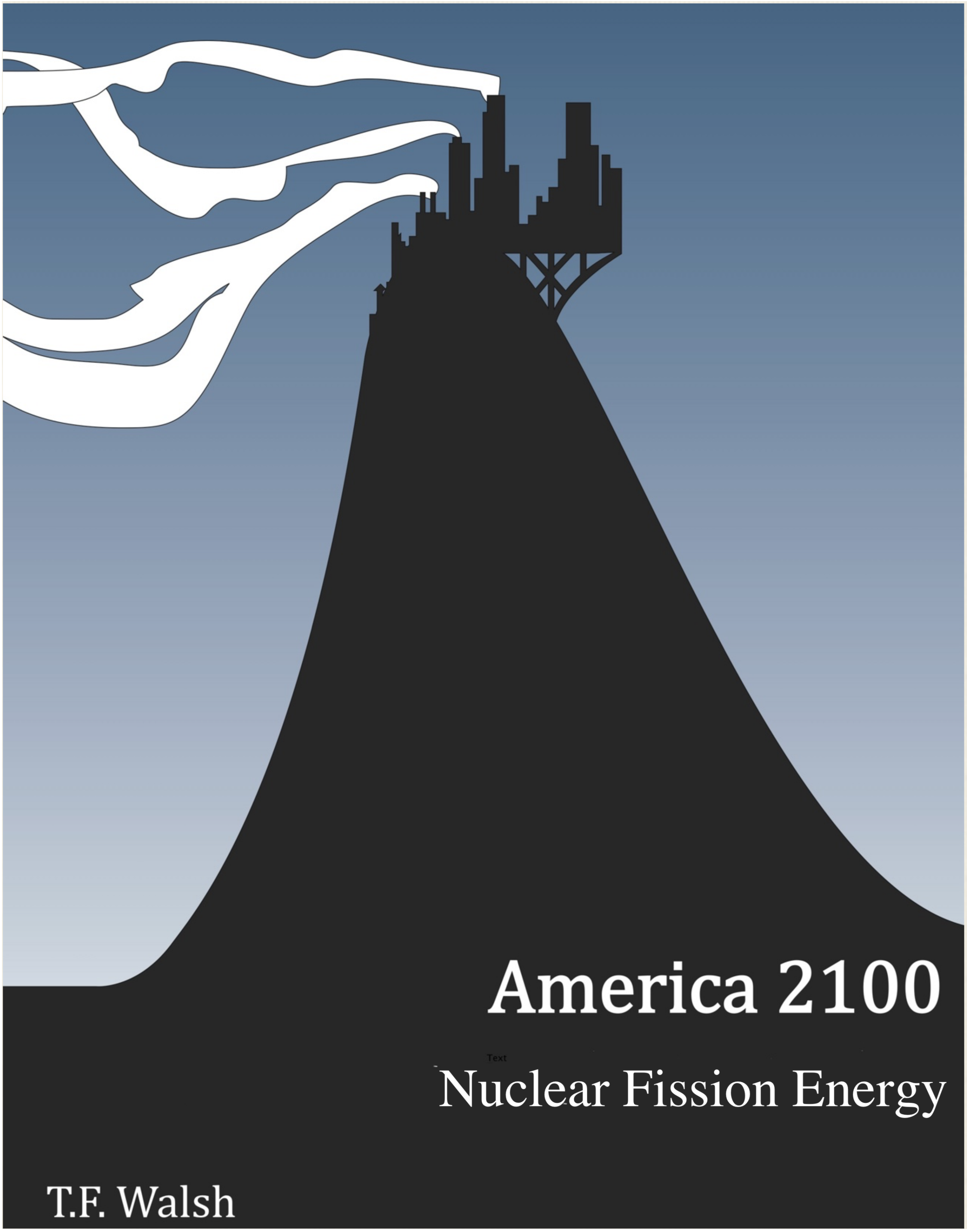


America 2100

Nuclear Fission Energy

T.F. Walsh

Preface

Electricity from nuclear power seems to be slowly dying in the United States, although now it supplies a fifth of our generated electricity. There are about 100 operating commercial power reactors, most of them 30-40 years old. At about 40 years they either need to be closed and replaced or renovated and their licenses extended. But, crucially, our aging nuclear power system produces a vital fraction of all our electricity. And only a handful of new reactor designs are being built. These new designs are arguably safer than older reactors. Alas, newer plants come to a great degree from companies outside the U.S.; our manufacturing capability is not what it was.

Perhaps the present nuclear decline will go on. There are many obstacles to reviving construction. But we will need fossil carbon replacement energy options in the decades ahead, and nuclear fission energy could conceivably recover. After all, this is a large scale energy source not dependent on declining fossil carbon. And it does not produce carbon dioxide that pollutes the atmosphere. And basic nuclear power technology is over sixty years old and it is well understood.

The difficulties and disadvantages of nuclear power are well known. With nuclear energy we face the task of building and maintaining hundreds of huge single facilities that must be ensured to be safe. The alternatives of intermittent solar and wind power both come from individually small units that have to be connected together. It might take many hundreds or a thousand of these small units to equal the power from one nuclear power plant. We will have to use a lot of land for them. So there will be land use problems we will have to face. There is also the severe problem of averaging out the intermittency by storing energy. Present intermittent power is so small in scale--about five percent of the total--that we have not had to face its problems yet.

This short book is about nuclear fission power, its nature, prospects and risks. Later books turn to other replacement energy sources that are currently more popular and, also, perhaps more realistic than nuclear power.

Introduction

The premise of these books is that nearly 85% of our present energy supply will go away over this century. That is: fossil carbon energy-coal, gas, oil. Of that 85% only a bit will be left by 2100--we cannot know exactly how much. But most available fossil carbon energy will be gone, the decline starting very soon, with oil. It is unrealistic to speculate that with rising prices much more fossil carbon will be available. It is not a conventional mineral like iron, aluminum or even uranium. There is just not that much of it. Most of it is expensive to get at and of low quality. We cannot mine a mile deep for remaining Texas oil rock, at any price. It would be good to recall that even Great Britain could not mine down to the estimated 4000 feet they needed to for the essential coal that was even known to be there. [1] We will need replacement energy sources.

We cannot escape this need solely by conserving energy, useful and important as that will become. We might, with a great conservation effort, and sacrifice, use maybe two thirds the energy per person that we do now. But saving most of our present energy use, and maintaining a modern civilization, is not a prospect. We simply cannot go on with even a tenth or less of our present fossil carbon energy use. Again, we *will* need replacement energy sources. [2]

Like it or not, one of those replacement energy sources is fissionable elements in the Earth--uranium and thorium. By sheer happenstance the ancient exploding stars that produced the elements we are all made of also made a lot of uranium and thorium that ended up in the crust of the Earth. Those elements are actually fairly common. Thorium is about as abundant as the industrial metal tin. Uranium has even been extracted from seawater. Both elements are very slightly radioactive and contribute to the background dose of radiation we all receive. Both, if they can be forced to break up into lighter nuclei, can release a million or so as much energy by mass as can be got by burning fossil carbon. Thus their utility as energy sources. Measured by energy content rather than mass, recoverable uranium and thorium probably amounts to up to perhaps a hundred times the energy from recoverable fossil carbon. So even uranium and thorium are not inexhaustible. But they will last a long time. [3]

I want to introduce here the present or near term uses of nuclear fission energy and then move on to the details in later chapters. That will also be the appropriate place to look into future fission reactors and how to make them safe against the large scale release of radioactivity in case of an accident.

Electric Power

We are familiar with nuclear power as electricity--about 20% of our delivered electric power is from nuclear plants. And electricity is going to be the main source of useful energy or power after fossil carbon. [4] Right now only four new nuclear plants are under construction in the U.S..

Our present nuclear plants are of two types, "pressurized water reactors" and "boiling water reactors". Both of them require heavy thick pressure vessels that are difficult to construct. [5] Most of these pressure vessels are made abroad, not here at home. We once made all our heavy pressure vessels here. No longer. (The exception is smaller naval ship reactors.)

A typical power reactor might be in the range of one gigawatt averaged delivered electric power (1000 megawatts). This is also about the size of a large coal fired power plant, although most of our coal power plants are smaller. Small reactors, in the range of 100 megawatts of electricity, can be built but are not now common.

The pressing issue for modern electric power reactors is to make them so that they do not endanger the public in the worst, "inconceivable", accident. Future reactors have to be unlike the three reactors at Fukushima that both melted their cores and released a large amount of radiation to the environment. It is folly to think that such an “inconceivable” accident cannot happen again. It has to be prepared for so that widespread land contamination cannot happen again even if the reactor itself is destroyed. I will come back to this requirement later.

Ship Reactors

The United States now has about 80 ships propelled by nuclear reactors. The reactors are small compared to our big electric power plants. The biggest ship reactors, on nuclear carriers, deliver about 100 megawatts of electricity. Submarine reactors are about a third as powerful as carrier reactors.

I mention ship reactors because about a tenth of all oil produced in the world now is used to power ships--mostly running the vast fleet of container vessels on which world trade depends. There are now about 40,000 of these, carrying bulk cargo and general freight. It is not imaginable that there will be this many in 2100 with much less fossil carbon. But some large ships may survive, powered by nuclear reactors. It seems reasonable that smaller ships will exist as well, using synthetic fuels and mostly wind power. [6]

So ship reactors will remain of interest.

Small Reactors for Combined Heat and Power

Heat is a byproduct of all fission power reactors--at present about two thirds of the energy produced from fission is wasted as heat and one third becomes useful electricity. There is interest now in combined heat and power plants, usually using coal or gas as fuel. A typical large such ‘CHP’ plant might produce 60 megawatts of heat, of which 20 megawatts becomes electric power. Essentially all the heat in winter can be used to warm buildings, apart from some losses in moving the heat around. One such installation might heat around 100 buildings, in addition to the electricity it generates. Right now it seems unreasonable to think of using a small nuclear reactor in such an urban CHP plant. This might change later in the century. Interestingly, the scale of such a plant would be around the size of a ship reactor in power.

If such small nuclear plants for electric power and heat are ever to become real, they will have to be inherently safe and quick to replace or refuel. A small reactor, called “EBR-II”, that had inherent safety was built by the Argonne Lab long ago, but it was cooled by the now somewhat unpopular liquid sodium, not pressurized water. There are more modern designs, which have not actually been built.

Reactors for Industrial Process Heat

About twenty percent of all the primary energy we use goes to industry in the form of heat for manufacturing processes--’process heat’. [7] This form of heat becomes most useful above 700 degrees Centigrade (1300 degrees F). This is above the temperature at which Aluminum melts, but well below the temperature at which the steel of your automobile would melt--a much higher 1400 degrees Centigrade or 2500 degrees F. So most process heat is not really at the sort of temperatures we associate with molten metal. But it is quite a bit higher than the temperature of the high pressure water in a modern power reactor. So our usual pressurized water reactors are no good for process heat for industry.

There is a lot of research underway to develop reactors that could produce process heat. They may become important once fossil carbon heat becomes rare, but none have been built yet for this purpose.

A common issue with all modern reactor designs is just that they are designs. Almost none have actually been built and operated. Building large complex devices where design confronts reality is where real world difficulties appear and must be dealt with. This actual practice of building different types of reactors was common during the early evolution of reactors but is uncommon today. The recent, often troubled, history of even slightly novel reactors demonstrates the importance of actual experience. [8]

Chapter 1-Some Nuclear Physics

The size of the things we know, and energy as well, is set by the dimensions of atoms. We understand that objects around us are made of vast numbers of atoms and that atoms are small. The period at the end of a printed sentence might be of the order of a million atoms across. A bacterium visible in a powerful microscope might be of the order of ten thousand atoms across and contain a trillion atoms in its total volume.

The atom of hydrogen, the lightest element, if broken up, becomes a free stable electron with a negative electric charge and a free stable proton with a positive electric charge. (The proton is about two thousand times heavier than the electron and its own diameter is about a hundred thousand times less than the diameter of an atom.) The hydrogen atom itself, like all atoms, is held together by the fundamental electric force--an attractive force for opposite charges, as in hydrogen. [1]

A strange peculiarity of hydrogen that we never hear about is that it exists at all. This is because the proton at hydrogen's center has a partner, almost the same particle of nearly the same mass, but having no electric charge at all and called a neutron. You cannot make an atom with a neutron--being electrically neutral, there is no electric force. A happy accident of nature makes this partner neutron a bit heavier than the proton, just enough heavier so that the neutron itself, if free, breaks up in about a quarter of an hour into its partner proton plus an electron plus another particle, the neutrino. The peculiar part is that there is no fundamental law of nature that determines that the neutron must be heavier than the proton by a little bit. It could be the other way around, with the proton heavier. And then free protons would decay and the truly stable particle would not be a proton but, instead, the neutron. Then our world could not exist--no hydrogen atoms and possibly no other elements at all. [2]

If you bring a neutron and a proton close enough together, about as close as their own diameters, an actual law of nature--the "nuclear force"--causes them to stick.

There is a loss of their joint energy, or mass, when a proton and neutron stick together and this lost energy reduces the mass of the neutron to the point that it *cannot* decay--as long as it is stuck to the proton. The resulting "deuterium nucleus" of a proton and a neutron is stable, and both hydrogen and this deuterium have been around since the big bang.

This nuclear force sticking process can go on. A number of protons can stick together with some number of neutrons, the neutrons cannot decay because of their lost mass, and the nucleus of a heavy element results. [3] Add electrons to balance out the charge of the protons in this nucleus and you have an atom, an element in our periodic table. Most of the atoms we are familiar with are stable, but they have not been around since the big bang. They were made either in stars or in the violent explosions of stars.

The central nuclei of the elements around us are tiny, a hundred thousand times smaller than the atoms themselves. But they are made of many protons and neutrons in which the energy of electrical repulsion of the protons is balanced out by the energetic attraction due to the nuclear force. This force, in a sense, "eats" about one thousandth of the mass of the protons and neutrons, or their energy, and this forms the "binding energy" of nuclei. It is about a thousandth of the equivalent "rest energy" of the neutrons and protons. Turning this around, if a nucleus breaks up as much as about a thousandth of the mass, expressed as energy, can in principle be released. By Einstein's famous $E = mc^2$ the tiny one thousandth of the mass gets multiplied by the enormous square of the speed of light. Result: an enormous energy release.

This energy release varies a lot and is seldom actually a thousandth of the mass--usually it is much less. But it amounts to almost that much in the case of the fission or breakup of the famous Uranium-235. The energy released amounts to the energy equivalent of about one gram (actually closer to 0.3 grams or the mass of an aspirin tablet) of matter per kilogram of Uranium. This is about a hundred million times the chemical energy released by a kilogram of explosive or the burning in air of a kilogram of fossil carbon. Or: a kilogram of completely fissioned uranium releases as much energy as about 100,000 tons of explosive or fossil carbon.

This is rough background. How does this fission process that we use for power work?

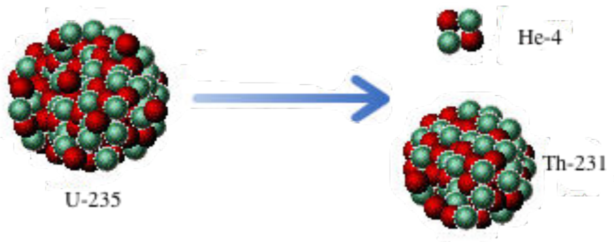
Fission is rare in nature. The only element that exists in nature that fissions easily is Uranium-235, and that does not actually fission without help. And natural uranium is mostly the isotope Uranium-238 (about 99.3%) that does break up or decay, but very slowly, half of any amount of it only decays in a time of 4.5 billion years, about the age of the earth. Uranium-238 does not decay by fission. It is very hard to get Uranium-238 to fission (it can be done!), but it is possible to get Uranium-235 to fission, although it usually does not--it decays normally, much like Uranium-238. [4]

Uranium and Thorium decay with time mostly because all the heaviest elements contain too many neutrons. Even lead, which does not decay at all, contains about three neutrons for every two protons. [5] Much beyond lead, there are just too many neutrons and the nucleus becomes unstable. Interestingly, most do not just spit out the extra neutrons, unless there are way too many of them, but instead, if undisturbed, they spit out He-4 which has two protons and two neutrons.

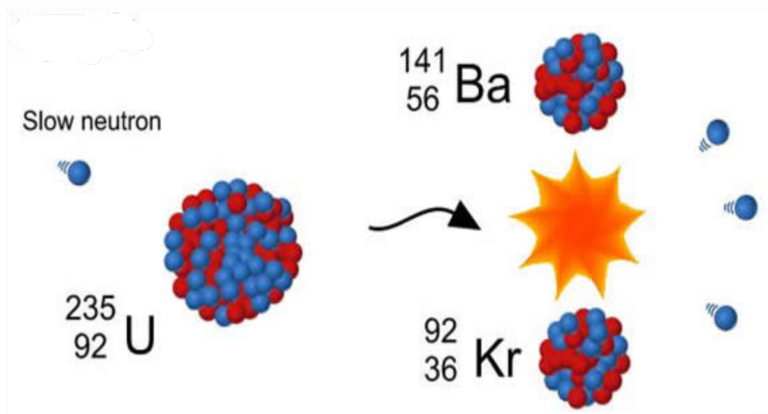
The uranium and thorium that are useful to us were made in the blast of neutrons from supernovae, and have not yet decayed away. It is their extra neutrons that make them useful, and it is neutrons that play such a big role in reactor physics.

Uranium-238 is the heaviest of the natural nuclei that is used in reactors, but it is possible to make heavier nuclei by adding neutrons; this happens in reactors. These heavier elements just decay faster than, say Uranium-235. The heavier nuclei are called “transuranics”. We will see that they are both useful in one sense and a problem as well.

Here are some pictures showing how decays and fission work. Normally, Uranium-235 decays this way, very slowly, into lighter Thorium-231 and Helium-4.



But when the U-235 is hit with a neutron, usually a slowly moving one, it breaks up instantly into two nuclei plus some number of extra neutrons (from stackex-change.com)

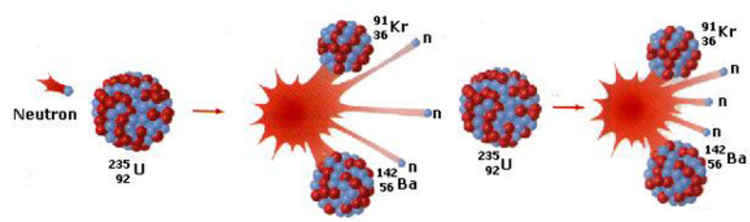


(one possible pair of fission fragments)

In a nuclear reactor, those produced neutrons are moving rapidly and can leave the area quickly. If they did that, pretty much nothing would happen. In a bomb--not a reactor--an often compressed sphere of almost pure Uranium-235 is so dense that the fast neutrons cannot get out easily. They lead to more fissions of the uranium, up to two or three per original fission. This is the “chain reaction” that leads to almost all the uranium fissioning quickly and releasing enormous energy.

Nuclear reactors typically contain only 4% or so Uranium-235 and there is no real chain reaction that can lead to a bomb-like nuclear explosion. But when a reactor starts up, it is possible to use the extra neutrons to increase the reaction rate up to what is needed.

Water, or other carefully chosen stuff, is present in a nuclear reactor to slow the neutrons down, so that they can react despite the low level of Uranium-235. On average in a running reactor, several neutrons stay around long enough so that one of them can go on to cause one new fission for each old one, roughly as pictured here. Notice that on average only *one* neutron goes on to fission another neutron--two of them are lost or go on to cause other reactions:



Of course, the trick with running a reactor is to get the total number of fissions per second up to create useful heat and then hold the fission reactions at that level.

So not all of the neutrons that come out when uranium breaks up go to cause other uranium nuclei to break up. Occasionally, one of those neutrons will hit a Uranium-238 nucleus, changing it to Uranium-239 this way

$$n + U\text{-}238 \rightarrow U\text{-}239$$

At this point, things get a bit complicated. That extra neutron inside the Uranium-239 isn't very stuck, so a neutron in the Uranium-239 *can* decay in a few minutes to a proton plus an electron and a neutrino Both the electron and neutrino leave the nucleus; the stuck proton stays behind. The nucleus still has 239 neutrons plus protons, but now one of the neutrons has become a proton. At this point it is a new element, called Neptunium-239. There are still too many lightly stuck neutrons so this happens again and the result is Plutonium-239.

This Plutonium-239, if undisturbed, will decay slowly over about twenty thousand years by emitting a Helium-4 nucleus (just as Uranium-238 and Uranium-235 do if undisturbed). So it is radioactive--much more so than either Uranium-235 or Uranium-238. It can also fission just like Uranium-235 if hit by a neutron. There are other elements created this way that are heavy and very radioactive, with long lifetimes.

The Plutonium and other heavy elements created over time in a reactor can be extracted from old fuel to recycle into new fuel. (A typical reactor ends up burning most of its initial 4% Uranium-235 and produces, as a result, about 1% Plutonium-239 and other similar heavy elements.) Of course, the Plutonium can also be extracted and concentrated to make a bomb, so reactors can indirectly be used to make bombs.

If the Plutonium and other heavy elements are left in the old fuel from a reactor, their long lifetime means that the radioactive waste is dangerous for a very long time--a few thousand years. The nuclei labelled “fission fragments” decay much faster than the heavy elements and are gone in decades to a century or so.

The heavy radioactive elements are a result of “extra” neutrons produced in the reactor by the fission of Uranium-235. There is another essential feature, though. When the Uranium breaks up, it results in a large energy release. This energy is the kinetic energy of the two pieces resulting from the fission or breakup of the Uranium. This is where the heat comes from to run the reactor. But the two pieces from when Uranium-235 fission are those the fission fragments just mentioned and shown in the figures. The original Uranium nucleus had too many neutrons. The two resulting pieces have “even more too many” neutrons. Normal stable light elements (not the heavy neutron rich ones I have been talking about) have roughly as many neutrons as protons. These pieces, although light, do not--compared to equally massive light elements they have *way* too many neutrons--about two to five neutrons too many. They do one of two things: some of them spit out a “delayed” neutron that goes on in the reactor to produce fission; the other thing is, those extra neutrons can decay *inside* the nucleus to a proton that remains stuck in the nucleus and an electron and neutrino. This produces extra heat. These overly neutron rich elements decay in time a bit like neutrons themselves--in minutes, hours or days. As mentioned, some decay slowly enough so that it takes a century or two for the elements to loose all their radioactivity. During that time, they still produce heat. If the fission reactions in a reactor are shut off, these elements are still there and will still produce heat inside the reactor. The reactor is not quite off--this heat has to be removed.

Putting this together, the picture would look like this, in very rough terms:

The reactor produces a lot of heat from the fission or breakup. The products of the breakup are radioactive and so also release some heat--much less than from the fission, but still heat. The extra neutrons released in the breakup produce Plutonium and other heavy elements. Those can be recycled as fuel or used to make fission bombs.

If the heavy Plutonium-like elements are removed from old used or “spent” fuel, the remaining radioactivity decays in that century or so above. If the Plutonium-like elements are left in the spent fuel, it remains radioactive for a long time. This is what we do now--just store the spent fuel whole, as it comes out of the reactor.

This is just a short account of the nuclear physics in a reactor. The physics is complicated, but the result is heat that can be turned into useful energy. This heat is now exploited in two types of reactors, the ones mentioned earlier--pressurized water reactors and boiling water reactors. I turn to those now.

Chapter 2-Pressurized and Boiling Water Reactors in the U.S.

Reactors make heat in a ‘core’ that contains the fissioning uranium. To exploit this heat it has to be transferred somehow so it can be used to make electricity. The core of a reactor is not large--a meter or so on a side. The core is contained inside a ‘pressure vessel’ that contains water. The water both slows down the fission neutrons to make more fissions and it also absorbs the fission heat. These pressure vessels are much larger than the core.

Our reactors are of two types--one, the boiling water reactor or BWR, uses steam directly from boiling water in the pressure vessel to run electric power turbines; the other, the pressurized water reactor or PWR, keeps the water pressurized and *not* boiling, because of the high pressure, and then transfers the heat in the water to a second loop where additional water *is* boiled and then this secondary steam is fed to a turbine attached to a generator to make electricity. Boiling water reactor power plants are much simpler than PWRs, but there are disadvantages. One problem is that neutrons in the reactor convert some of the oxygen in the water to radioactive nitrogen. So the steam, if used directly, contains some radioactivity--not much, and it decays quickly. But it does create a problem. [1]

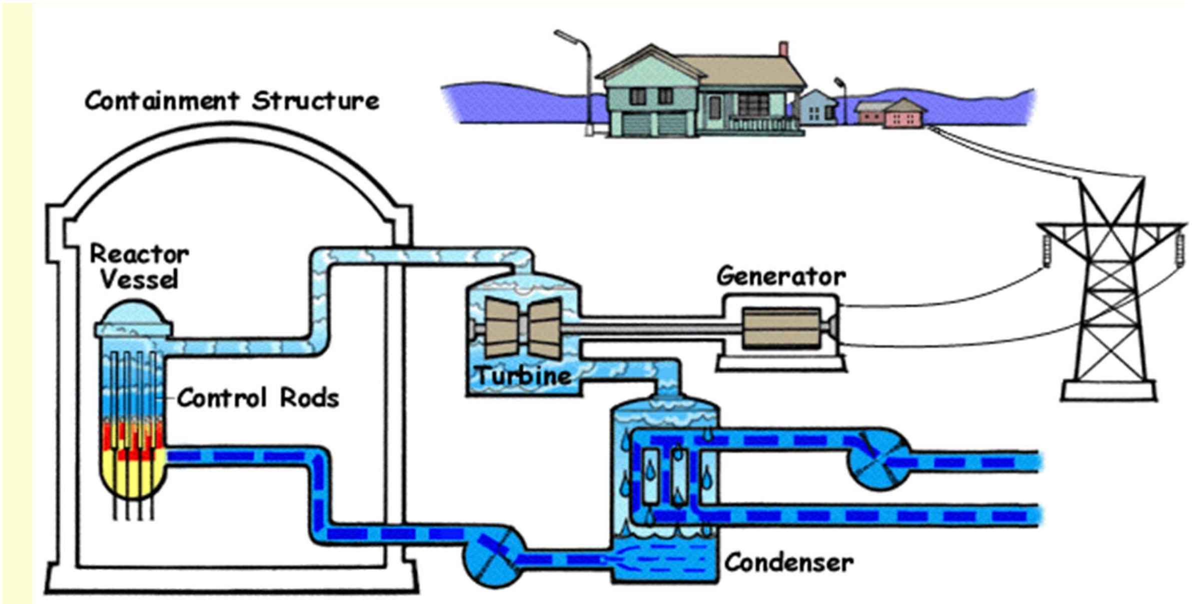
With some imagination, we can see why these reactors--both types--contain water under high pressure. Think of the steam coming off of a rapidly boiling swimming pool at normal atmospheric pressure. There is a lot of steam but it cannot produce much useful energy, it just blows off in a large volume of air. If, instead, the volume is small and the pressure is very high, produced steam can be both hot and very dense. A common pressure cooker shows this--it works by increasing both the temperature and the steam pressure. There is a lot of steam, and heat energy, in a small volume at a high pressure. Running high pressure steam from a reactor pressure vessel directly through a turbine can produce a lot of electricity in the attached generator. This would then be a boiling water reactor. A pressurized water reactor is quite different, as mentioned above. It has to keep the water in it from boiling--hence at higher pressure. Circulating this high pressure hot water through a boiler can then produce the steam that a steam turbine uses. So there are two loops, one from the reactor to the boiler and a second steam loop from the boiler to turbines. The result is that a pressurized water reactor vessel needs to operate at about twice the pressure of a boiling water reactor, or about 150 times the pressure of our atmosphere for a PWR. It also needs the secondary steam boiler, which is complex and failure prone. (These boilers are full of narrow tubes containing steam at high pressure.)

It is quite common to hear of problems at a nuclear power plant. Most of these problems are due to failures in the boiler; the release of radioactivity is small. It is similar to the radioactivity of the steam from a BWR. Because of their complexity, boilers need to be replaced a couple of times during the life of the PWR.

Both reactor types, to produce acceptable power, also need to operate at very high temperature--about two hundred degrees Centigrade over the normal temperature of steam of 100 degrees C. Both types of pressure vessels containing the reactor core need large thick--six to eight inches--steel pressure vessels that are difficult to make. At higher pressures, they can be tricky to make. So far, none of these large pressure vessels has failed by cracking into pieces from the internal force.

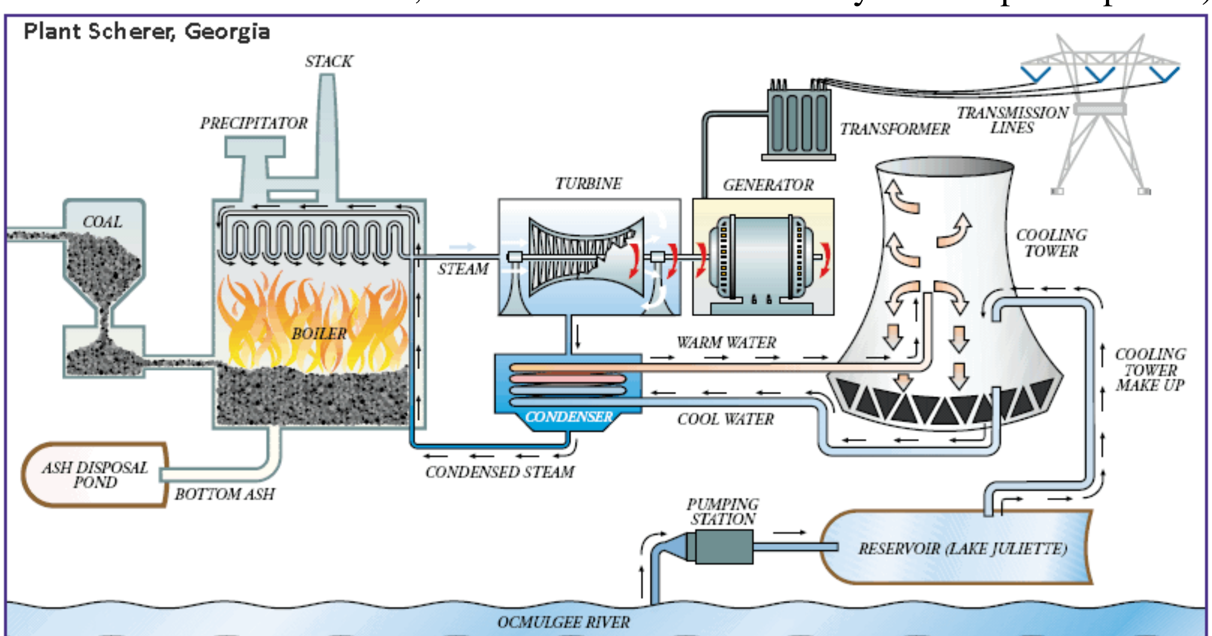
More on BWRs

To keep this simple, I will first show some more details for BWRs, despite the fact that only about a third of U.S. reactors are of this type. Here is a Nuclear Regulatory Commission (NRC) conceptual image of such a plant



Public domain image by US NRC.

The nuclear part of the plant-the reactor pressure vessel and its core--is inside the "containment structure" for safety--the rest looks very much like a large coal fired power plant--here is an image of a coal plant from water.usgs.gov that shows more detail on the equipment used to condense the steam from the turbines back into water that can again be fed into the boiler. (This part, where the heat from the condensed water is extracted, is also similar to that in many nuclear power plants.)



Credit: Georgia Power

The large difference in a BWR outside the reactor building is the need to deal with the low level of radioactivity in the water and the steam into the turbines. This radioactivity decays quickly (seconds to minutes) and is mostly gone by the time the condensed water is fed back into the reactor.

Remember the reasons why we are interested in the nuclear plant. By mass, it uses about a million times less material (coal versus uranium). The coal fired plant has a large amount of chemically active solid waste, plus carbon dioxide gas. The nuclear plant has much less, but radioactive, waste. The nuclear plant emits no or very little of the carbon dioxide that is a climate concern.

So the real complex stuff that concerns us is inside the reactor building-the reactor itself and the water and steam piping. Here is a very simplified image of a BWR internals, emphasizing the core that contains the nuclear material: [2]

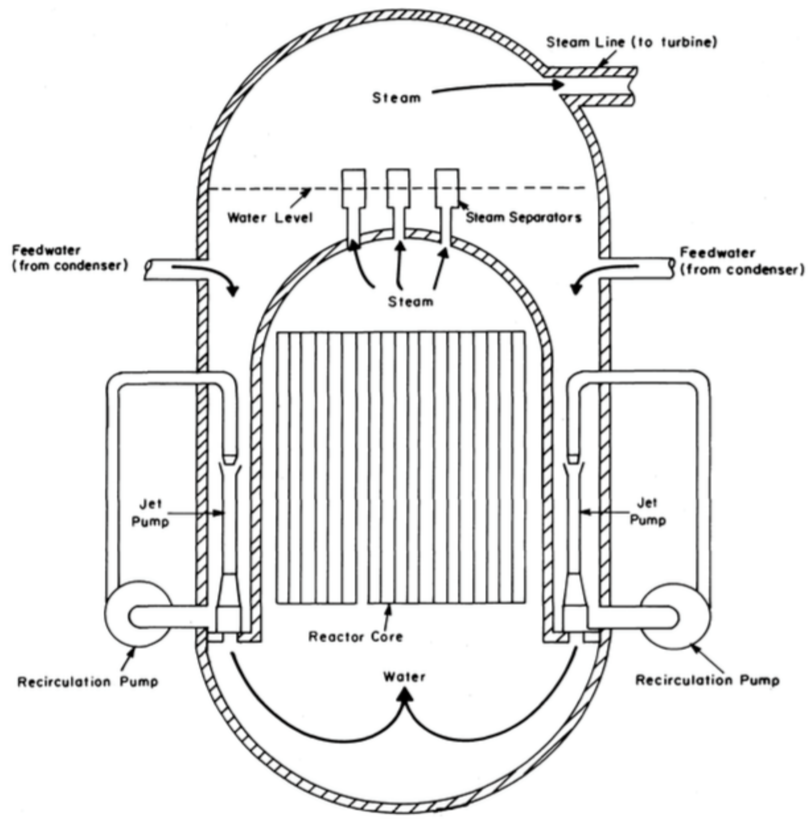


Figure 1-9.
Schematic Arrangement of BWR NSSS.

A nice feature of BWRs, mentioned earlier, is that this is pretty much the concept of the entire reactor system. Steam comes out and is directly sent thru a turbine to make electric power. This pressure vessel is inside a "containment" that is supposed to keep radioactivity out of the environment in normal operation and even in an accident. It was the containment that failed to do its job at Fukushima after three reactor cores melted (a fourth reactor was offline when the accident happened). I will come to containments in the next chapter.

The reactor core contains fuel rods that contain the fuel in the form of small pellets that are about one centimeter by one and a half centimeters. The pellets are slightly enriched uranium and just fit inside fuel tubes. [3] It's clear that for such a huge device, there must be an enormous number of these pellets and an enormous number of the hollow tubes containing the pellets. This is unavoidable, given that water has to flow thru the core to both slow down the neutrons and carry away heat. The individual tubes full of pellets, somewhat over a centimeter in diameter, are packaged into “fuel assemblies” and a reactor might have hundreds of these assemblies and, in total, many thousands of rods containing the fuel pellets. [4] There might be many millions of pellets in a reactor core. These pellets are not uranium metal--they are uranium oxide, which has a very high melting point. So the pellets are very good at keeping most radioactivity locked inside, even in an accident.

Remember that the idea of a nuclear reactor is that each uranium nucleus that breaks up releases a number of neutrons that go on to break up further uranium nuclei. This can lead to a chain reaction. But in a reactor each breakup should only lead to *one* other breakup. That way there is a steady number of uranium nucleus breakups each second--steady power put out by the reactor. So on average only *one* of the neutrons from a breakup leads to another breakup. The remaining neutrons have to be either lost from the core or soaked up somehow. This soaking up of extra unwanted neutrons is done by inserting rods into the reactor core that absorb neutrons. Adjusting these “control rods” adjusts the neutrons in the core and thus the power produced from the reactor. When the rods are fully pushed into the core, the fission reaction stops completely--there is no excess of neutrons that can carry the reaction on. Usually shutting down the nuclear reactions is done slowly, but in an emergency the fission reactions can be stopped in a second or so.

The picture above shows water rising through the core, where it is heated and emerges as a mix of steam and hot water droplets. This also shows “steam separators” which separate the steam from the water droplets so that only steam goes out to the turbine that makes electric power. In a real reactor, these steam separators can get quite complicated because the water has to drop back into the water level of the reactor. The whole assembly that cleans the water droplets out of the steam can take up more than a third of the whole reactor vessel. But it is just a static collection of parts. The presence of this steam separation and cleaning assembly does mean that the reactor core has to have its control rods coming out the *bottom* of the reactor pressure vessel. [5]

Every year or two the used up uranium in the core has to be replaced. (Remember that only about a twentieth of the uranium is the fissionable Uranium-235.) This is done by unbolting the reactor lid dome, lifting out the steam cleaning assembly, and pulling out and replacing the individual fuel assemblies, each containing its multitude of pellet containing tubes. The old assemblies are very radioactive, the new ones hardly radioactive at all. This is because the old assemblies contain all the pellets with their load of radioactive decay products from the fission reaction.

More on PWRs

Pressurized water reactors differ from BWRs in several ways, as I indicated earlier. The pressure vessel is full of water only at high temperature and pressure--no steam at all. The steam is produced in a separate set of "steam generators" that are usually inside the containment. Most U.S. power reactors are PWRs (about two thirds) because the technology was very well developed from early naval reactors. There is less stuff inside the pressure vessel, compared to a BWR. The pressure vessel is smaller and at about twice the pressure of a BWR. So the core sits higher up and the control rods emerge from the top of the reactor. Because the steam generators are separate and also in the containment, the whole arrangement looks very complicated [6] In fact, the really complicated part, compared to a BWR, is the two to four steam generators that each contain many thousands of small tubes with high pressure "primary coolant water" from the reactor that produces steam from a secondary water "loop"; this steam then goes to the turbines. The advantage of this is that the very slightly radioactive primary water from the reactor is separated from the secondary and nonradioactive steam that goes to the turbine. The disadvantage is that these steam generators and their thousands of tubes are twenty or so meters tall and each weigh hundreds of tons. They are also prone to failure and have to be replaced after 15-20 years. So a power reactor that can last 40-60 years can easily go thru three sets of steam generators.

It is a bit of an irony that most news stories about trouble at a nuclear power plant are due to failures in these steam generators, not failures in the reactor itself. Steam generator failures--leaks of primary coolant water--lead to the same sort of radioactivity that is a normal feature of BWRs. Steam generator failures in a PWR are not very different from steam generator failures in a coal fired power plant, which also involve a huge number of small tubes containing water that is turned to steam in the tubes themselves. In both cases, the total length of all the tubes can easily reach several hundred kilometers, just in a complex mass. The images of the interior of a nuclear plant steam generator look a bit like a plumber's nightmare. But there is really no danger from them.

The real concern with both BWRs and PWRs is some sort of failure in the reactor pressure vessel itself, with its core of fissioning uranium and the highly radioactive byproducts of that fission.

Chapter 3-Accidents and Radiation Dangers

Large thermal power plants fail, sometimes in a spectacular or horrifying way. Coal fired power plants are not immune. We seldom hear of such failures unless there is a lawsuit or people die. A famous example is the coal slurry fired Mohave Power Station where a ruptured large high pressure steam line killed six people. The accident even has its own Wikipedia page. The failure of a hydroelectric plant can be epochal, especially if the dam itself collapses. But hydroelectric water turbine failures have killed many. Perhaps the most infamous is the Sayano-Shushenskaya power station disaster with its 75 killed--another incident with its own Wikipedia page.

Much of a nuclear power plant is similar to a coal fired power plant and can suffer similar failures--boiler tubes, steam lines, turbines and the like. But there is an essential difference between a coal fired power plant and a nuclear plant. A coal fired plant may take time to shut off in an accident because of burning coal and stored heat energy, but it will soon stop entirely and go cold. This is not true of nuclear power plants. An operating plant generates most of its heat energy from fission--but not all of the energy in the core arises this way. The neutron-rich products of fission breakup also produce heat. It is easy to stop the fission heat production by inserting the control rods. But the *fission product heat* continues on until the elements decay away. This can take a long time.

At reactor shutdown, with fission energy stopped, there is still about six percent of the heat generation that the reactor core produced just before it was shut down. This is the heat energy production by the fission products mentioned above. This six percent declines to a half percent after a day (a tenth as much), 0.2% after a week and 0.05% after a year. After a year or two, the extracted fuel can be stored permanently. Actually, when reactors are shut down for maintenance, after a few days, the temperature is about 100 degrees C at atmospheric pressure and the pumped water flow to remove the residual heat is very low, a few hundred kilo-grams per second.

The problem is that if the reactor is generating a usual 3000 megawatts of heat right before shutdown, it *still produces 200 megawatts* of decay heat right after shutdown and 15 megawatts after a day

Right after a reactor is shut down, it still generates enough heat to turn about 80 kilograms of water to steam every second. This is about what a person weighs--it does not seem like much, at least per second. But over an hour this amounts to *about 150 tons* of water at the average decay heat power of about 3%. A typical reactor vessel contains about this amount of water, 150 tons or so. If the reactor pumps are working and the reactor core is underwater, this is not a problem at all--at full power the reactor has to remove about twenty times as much heat. A day after shutdown, this decay heat is about 15 times less than it was at shutdown, so the need to remove heat goes down quite a bit. The problem is the first couple of hours after shutdown there is a *lot* of decay heat generated and this heat has to be efficiently removed.

An accident happens when, in these critical first few hours, the core is not covered with water so the decay heat can not either be absorbed by the water and pumped away or boiled off. Then the heat goes into the metal structure of the uncovered core itself. Here is where some heat physics leads to trouble. If a given amount of heat warms a kilogram of water by *one degree*, then the same amount of heat will warm reactor metals by *fifteen degrees*. The uncovered reactor core, uranium and metal structure, heats up very fast and begins to melt. Very unpleasant consequences result.

One thing this means is that with enough water in the reactor it is possible to get the decay heat out even with much weaker pumps, and less water, than the reactor normally needs to operate. It is not easy in an emergency situation to get enough water into a reactor vessel to cool the shut down core, but it is possible. A key is that either the operators have to know the water level in the reactor vessel, and have some working pumps, or enough water has to flood the vessel automatically if there are no working pumps. The problem of cooling the core then becomes much less day by day.

However, if a reactor core has melted it becomes a lump of molten material inside the pressure vessel that is now hard to cool. The molten lump might stay hot long enough to melt through even the thick pressure vessel or even beyond. It does not cool off entirely for quite a while because the molten material is still generating radioactive heat. But if the pressure vessel is intact and even some water can be pumped in, it may be possible to cool even the congealed core material because of its declining heat production. After a year or so the heat generation in the congealed core will be down to tens of watts per kilogram and one can think about what to do next.

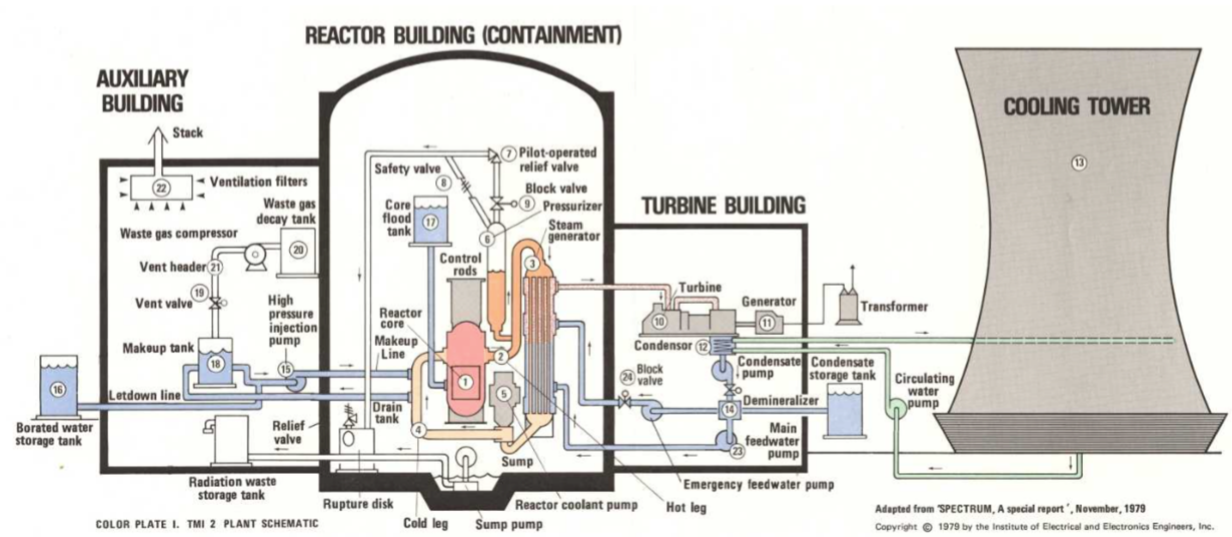
The following is a very brief, and somewhat subjective, description of specific accidents; there is a lot of material available on the Web and I do not want to repeat it. I avoid Chernobyl because our reactors are not of this particularly dangerous type.

Three Mile Island

From the beginning of the era of commercial nuclear power, the great fear was of a dramatic quick loss of water cooling, perhaps due to a large cooling pipe break. [1]Automatic systems were developed to cool off the decay heat of the core in this case--“emergency core cooling”. What was not imagined was a sequence of small failures that led to confusion and a loss of the ability to cool a reactor core that was heating up due to an unrecognized loss of cooling water. That was what happened at Three Mile Island reactor number 2. [2]

It is easy to think of accidents as due only to an equipment failure, or a series of them, or perhaps some outside disaster that it is impossible to cope with. The great service of the “Kemeny Report” of the previous note is that nuclear accidents are much more complex than that. The Three Mile Island accident was in large part a management and conceptual failure by the builders, the operating company, and the Nuclear Regulatory Commission (NRC). Without these interconnected failures the actual equipment failures, and there were many, could not have produced the disaster that resulted. If there is a larger lesson to the TMI accident it is that reducing the likelihood of equipment failures is far from enough--nuclear accidents are system failures.

That said, what happened at TMI? Here is a diagram of the plant that I have found useful:



(The numbers refer to the “Rogovin Report” in the notes. This image is derived from a report in the IEEE magazine “Spectrum”[3])

Here is a short account of how the accident progressed.

The first event was the automatic shutoff of the “Condensate Pump” in the diagram. The cooling tower provides outside water to condense the steam that goes from the steam generator thru the turbines. The condensate pump pumps this condensed water thru a system that removes minerals, and into the main water line. This system likely failed, number 14, causing the condensate pump to shut off. When this happened, the main pump that moved this water thru the steam generator had to shut off as well, number 23. With no water flowing thru the steam generator, the turbines then automatically shut off, number 10. At this point, the control rods were pushed into the reactor core, number 1, shutting off the fission reaction--94% of the heat generation stopped at this time. This left 6% of the heat from the core continuing, due to decay of the fission products in the core. These automatic processes took about 8 seconds. The pump shutdown and reactor shutdown had happened before.

As a consequence of the shutoff, the stored heat in the reactor cooling water caused the pressure to rise, opening the pilot valve, number 7. This valve dumps reactor water to a waste tank until the reactor water pressure drops. When the pressure drops enough, the valve is supposed to close. But it did not, and this initiated the accident. If the operators had known the valve was stuck open, they would have closed a valve, number 9, in line with it. But they did not know because the control panel instrument led them to think that the pilot valve had closed. Over about the next hour and a half, about a third of the reactor vessel water left thru this stuck open valve.

This was the key to the later core melting. This was a pressurized water reactor; it was supposed to be full of water at all times. But with water lost, the reactor cooling loop got steam in it--mostly in the reactor vessel as the water level dropped and the rest of the reactor vessel filled with steam. But steam bubbles developed elsewhere as well. Over the next few hours, this steam blockage process involved a lot of the reactor instrumentation and the operators were left dealing with an unintelligible system. They could not figure out what was going on.

About six minutes into the accident, another automatic system started up. The pressure had dropped so far that this emergency core cooling system began to pump water into the reactor vessel. This system was present to deal with a sudden break in a main cooling pipe. It could pump enough water to absorb the decay heat produced just after the shutdown. Not knowing that the reactor was low on water, despite the low pressure, the operators reduced the rate at which these pumps moved water into the core. More water continued to be lost, more steam filled the system and confusion increased.

This emergency core cooling system only works if the main coolant pumps operate, pumping water through the steam generators so the heat can be removed.

(Even this part briefly malfunctioned, but the problem was quickly fixed.) Alas, the system had steam in it and the pumps vibrated and were gradually shut off. The operators probably thought that there was enough water to cover the core and there was little enough heat so that convection could remove it. This was wrong, there was no pumping of the water thru the core to the heat exchangers and water was still being lost thru the stuck valve. Already too late, the additional valve was closed and the water loss stopped. But the core was uncovered and melting. [4] The pumps were started up a couple of times and eventually the cooling stopped the core melting. It never melted to the point where it could burn through the bottom of the reactor vessel. Eventually it congealed and solidified and could be removed over a period of years at great cost.

With the core melting going on, radiation was released into the containment and even a neighboring building. Most of this was radioactive Xenon, which can be dispersed into the atmosphere without great harm. Fortunately, the core pellets did not melt, so there was only a small release of really dangerous stuff--radioactive Iodine and Cesium. (They are mostly in the fuel pellets, Xenon leaks out.) There was no net danger to the public. This lack of destruction of the fuel was very important. Both Chernobyl and Fukushima released huge amounts of dangerous radioactivity because of the destruction of the fuel itself.

The report on this accident by the "Kemeny Commission" did not blame the operators. It happened that several of them were from the nuclear division of the U.S. Navy. They were not neophytes. The failure was a system failure--at the builders, the operating company and the NRC. The instrumentation was not only inadequate to this sort of accident, it was actively misleading. Among other failings, there was no instrumentation that told the operators the water level in the pressure vessel! They had to guess from a vast array of instruments showing other, sometimes irrelevant, information. Many of the actions they took were in exact agreement with their training. But the training was very wrong for an emergency. They had been told to protect the main pumps, whose loss would be minor compared to a melted core. The system failings were very numerous, detailed in the report.

Three Mile Island would have been a vastly more serious accident if the electric pumps to drive cooling water to the damaged core had not been available or had been left turned off. We were fortunate. Whether the lessons of TMI were properly learned is a hard question to answer.

For me, reading the Kemeny Commission report now, after Fukushima, and also reading the NRC "Ten Year Response" to the Kemeny Commission is worrying. [5] It is hard to believe that nuclear power in this nation can play a significant role after fossil carbon if the present configuration of industry and regulators continues. The risk to the public is simply too great. Maybe we need to revisit the Kemeny Commission report and actually, thirty five years later, implement its key recommendations-at the very least. New and safer reactors are good, a robust system to operate and oversee them is critical.

That Three Mile Island was a broad linked set of system failures should force us to realize that failures of this sort are not just in the nuclear power industry. TMI was one of the the most carefully analyzed system failures. We should beware of other and newer types of system failure as we move beyond fossil carbon energy. The TMI accident--or even Fukushima--could be dwarfed by future unexpected failures, toward the end of the century, that hit a big part of our energy infrastructure.

Fukushima

There were six reactors at Fukushima, all of the boiling water type. At the time of the earthquake and tsunami, four of them were shut off. Number four had its core fuel removed and stored in an overfull storage pool, which caused later problems. Numbers five and six were shut down, but still had to be cooled because of the residual heat generation of all shut down reactors. The post tsunami problems of these last two were minor and I will skip them. [6]

The problem reactors were numbers 1, 2 and 3. The first was an older and lower power design, 2 and 3 were more recent. (Emergency core cooling was done differently in reactor 1 than in 2 and 3.) Boiling water reactors send steam from the reactor directly to turbines to generate electricity, unlike the pressurized water reactor at TMI. If the BWR is shut down in an emergency, the main steam line to the turbines is shut off, to keep radioactive water out of them. There is an alternate steam line directly to the water condensers. [7] So, if everything is working normally, the reactor can be cooled down through this alternate line without the turbines generating electricity.

The Richter 9.0 earthquake acceleration at Fukushima was about 25% beyond the plant design limit. Apart from much debris that caused later problems, it is likely that the earthquake alone would have been survivable. The reactors shut down correctly and the steam line to the turbines was shut off. The earthquake cut off the external electric power from the power grid, but the plant emergency diesel generators switched on as they were supposed to do. There was also DC power from batteries to operate valves and instruments. The emergency core cooling turned on. This is all automatic. [8]

About 50 minutes after the earthquake, the main tsunami wave, about 14 meters high (about 45 feet) flooded the area. There had been advance planning, and a seawall, for a tsunami, but it was assumed that it would only be 6 meters high. The plants might have been able to withstand almost 10 meters, but what happened was that almost all the backup emergency power--diesel generators, batteries and the electrical panels and power distribution--ended up being 4 meters under water. Most of the equipment was damaged beyond use. (Some batteries for reactor 3 survived, as did batteries and a diesel generator for reactor 6.) The tsunami also destroyed the diesel fuel tanks on the site. At that point there was no AC power from outside the site and no power for most of the reactors. The small amount of battery DC power that was available did not much affect events.

The tsunami also damaged, and made unusable, the main water pumps that moved cooling seawater to the large unit that condensed the steam from the reactors. The result of that was that, lacking these pumps, even with electric power, the residual heat from the reactors could not be dumped to the ocean. It is not clear how the Fukushima reactors would have fared if there had been backup diesel power, given the damage to these critical pumps.

Reactors 1-3 were doomed and the overfull used fuel pool for reactor 4 was endangered as well. This progressed toward disaster; the operators on site could mitigate events, but it is hard to imagine how they could have stopped the reactor cores melting at least partially.

Reactors 1 and 2 had no power at all, and the operators were without instruments--they could not even tell what was going on. They could only estimate that, given the heating rate in the reactors, the cores would be uncovered about six hours into the accident. [9] This water loss would happen, without damaging the pressure vessels, because of the existence of mechanical pressure relief valves. About six hours in, the operators measured high radiation levels in the reactor 1 building. It was likely that there was already core damage to reactor 1, so that automatic cooling had not worked properly. About 11 hours in, a team got into the reactor 2 building to check on its automatic emergency cooling system, which seemed to be working. [10] It was no longer likely that the reactor 2 core was uncovered.

All along, the core cooling systems, such as they were with no external power, had to operate at the high pressure of the reactor. They could use extra water stored in the containment, but only for a time. Fukushima had fire trucks with water pumps, but they could only pump at about a tenth of the full pressure in the reactors. So the reactors had to be depressurized to use the fire truck pumps. About 12 hours in, the pressure dropped to the point where the fire truck pumps could work, feeding cooling water into reactor 1. This reactor containment was pressurized and leaking and the operators vented it to the atmosphere to keep the pressure down.

About 24 hours in, give or take a few hours, two things happened. The emergency-cooling system for reactor 3, which had some DC power for instruments and valves, began giving trouble. Remember, there was only so much water available in the containment. The system continued to work, but with difficulties. The second thing that happened was a hydrogen gas explosion in the reactor 1 building. The core was damaged and heat driven chemical reactions generated the hydrogen; also, the reactor pressure vessel was plainly leaking--that is where they hydrogen gas had to come from.

About a day and a half into the accident, a combination of events made it impossible to cool the reactor 3 core. Also, it was not possible to depressurize the reactor to use fire truck pumps to inject cooling water. The reactor was eventually depressurized--this was due to scavenged auto batteries powering the valves.
As the accident progressed, there were hydrogen explosions due to leakage from the pressure vessels in both reactor 1 and reactor 3.

With all three reactors eventually at atmospheric pressure, fire truck pumps can flood the pressure vessels with water, up to about 80 tons per hour. [11] This is enough to cool the now melted core, by boiling off the water, *if* it has not melted through the bottom of the pressure vessel. If it has melted thru, the water ends up in the containment with the core *if* the containment is intact. At Fukushima, the containments all seem to have been damaged. After about a week, the radiation heat had declined enough that not much cooling water is needed. We will not know the actual conditions of the reactor pressure vessels and containment for a long time.

Yet another unexpected by product of this accident was the presence of huge amounts of cooling water flushed thru the reactors. It became radioactive. Much of this water got out of the damaged containments and is an ongoing problem at Fukushima.

From the release of radioactive Cesium, Iodine and Strontium among other elements, we know that the fuel in all three reactors was very damaged. Since the containments were damaged and sometimes even vented to outside, much of this radiation got out. This was the real Fukushima disaster. The total radiation deposited outside the reactors was about a tenth of that at Chernobyl and most of it went out to sea. So far, nobody has been killed by the radiation, although over a thousand people died during the evacuation that the radiation release caused.

The public health effect of the radiation was probably not too serious. The average radiation dose was about three times the dose everyone gets from background radiation having nothing to do with the accident. [12] The major concern is thyroid damage in children due to Iodine-131. This isotope has a half life of 8 days, but can still be dangerous. Estimated overall health effects were examined by the World Health Organization and considered not serious, although about a hundred premature cancer deaths have been projected, using an assumption that has been questioned. [13]

My own view is that the health effects are a secondary issue. What has happened is widespread land contamination--many thousands of square kilometers--by radioactive isotopes, mainly Cesium-137 that has a half life of about 30 years. Unfortunately, this is often lumped together with Cesium-134 that has a much shorter half life, so the actual troubling Cesium-137 contamination is unclear, to me at least. The problem is that, in the old units I am used to, the contamination (including the 134 isotope) amounts to about 15 microcuries per square meter and up. [14] This is a lot--physics demonstrations that I am familiar with calmly use 1-5 microcurie sources, but not per square meter over a land area of several thousand square kilometers, as at Fukushima. Even reducing this minimum contamination by a factor ten would take over a century of radioactive decay. This sort of public release of radiation should never happen in the U.S. [15]

It is still an open question whether or not our hundred nuclear reactors are really safe against a Fukushima level disaster. [16] If nuclear power is to have a future in America, the public needs certainty that Fukushima levels of radioactivity release can not happen here. Mere calculations of reactor failure rates do not qualify as reassurance. We need to be *certain*.

Chapter 4-Safer Reactors

The key lesson of Fukushima and its older reactors was that if all electric power is lost for many days--AC from the grid and backup generators and DC from local batteries--it is almost impossible to prevent a core meltdown. Heroic efforts might, at best, mitigate the meltdown to the point that the reactor containment is not breached by the molten core, or at least make the breach minor. Then it *might* be possible to prevent a major release of radioactivity from the fuel to the environment. This failed at Fukushima, of course. Also, remember that the TMI accident went on a long time due to equipment failures and operator confusion. There was electric power the whole time. If the situation had progressed a few more hours, it is possible that the core would have melted out of the main steel pressure vessel into the containment.

It is unclear if modifications to the Fukushima containments might have at least reduced emissions. Containment passive filtered vent systems are now common on European reactors. They do not require either power or operator action. I believe that one of the original ones, in Sweden, was introduced specifically on a Fukushima design reactor because of meltdown concerns. It is bizarre that neither U.S. nor Japanese reactors had passive filtered vents. We still do not. [1]

After Fukushima there was pressure to make the existing hundred reactors in the U.S.safer--particularly those similar to the Fukushima reactors. The big concern is a Fukushima-like "station blackout" where all power is lost. Not much has actually happened to mitigate such a disaster; you can read the story in the Union of Concerned Scientists report mentioned earlier.

Our existing reactors are vulnerable.

For example, there is much discussion about making reactor containments safe against a deliberate aircraft strike. But anyone attacking a nuclear power plant need no aircraft. If backup AC generators and DC power are in the same building and the main AC power switchyard connection to the grid is nearby, two truck bombs would produce a situation not unlike Fukushima. The attackers need only wait a day or two for the result.

As another example, a widespread electric power grid failure might lead to multiple transformer failures. It is very time consuming to replace damaged or destroyed high voltage transformers. Restoring AC power to a plant could take much longer than either the available DC power (often, in the U.S., only good for 4 hours) or the fuel for backup generators. If, to save money, someone also fails to fill up the backup diesel fuel tanks a meltdown could be hours away. If grid failure happens during a flood little help will be available.

But it should not be necessary to think up outrageous disaster scenarios. It is better to make a general release of radiation as unlikely as possible by proper reactor design--even in the case of a Fukushima level accident. We are not there yet. Rather than continue with present reactors, I want to go on to present safer designs; they may not be perfect, but they may be good enough in a Fukushima situation where all outside electric power is lost.

The post-Fukushima reactor design improvements are very extensive--the idea being to avoid a catastrophic failure in the first place. Those failures that can be assigned a probability are very unlikely in these new designs. What really should matter to the public though is the protections to avoid a new Fukushima scale release of radiation to the environment. That is what I will focus on here. [2] These newer designs are only intended to represent what is being done.

I think that there are two basic principles; all others that arise are generic safety engineering issues.

First: It should be as unlikely as possible, preferably impossible by design, for the reactor to suffer a core meltdown no matter how severe the circumstances. Achieving this often leads to calculations of the probability of an accident. Unfortunately, such probabilities can never be tested.

Second: If the core does melt anyway, it should be as unlikely as possible, preferably impossible by design, for radioactivity to escape from the confinement even if the core melts through the thick steel pressure vessel.

It would be well to remember just how infrequent such an accident is likely to be; it may even be the case that no such accident will ever happen in the U.S. The point is that such accidents *have* happened. We cannot know what unfortunate constellation of events might cause such an disaster to happen again.

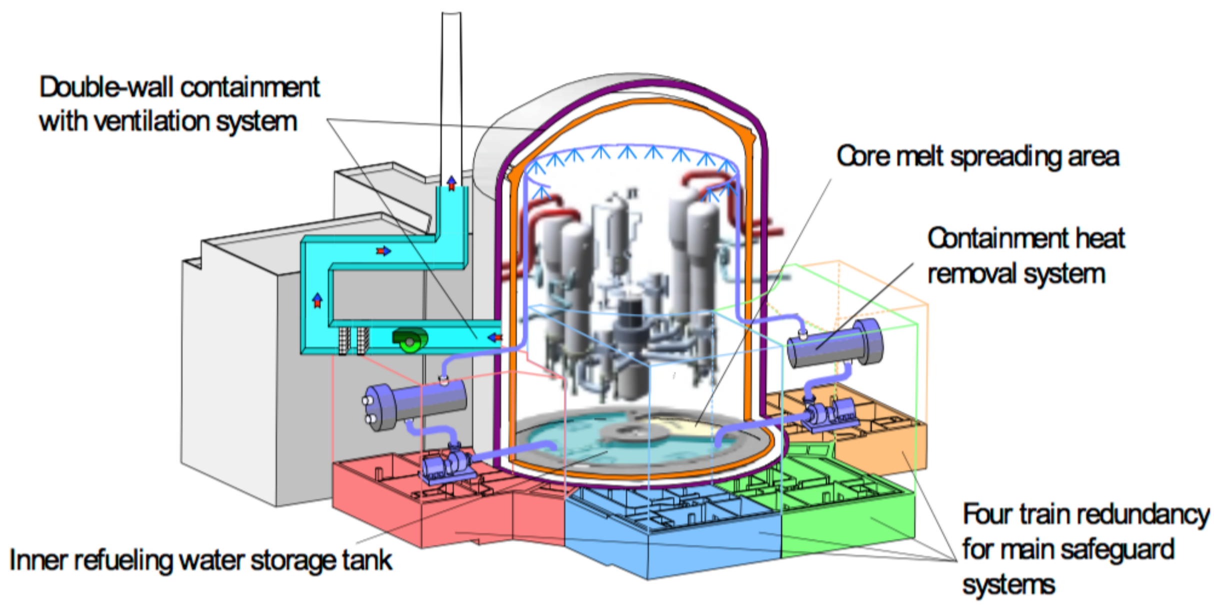
The European Power Reactor (EPR) [3]

The EPR is a PWR design that it is particularly interesting because of the second objective--it has something called a "core catcher", to confine a melted core inside the containment. The containment, if it remains intact, keeps any radioactivity from the environment. The idea of a core catcher is, in its simplest form, a pot to catch a molten core that has melted thru the reactor pressure vessel. A catcher can accomplish things that are hard to do otherwise. It can be big enough to spread out the molten core to cool it; it can contain sacrificial material that, mixed with the molten core, dilutes it without unwanted chemical reactions; the material of the catcher can contain neutron absorbers that prevent renewed fission reactions. It is certainly possible to engineer a core catcher that molten core material cannot melt thru. [4]

It is not part of my discussion here, but perhaps the first actually built core catchers were for the Russian VVER series reactors (now VVER-1200). These catchers are just large steel pots with sacrificial material inside, that can be flooded on the outside with water to cool the pot. Russian core catcher designs appeared as a response to the Chernobyl accident. A number of these light water VVER-1200 plants are under construction. Like other modern designs, they also incorporate other safety features, not just a core catcher. [5]

The EPR, in addition to other new safety systems, has an unusual containment design. There are actually two containments. The outer containment is reinforced concrete to resist impacts or external explosions. The inner containment is what used to be considered the containment--concrete with a steel liner. The inner containment is large, and the space between the inner and outer containments is connected to a filtered vent system. Radioactivity that escapes the inner containment is vented through the filtered vent to the outside.

So the EPR has both a core catcher and a containment vent system; here is an image of them, from an IAEA collection:



The EPR design also puts the emergency diesel power into two well separated concrete buildings. I have not found how DC power is handled, nor protection against damage to the grid power connection is managed.

This design is not yet licensed by our NRC for construction in the U.S.

The AP1000 Pressurized Water Reactor

Examples of this reactor are, as of 2016, being built in the U.S.-two each in Georgia and South Carolina, to start operation by 2020. The cost will be about $7 billion per reactor. This is a bit less than twice the cost of a modern IGCC (gasification based) coal plant of the same size.

The AP1000, by Westinghouse and Toshiba, is usually called a “Generation III” or “Generation III+” plant, based on passive safety principles. The main feature of the plant is its claimed ability to last three days into an accident where there is no AC electric power and no operator intervention. The design does have batteries for DC power, needed for valves and for operating the control room. The batteries are claimed to last for three days before becoming exhausted. The reports I have read are vague on the question what would happen if both AC power and DC battery power were lost.

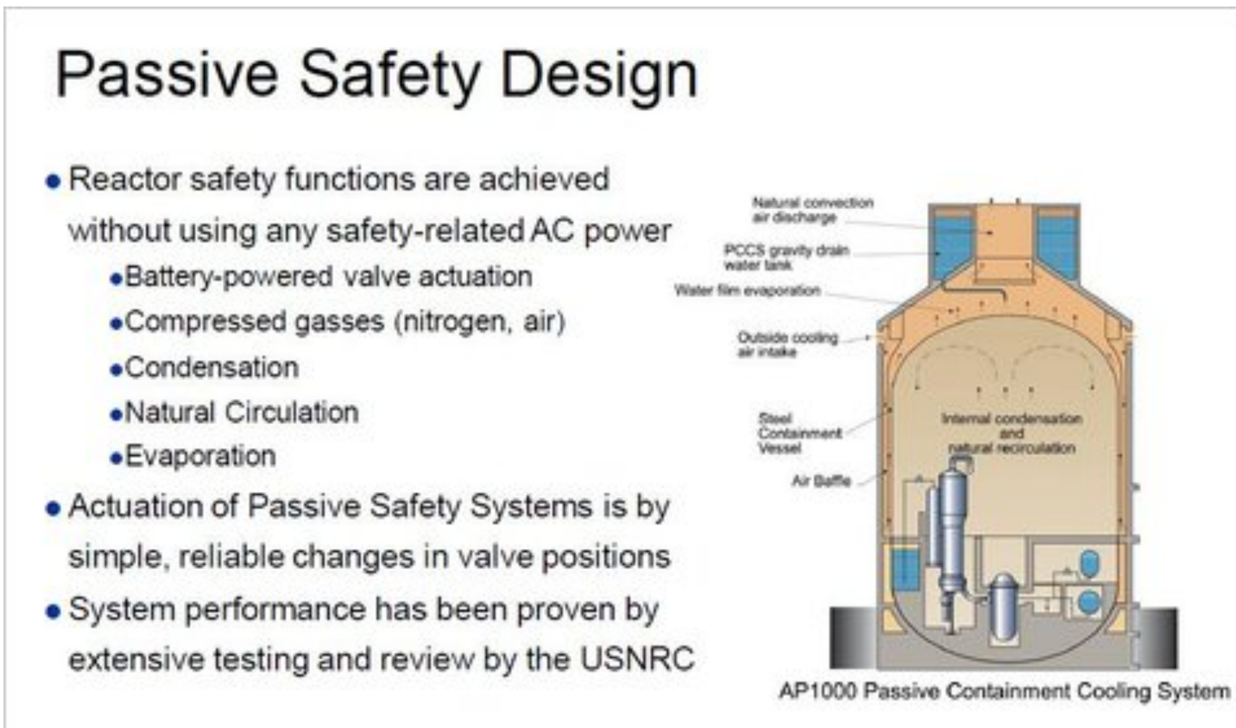
So the plant can reportedly survive three days into a station blackout with no outside or backup AC power. After that three days, the plant needs diesel backup power. [6]

The design is ingenious. There is a large water container, inside the containment, that is used to absorb the fuel decay heat from the shutdown reactor. The decay heat causes hot water from the reactor vessel to move thru the large water container, with cooler water flowing back to the reactor. The large water container is there to absorb fission decay heat from the reactor core. No pumps are needed for this. Of course, eventually the water in the large container will boil and steam is released into the containment. If this were the only feature, the containment would fill with steam from this large water tank and the pressure would cause it to rupture.

The plant also has a water container at the top of the containment building that cools the containment by spraying water over it. This part of the cooling is due to the evaporation of the spray water into an airflow over the containment. The flow of spray water is entirely due to gravity, no pumps are used. Evaporation of this water cools the containment and leads to the steam in it condensing and flowing back into the large water tank. This leads to a cooling cycle, and this is the clever design part.

After three days are up, the water from the tank on the top of the building is used up. Diesel generators must then be used to either refill this tank or otherwise supply spray water to cool the containment; an outside backup tank has a week's worth of water. After a week, the diesel generator fuel is gone and has to be replaced. But there is still considerable on-site water.

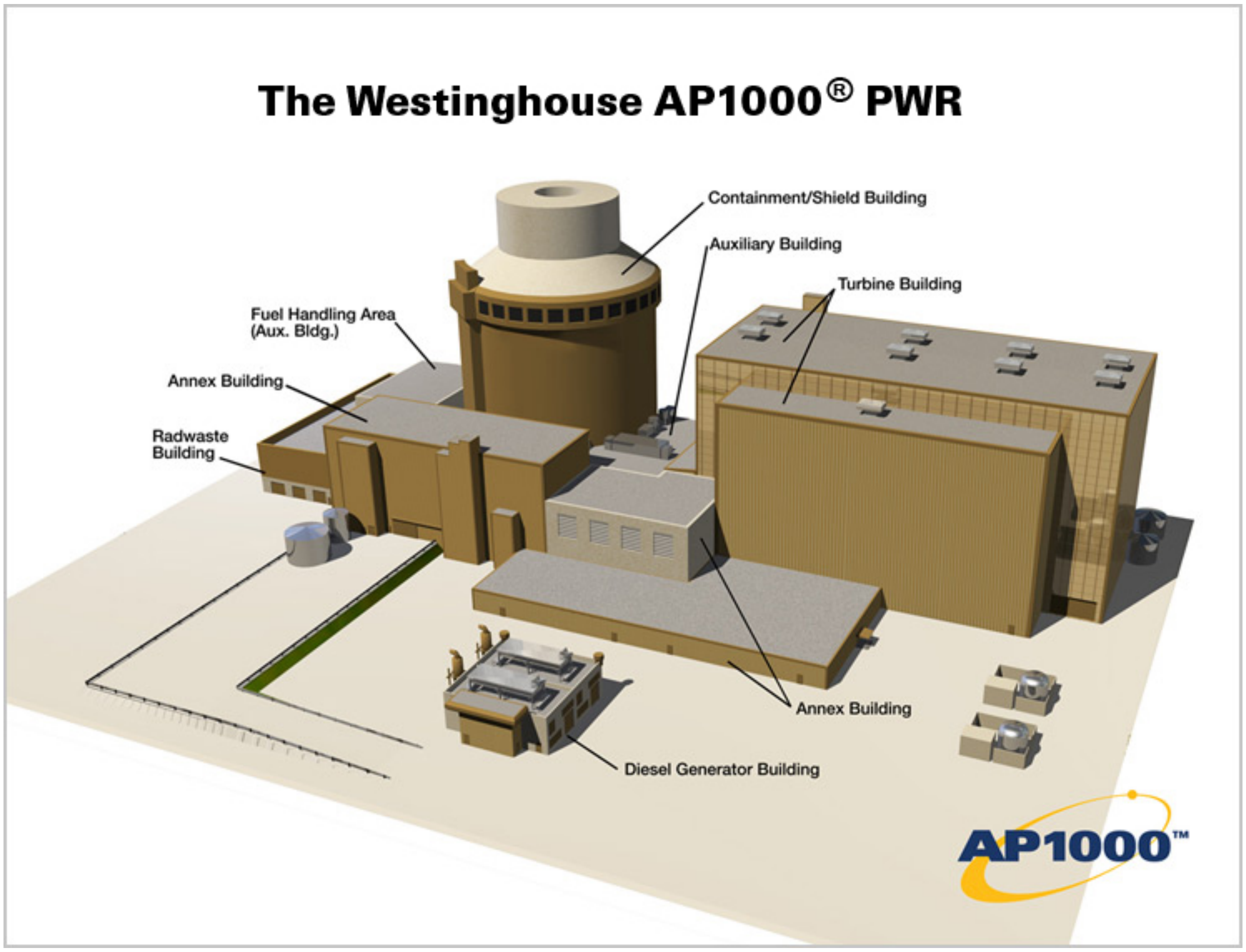
Another feature of the plant is that it has about half or so of the components of a traditional nuclear power plant. The construction of the containment is somewhat unusual. There is an outer concrete building, including the three day containment cooling water supply. This all encloses the actual steel containment. This steel containment is what I have been writing about above. Here is a Westinghouse image of the containment and its claimed features:



Besides the reactor and containment passive cooling, the design also provides for cooling of the spent fuel containers. The difficulty of cooling these caused much confusion during the Fukushima accident.

At Fukushima, the core melting process released hydrogen that led to three explosions. The AP1000 and other reactors now have ways of either burning the hydrogen off or catalyzing it. It is claimed that that no hydrogen explosion can result.

Another feature is the small size of the entire facility; notice that there is one diesel generator building. The EPR has two.



There has been some criticism of the relatively small containment, when compared to legacy PWRs. It is also sometimes claimed not to be robust against being hit by a large aircraft. [7]

What I find odd about the design goes back to my original two points. It does seem likely that, if all outside power is lost the reactor can indeed be cooled for three days. The fission product heat will be reduced by then. But what about after that? At least one of the Fukushima reactors (I believe that it was number two) melted down after three days of failed attempts to cool it. Is a core meltdown really excluded in the AP1000? And what would happen if the core did melt?

First, a core meltdown should be essentially impossible by design (it might happen anyway, of course, and this should be prepared for). What this means in practice is that the reactor should be able to survive a long station blackout--meaning that *all* AC power is lost, including station backup generator power for days or longer. [8] It is reasonable to suppose that some battery DC power is available, assuming that the battery station and distribution system is isolated from other backup power. The AP1000 design assumes that diesel backup AC will be available at the end of the three day passive time period. [9] Unfortunately, this assumption may easily be wrong in some credible extreme accident scenario. The backup generators might be damaged and unusable or the fuel might be lost in the course of the accident or sabotage. Roads might be impassible, as could easily happen in a major flood that leads as well to an electric power grid failure. In a few words, there may be no AC power for a long time, not just three days. This will likely mean a core meltdown.

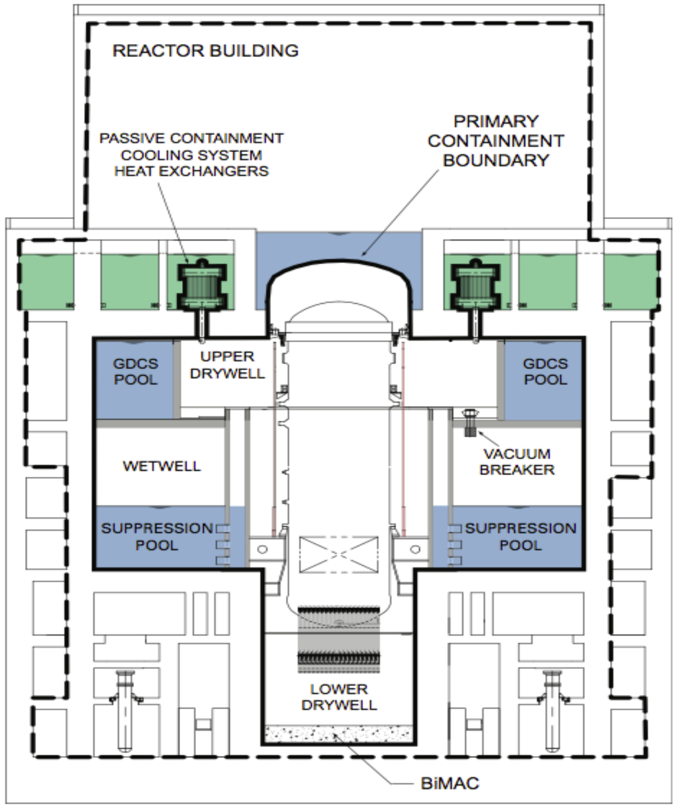
I do not entirely understand the AP1000 protections against a core meltdown in an extreme accident. The design idea is, admittedly, ingenious--to keep the melted core inside the reactor pressure vessel. The trick is to effectively cool the outside of the pressure vessel so that the decay heat cannot melt through it. The design depends on flooding the bottom of the vessel with water. There have been doubts that keeping the melted core debris inside the reactor pressure vessel will work [10] If the core *does* melt through the pressure vessel, there will be a lot of steam generated from the water pool around the bottom of the vessel. This will be mixed with radioactivity from the melted fuel. All this happened at the three Fukushima reactors and was combined with the containment failures that released radioactivity to the environment. I do not see why the same scenario cannot occur in an admittedly very unlikely AP1000 core melt thru.

Logically, the release of radiation in this case could only be prevented by a filtered containment vent. Such vents can reduce the dangerous radioactivity release by a factor of about 1000 and also prevent the rupture of the containment, such as happened at Fukushima. It is not clear to me why the AP1000 design has no emergency filtered vent, preferably a passive one, so that in an extreme case the operators do not have to open it. The only (manual) vent in the design can, I think fairly, be described as baroque. It is hard to imagine it working effectively in a really extreme accident. This is really unsatisfactory. Why the AP1000 design was certified without a proper last-ditch protection for the public is mysterious to me.

The ESBWR Boiling Water Reactor

This "Economic Simplified Boiling Water Reactor" has been certified by our NRC, but no reactors are under construction anywhere. Its principal feature is that there are no pumps in the steam loop at all--convection carries the water to steam inside the pressure vessel and then to the turbines. (The return condensed water loop does contain pumps.) Apart from the high pressure, the reactor acts like a plain pot of boiling water. [11]

Like the AP1000, the containment has inside large amounts of water available for emergency cooling. (The AP1000 also has water that can cool the containment from outside in an emergency.) The layout of the reactor, confinement and the reactor building are shown here, from a GE-Hitachi general description:



Notice that the containment is not large. Like the AP1000, the reactor is supposed to be able to cool itself (remove decay heat) for three days after a shutdown without either AC or DC electric power. The design does this by diverting steam from the reactor core to an external cooling system, which condenses the steam to water, with the condensed water returning to the core. The water in the core then boils further, with the heat removal continuing on. This passive circulation system is what removes the decay heat from the core. It is shown in green in the colored image. Of course, the heat that is removed from the core has to get out of the reactor building somehow, and this works by evaporating the water in the pool of water around the heat exchangers. The resulting steam is vented from the building. It contains no radioactivity. This can go on beyond three days, up to seven days, until the pool water is mostly evaporated. It does not need DC power, although the plant batteries can supply power for three days. This power is needed for other valves and the control room. Some of these DC operated valves are needed after three days. Beyond about the first day, the reactor vessel is mostly depressurized. Before the seven days are up, the pool water needs to be replenished. [12] After seven days, only minor intervention is needed to keep the core cooling going. (Remember that after a week, the decay heat is very much less than at the beginning.)

The above image contains other water sources that are there in case of a major accident beyond a “station blackout”, such as a large broken pipe.

If every feature to keep the core cool fails and the core melts, there is no way to keep it in the pressure vessel. This vessel has control rods passing thru the bottom, because of the steam management hardware needed in the top of the pressure vessel. If this vessel failure were to happen, there is a simple core catcher in the base of the containment below the pressure vessel. The idea behind this core catcher is that as the molten core leaks thru the pressure vessel. cooling water is released into piping inside the core catcher. This is supposed to gradually cool the core material. After the entire core has melted thru into the catcher, it is flooded with water to continue the cooling. The problem with all recent core catcher designs is that none of them have been experimentally verified. The only experiments applied to smaller reactors.

What is very odd about the ESBWR design, as with the AP1000 design, is the absence of a designed-in passive filtered containment vent system. In any of these designs, a molten core that leaves the pressure vessel will certainly fill the containment with highly radioactive material from the molten fuel. (The most dangerous is Cesium-137.) If the containment has water in it, the containment will get pressurized as the decay heat turns the water to steam. This can even happen almost explosively if the molten core simply drops into a large amount of water in the containment. Both the AP1000 and the ESBWR have small containments. In a really bad accident, they could both become over pressurized and rupture. [13] This would just lead to a version of the Fukushima accident, where the containments were in part vented deliberately (with no filtering) and in part ruptured. Those Fukushima containments (the “Mark I” BWR version) were also small.

Curiously, both the AP1000 and ESBWR are derived from lower power plant designs (the AP600 and SBWR) that would be easier to protect in case of a disastrous accident. The rationale for the larger plants is economic and is not related to public safety.

The only design that seems to take the possibility of containment overpressure into account is the EPR, the first one I discussed here. It has a relatively large containment, which would be slower to over pressurize; it also has a filtered vent.

The reactors here are only three of many newer designs that will become important over the next decade. Experience in Japan has shown that it is possible to build reactors that are acceptably resistant to earthquakes. The plant may be damaged and need repairs, but no disaster follows from the earthquake. Fukushima was due to bad design and the tsunami. The challenge for newer reactors is to reliably resist the effects of unexpected disasters--some combination of earthquakes, floods, grid power loss, and mechanical or metal failure.

A serious *present* concern is protecting our old reactors against such disasters.

Once it is clear that recoverable fossil fuels are becoming scarcer, along with existing fossil fuel climate change worries, there will be much pressure to proceed with a newer generation of reactors. It is hard to understand why the NRC has not taken a more serious position on the post-Fukushima design problems of newer reactors.

Chapter 5-Some Future Reactors

The newer plants of the last chapter are sometimes referred to as "Generation III" or "Generation III+" reactors, likely reflecting passive failsafe ideas in their designs. There is an international effort of sorts to move beyond these to what has been called "Generation IV" reactors.

There is a lot of information on Generation IV reactor plans on the Web and I do not want to cover that territory. Progress on these advanced reactor types looks slow to me. Even optimists do not see real next generation plants before 2040 or later.

If there is an expansion of nuclear power during the time we start to loose recoverable fossil carbon resources, in the 2020's and 2030's, it will almost certainly be done using existing designs. These are all PWRs or BWRs using Uranium that is about 4% or so Uranium-235 and 96% Uranium-238. Sometime later in this century the world will run short of this enriched Uranium and most future reactors, if any, will have to use Uranium-238 and Thorium-232 as their primary fuel.

There is a lot of mineable Uranium-238 and Thorium-232, but these isotopes are not usable as is. They are not themselves fissionable as is Uranium-235, so fissionable material will have to be created in the reactors themselves--breeder reactors-also called "fast reactors". [1] The fissionable isotopes that are bred and can then be used to produce the actual electric power are mainly Plutonium-239 from Uranium-238 and Uranium-233 from Thorium-232. These fissionable isotopes can then also be used in other reactors that do not breed their own fuel.

Breeder or fast reactors do not use water to slow neutrons, the neutrons are fast-at least compared to the slow or thermal neutrons in our present reactors.

Fissionable isotopes that are bred in these "breeder reactors" have to be extracted or separated out to reintroduce and use as the main fuel in the reactors themselves. [2] Of course, breeders or fast reactors can also be used to make fission bombs--as can *any* reactor. Breeder reactors and the separation technology that goes with them were ended in the U.S. twenty years ago because of the risk of proliferating bomb material. If breeder reactors are to return, this proliferation risk will have to be dealt with.

Unfortunately, we now know more about nuclear weapon proliferation than we did twenty years ago. Besides the major powers--the U.S. Britain, France, Russia and China--other states have got nuclear weapons. They are, or were, Pakistan, India, North Korea, South Africa and Israel. Only India got its original weapons by separating out plutonium from power reactors. The other states got them by other and more direct means--uranium enrichment or specialized plutonium producing reactors. No state so far has got nuclear weapons by the other obvious route: buying or stealing them in a world that already has far too many bombs. Breeder reactors are not the only route to nuclear weapons. What this means for any future breeder reactors in the U.S. is completely unclear now. It is also beyond the scope of this book.

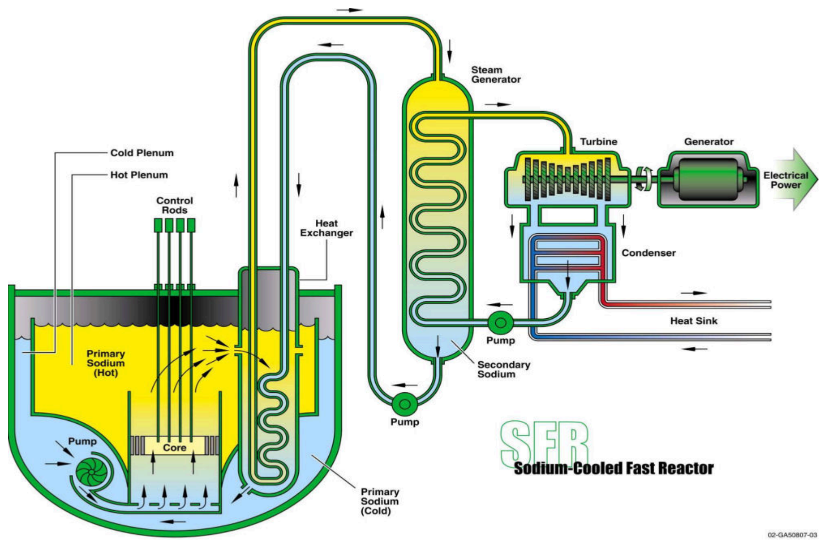
Breeder reactors have to make the proper fissionable fuel by absorbing fast fission neutrons in either Uranium-238 or Thorium-232. After some nuclear decays the result is Plutonium-239 and Uranium-233, both acceptable fissionable primary reactor fuel. Ordinary present power reactors do not do this well. They use water to slow fission neutrons so that they will stick around and fission further nuclei. Remaining neutrons are occasionally absorbed by Uranium-238 to make Plutonium isotopes, just too infrequently to be useful. A typical modern reactor might start out with 4% Uranium-235 and end up with much less of that and perhaps 1% produced Plutonium-239 (plus some other fissionable isotopes). A water reactor can be designed to make about as many fissionable isotopes as it burns up, but only one such was ever built.

To make fissionable fuel, a breeder reactor has to make many neutrons and not slow too many down, so that the now “fast” neutrons make, in a uranium reactor, plutonium isotopes. Lots of neutrons, and the low probability of absorbing a fast neutron, means that such a reactor has to have a lot of fissionable material to start with--Uranium-235 or Plutonium-239. A typical number might be 20% fissionable material and 80% Uranium-238 or Thorium-232. Also, water is not a good way to extract heat from such a reactor--it slows down neutrons too much. These constraints pretty much limits the sort of reactors one can build.

Since breeders make their own fuel, this fuel has to be extracted from the reactor somehow so that it can be used by turning it into new fuel rods. This means that a very radioactive mix of uranium, plutonium and fission products has to be separated out into fissionable material and the fission products. This is very radioactive chemistry on a big scale. It is done now on spent (used) fuel from conventional reactors, principally in the UK and France. It was done in the U.S. to make plutonium for bombs. The reprocessing for breeder reactors will be different, a complex task of its own.

Rather than going into the many present designs for breeder reactors, I think that it is better to describe only a few actual reactors that have been built and their use. I want to limit this to two lines of reactor development. One is the line of Experimental Breeder Reactors (EBR-I and, mostly, the very successful EBR-II) built and operated by Argonne lab in the U.S. This line ended with the Integral Fast Reactor, for which EBR-II was the first prototype. The IFR was never built. [3] The second line is a remarkable series of fast neutron reactors built and operated in Russia, from the 1960's to the present. Both these lines used liquid sodium for the reactor coolant. Both involved, in time, fast neutron reactors that operated successfully for decades. [4] Development reactors are often small, but the recent Russian ones are quite large.

The following image (from Wikipedia) is a schematic of a type of liquid sodium reactor, the "pool type", good for orientation in what follows. This sort of reactor has the fissioning core submerged in a pool of liquid sodium. This sodium becomes radioactive due to the neutrons. It is best to keep this sodium inside the pot. So *within* the pool there is a heat exchanger to transfer heat to secondary nonradioactive sodium and pumps to move it outside the reactor vessel. This is all at nearly atmospheric pressure, so the vessel need not be very thick. The sodium has a large heat capacity, so even a core accident need not necessarily mean disaster.

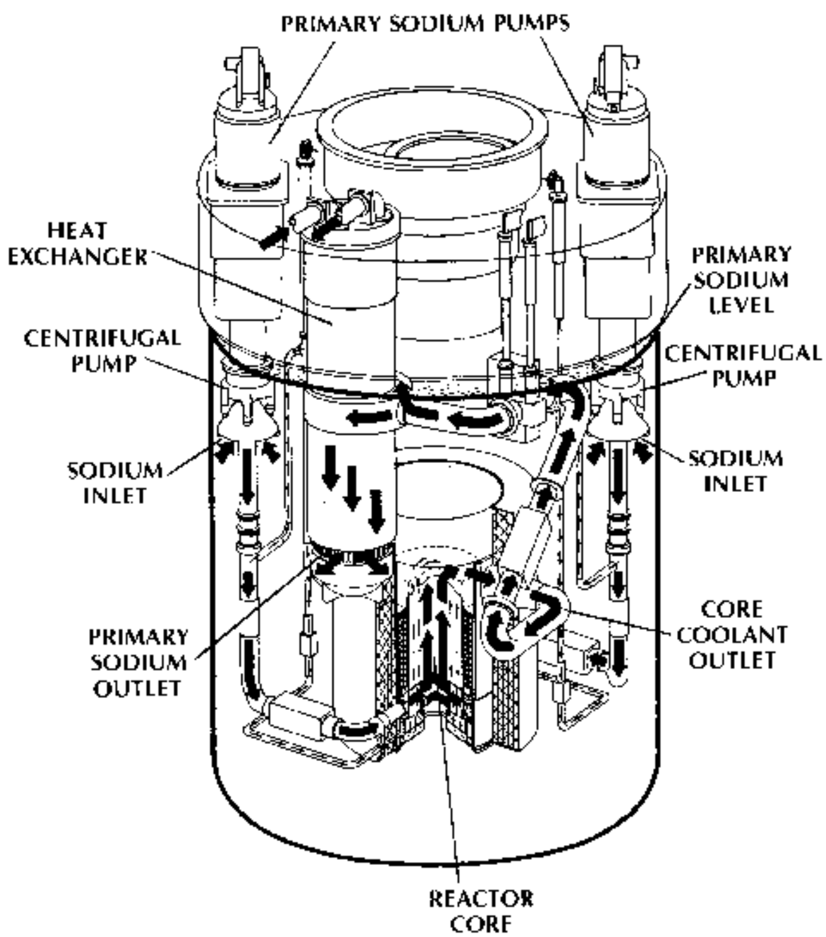


The EBR-II and the IFR

The EBR-II reactor was the second Argonne Lab breeder reactor. The first, EBR-I, started up in 1951 at a new Argonne Idaho facility. The EBR-I was very small, the core was about the size of a football; the coolant was liquid sodium and potassium metal. [5] The heat power was tiny, 1.4 megawatts, but it did suffice to produce the first electric power, 200 kilowatts. More important, the EBR-I had a Uranium-235 metal core surrounded by Uranium-238 and it did produce, by neutron irradiation, more Plutonium-239 in the surrounding “blanket” than the Uranium-235 it used. It was a breeder reactor, the first one. It also suffered a core melt down about four years later, when a key control rod was inserted a bit late during a test. The core was destroyed, but no melted fuel resulted. Interestingly, if the rod had not been inserted at all, the core melting would probably have stopped on its own. (No ‘prompt criticality’)

The EBR-II started up in 1964 and set the pattern for many future breeders. It was, by present standards, small--only 62 megawatts heat power. But it used sodium coolant, the core was placed in a “pot” full of liquid sodium mentioned earlier, the primary--eventually radioactive--sodium coolant was circulated in this pot and fed heat to a secondary and nonradioactive sodium loop that was used outside the reactor vessel to produce steam for a turbine that made electric power. Unlike a modern power reactor, there was no pressure vessel--the pot was at atmospheric pressure. This made it much easier to build.

The image here shows the sodium flow in the EBR-II



Among its many novelties, the EBR-II could recycle plutonium from the Uranium-238 breeder blanket to make new fuel rods. This was also a first. The concept was to make the plant eventually self-sufficient, with all the reprocessing and creation of new fuel rods a part of the plant. As it happened, the EBR-II was turned into a research facility and full reprocessing, with the reactor running entirely on its own generated plutonium, was never achieved. But much was achieved toward this end before the reactor was finally shut down in 1994, after 30 years. What was done was to lay the groundwork for a larger EBR-III or, as it was later called, the IFR.

This brief account of reactors that were built and operated is necessary because it explains why an unbuilt reactor, the IFR, is important. What follows is my selection of material from the book "Plentiful Energy" mentioned in an earlier note.

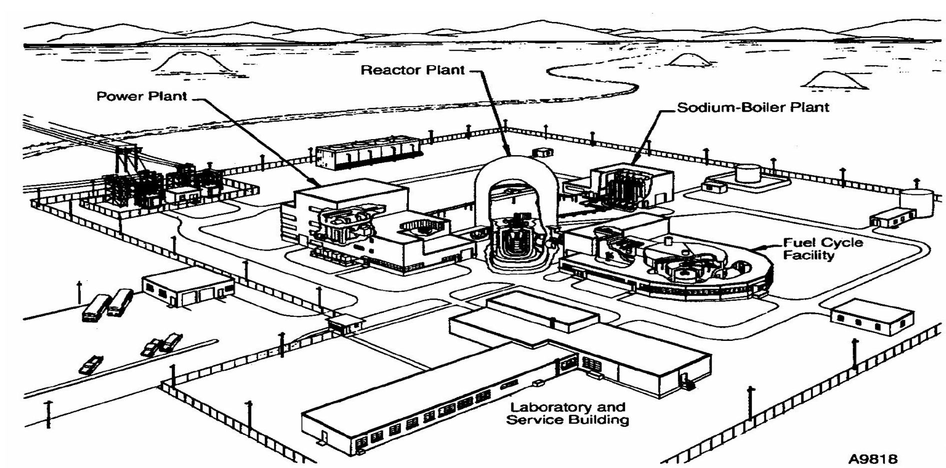
Catastrophic failure in a breeder would be different than in our conventional reactors. The breeder fuel is about 20% fissionable and if it were melt and pool, it could go critical, with fission reactions restarting, and the sudden heat generation would cause a fuel explosion. This could break a containment vessel and spread radioactivity. The EBR-II was actually tested by cutting power to the main pumps and the reactor shut down on its own. Similarly, power was cut to the secondary pumps and the same thing happened. This was possible because of the heat conductivity and heat storage capacity of the sodium coolant, and the presence of heat conducting metal fuel. The sodium did heat up by about two hundred degrees C, but this was another two hundred degrees below the dangerous boiling point of sodium. This automatic shutdown would not have worked with a reactor that used water as a neutron moderator and coolant. A somewhat surprising result of the EBR-I core meltdown was that the expanding metal fuel actually shut off the fission reactions (the fuel expanded and the low neutron absorption cut off the fission).

A real danger would be if the primary sodium pot cracked--due to an earthquake, for example--and this led to a loss of sodium. Then the core could melt. This is why all more recent IFR like designs have a second pot outside the first. If the first pot cracks and looses sodium, the second catches it and keeps the sodium level above the reactor core. Rather than a core catcher, pot type breeders have a sodium catcher.

A problem with liquid sodium reactors is that the final turbines are run with steam or other gas. The EBR-II and IFR had a hot sodium to steam heat exchanger. But sodium burns in air and reacts violently with water. Some later liquid sodium reactors had serious problems with the sodium-to-steam heat exchangers due to leaks. An interesting aside on the EBR-II is that the steam generator was carefully designed not to leak and it did not leak for the entire 30 years of the project. So it is possible to prevent sodium-to-steam leaks, despite the fact that they have happened.

If a fast neutron reactor is used to breed its own fuel, there has to be a way of recycling fuel. A breeder will make some plutonium in its fuel rods. After all, they are roughly 20% plutonium and 80% Uranium-238. Some of the uranium will be transmuted to plutonium. But breeders also have a “blanket” of rods that are, at the beginning, pure Uranium-238. These will also develop plutonium in them, due to the neutrons in the reactor. The problem is how to extract the plutonium from fuel and blanket rods to make new fuel rods with the 20%-80% mix. The IFR method, developed in the EBR-II, was to use the metal fuel idea again. Once the metal fuel was separated from the tubes it had been contained it, it could be separated by “pyroprocessing” into the useful fissionable material and the fission products that could not be used for new fuel. The fissionable material could be recycled into new fuel rods and the fission products solidified and placed in permanent storage. Since the fission products are short lived, they could be stored someplace that is safe for a century or two. They would then be relatively harmless.

This Argonne Lab image of the EBR-II site shows how the reprocessing facility was attached to the reactor (it is the oval building next to the reactor building)



The ability to separate off the fissionable material to make new fuel rods makes it possible to also use old rods from conventional reactors to extract fissionable material for new rods-either for conventional or IFR reactors. The used material from our familiar reactors can even be separated into fissionable material for an IFR (plus fission products that can be stored), thus fueling an IFR directly An IFR of the right design can even burn existing plutonium without making new plutonium. (This is a “burner” reactor).

GE-Hitachi is currently trying to find buyers for their version of the IFR, called S-PRISM, which can either burn plutonium or be configured as a breeder, with an attached reprocessing facility.

Larger sodium cooled breeders of the EBR-II type are arguably as safe as the EBR-II itself. Some questions were raised by a very preliminary NRC review of a larger IFR version called SAFR. While the EFR-II and other designs are passively safe, in that a loss of sodium flow shuts the reactor down, there is some doubt what would happen if an obstruction in the core caused local sodium boiling and high temperatures that might melt some core fuel. The rejoinder of the IFR designers, if I understand it correctly, is that the resulting molten fuel disperses in the upper core and the sodium coolant. The reactor still shuts down, but with a damaged, not molten, core.

Whether or not reactors of the IFR type are a good idea or not, there is no substitute for building prototypes and operating them. The entire field of reactor engineering has suffered from a lack of prototyping. At present built reactors have to be licensed by the NRC by rules that almost restrict designs to reactors like those already built. The AP1000 and ESBWR did get licensed, but they are modifications of existing reactors. Even so, there has been criticism of them.

Russian Liquid Sodium Reactors

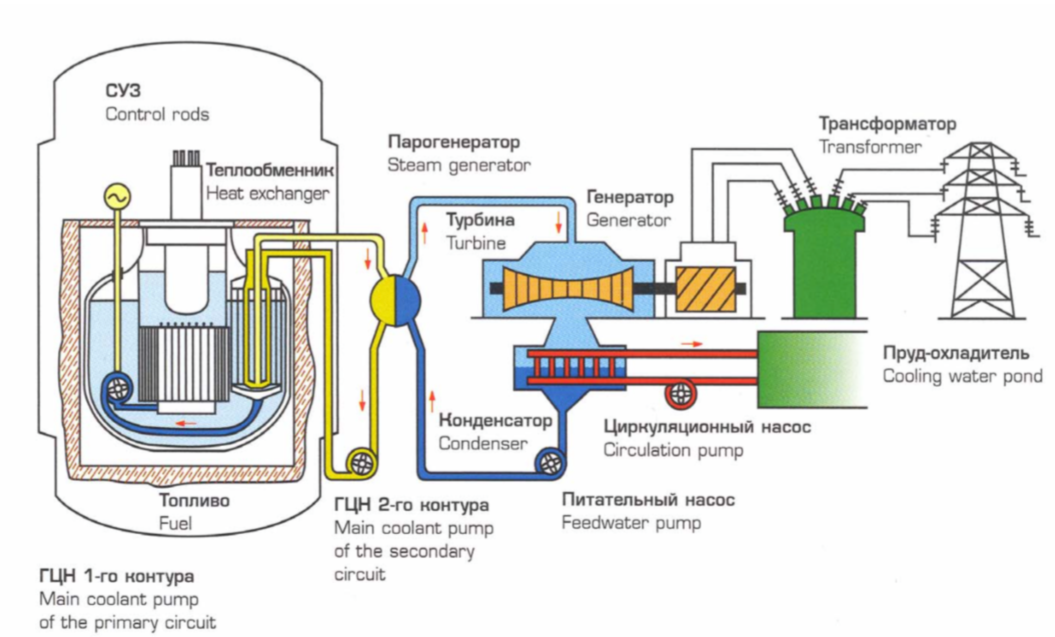
Russian liquid sodium breeder reactors started on about the same path as the U.S. The analog of the U.S. EBR-I was the BR-5/BR-10 (with about five times the thermal power of the EBR-I). The analog of the EBR-II was the BOR-60 with about the same power. These were all sodium cooled. By 2014 BOR-60 had been operating for 45 years, longer than EBR-II. By the time it is shut down it will likely have been operating for over fifty years as a fast neutron research reactor (it also generates electricity). By contrast, EBR-II was shut down before its research program was complete.

The BOR-60 was unlike the EBR-II in two main ways. It was not a pool or "pot" type of reactor. The primary (radioactive) loop of sodium pumps were outside the reactor vessel, not inside as with EBR-II. And the fuel was not uranium and plutonium metal but mainly uranium oxide; other fuels have been tested also. BOR-60 fuel has been reprocessed by the pyroprocessing method; the pictures look a lot like the ones from EBR-II pyroprocessing.

Russia after the Soviet Union breakup did not stop with the BOR-60 but went ahead to develop what, in the U.S. would have been EBR-III or the IFR.

An early stage in this process was the BN-350, which was designed a bit like the BOR-60, had 750 megawatts of heat power, 130 megawatts electric power. Some of the heat generation, about 150 megawatts, was used to desalinate water. It ran for about 25 years and is now being decommissioned. It was also used to generate bomb plutonium, which may account for the unusually high concentration of Cesium-137 in the sodium coolant, from the fuel, in contrast to the very low value for the EBR-II. The reactor also suffered from leaks in the steam generator--water leaked into sodium. This was a continuing problem. The BN-350 was really a temporary offshoot of the line of development of modern Russian sodium fast reactors.

The real successor to the BOR-60--what the EBR-III or IFR might have been--is the BR-600. It is a roughly 600 megawatt electricity generator, intended to make power commercially and test breeder concepts and fuels. A simplified plant design is shown here [6]. As I mentioned, the BR-600 has similar design ideas to the EBR-II and SFR: the primary radioactive sodium coolant is in a pot with a heat exchanger to the secondary nonradioactive sodium. This secondary sodium loop then exits the reactor and goes to steam generators. The reactor has been operating since 1980 and during its first decade the steam generators suffered leaks with water. The leaks were due to problems with welds and the last one was in 1991. There have been no sodium leaks to water in the last two decades. There were early sodium to air leaks. Such leaks are easy to extinguish with powder; sodium-air fires are not violent.



Most of the fuel for this reactor is highly enriched (about 20% or so) uranium dioxide--not the metal envisaged for the IFR. As a part of a deal with the U.S. to reduce weapons grade plutonium, the Russians are making “mixed oxide fuel”, uranium-plutonium-oxide to burn up plutonium in fast reactors. There is about forty years experience with this “MOX” fuel and it has been tested in the Russian reactors mentioned here. It is intended to be the main fuel in the currently operating BR-800 reactor. At some point in the future, there will be efforts to breed fuel, but at the moment these reactors are operating as “burners”, not breeders.

There is some dispute about the viability of the BR-600 and BR-800 in the West, but my overall impression is that the BR-600, at least, has been successful. It has overcome the early technical problems that almost all prototypes face.

The BR-800 reactor has been operating since the end of 2015, but at lower than planned power. This may be due to the fact that it runs solely on MOX fuel, but I can find no reports with details. The BR-800 uses the same size sodium vessel and many of the components designed for the BR-600, but with improvements beyond those already incorporated into the BR-600. An unusual feature is that the BR-800 has a core catcher inside the primary sodium vessel. This indicates some uncertainty about the ability of the reactor to passively shut itself down in the event of an emergency.

There are plans to build a somewhat larger liquid sodium reactor, the BR-1200 that will use breeding to generate new fuel in a closed cycle for the first time.

At present, used (or spent) Russian fuel is recycled, but in an old reprocessing plant. (These old plants generate a lot of waste.) Real recycling will require a much more modern plant that can produce both fissionable fuel and solid wastes containing the fission products. The promise of modern recycling is that the only waste leaving the plant is this solid fission product containing material with a century or two lifetime that can be stored effectively.

The Russians appear to have solved the technical and operational problems of sodium cooled fast reactors. There is no convincing evidence so far that they have made much progress on reprocessing so as to create a closed cycle of fuel. If they can do this, they can use as input fuel all the uranium, not just the tiny fissionable Uranium-235 fraction. From all appearances it looks as if they will proceed with this effort, no matter what the U.S. does. Both Japan and China have licensed the BR-600 technology, so wider sodium breeder development is possible.

The reprocessing of spent fuel is *the* problem facing fast neutron reactors. In the past, during and after WWII, a lot of dangerous waste has been produced from plutonium bomb reactors. Cleaning up those old facilities is risky, expensive and very time consuming. There is little public tolerance for this to continue. Whatever is done in the future, it has to adequately contain radioactivity and be straightforward to clean up.

Reprocessing of large amounts of breeder fuel also creates the possibility of proliferating nuclear weapons. It is true that there is an easy route to nuclear weapons via either uranium enrichment by centrifuges or small cheap plutonium producing reactors. But it would be foolish to make it easy to divert plutonium from reprocessing. [7]

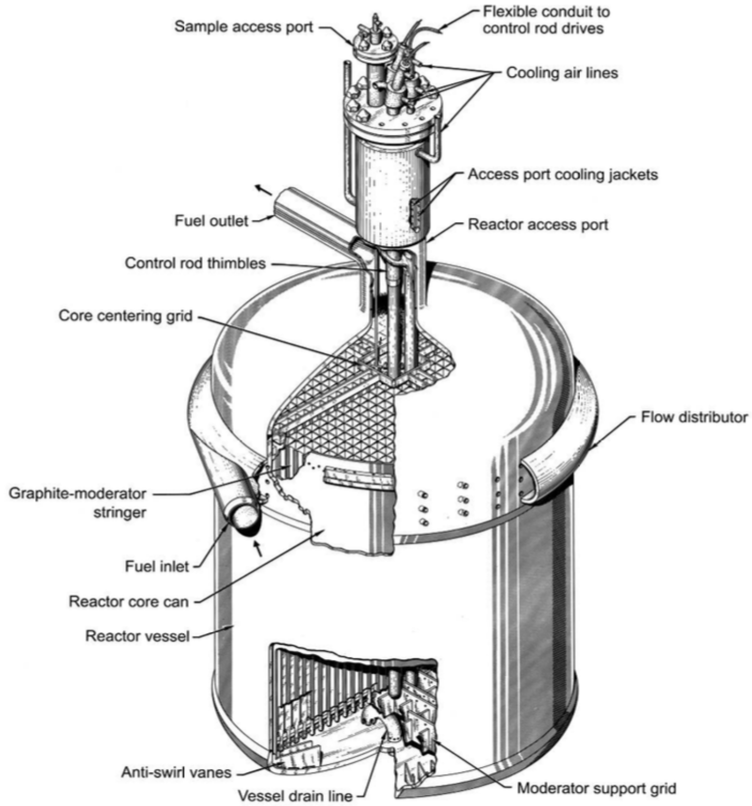
This concludes what I have to say about breeders with which there is some operational experience. There are many programs around the world, not just the selected few here. Mostly the programs involve designs rather than operating prototypes.

There is one program that has attracted attention but for which there is no modern construction and operational experience. That is the molten salt reactor.

An Orphan: the Molten Salt Reactor

At its beginning, the U.S. reactor research and development program got on a single path: the light water reactor. This was due to the U.S. Navy decision to use this type in its submarines. The only survivor of this decision was, for a time, the sodium cooled fast reactor. Another line of development, also a fast reactor, was the molten salt reactor and it was killed off before much research was done. There is a widespread effort to revive this reactor concept, but nothing has been built. So I do not have much to say about this.

Early on, the Oak Ridge Laboratory originated the idea to build as many small reactor prototypes as possible. [8] One of these was the molten salt reactor. The idea was startlingly original: dissolve the reactor fission fuel in molten salt and pump it thru a core that moderates the neutron flux (to get fission). There were two of these novel reactor prototypes. One was the Aircraft Reactor Experiment. The other was the Molten Salt Reactor Experiment. This is the one that interests me. It was a small, 7.5 megawatt heat power test device. The basic original idea was to use chemically very stable salts such as Lithium Fluoride or Beryllium Fluoride. They could naturally match the fuel if it was also a fluoride, uranium fluoride. The resulting hot fluid was transparent and had about the viscosity of water when hot so it was easy to pump. (It melted at about 430 C.) The salt mix was pumped thru a graphite core and gave up its heat to a heat exchanger and then to air. Here is an image of the original MSRE core, which started up in 1966:



(The reactor vessel itself was inside a concrete shielding, along with pumps and piping.) One of the original plans was to use the reactor as a breeder, with breeding done by a different salt-fuel mix outside the core. The reactor was tested with Uranium-233, which is also fissionable. The hope was to fuel the core with a Uranium-233 salt with a Thorium-232 salt breeder blanket. But this never happened. The program was shut down before the experiments got very far.

The MSRE had a number of good features. It ran at atmospheric pressure, meaning that the reactor vessel did not have to be thick. It could also automatically drain the fuel out of the core in the event of an accident. Since the core maintained the fission reaction, this meant a safe shutdown. It could even be made automatic. A hope was to continually remove bred fuel and the dangerous fission byproducts. So a shutdown would involve little residual heat in the fuel.

One interesting feature of molten salt reactors is the high fluid temperature. They would be well suited to providing process heat for industry. But this has never been really explored with a prototype.

The originators ran the prototype MSRE reactor intermittently until 1969 when it was shut down. The program continued in other ways until it was ended in 1973. The Atomic Energy Commission at the time wanted to concentrate on sodium cooled reactors.

By the late 1960's, there had been a number of Oak Ridge design studies for a 1000 megawatt electric molten salt breeder reactor. It would have bred Uranium-233 fuel in a Thorium-232 blanket. They went into some detail about how to build such a plant. But it never came to anything.

Research on the MSRE concept continues with reactor designs and computer modeling. But no full work has been done on even the scale of the EBR-II. And there is really no substitute to building and operating test and prototype reactors. However useful design work and computer models are, they are a kind of fantasy at present.

Reviving the IFR in the U.S. would take decades to build up the experience and people it would need. Nothing will happen soon. So if the nation were to decide to also start up a new MSBR program in parallel, there is time to do that. This is not the present Generation IV program, which is spread out among a number of nations. But the Generation IV program does not envisage a significant U.S. need for breeder reactors.

Chapter 6-Uranium and Thorium Supply

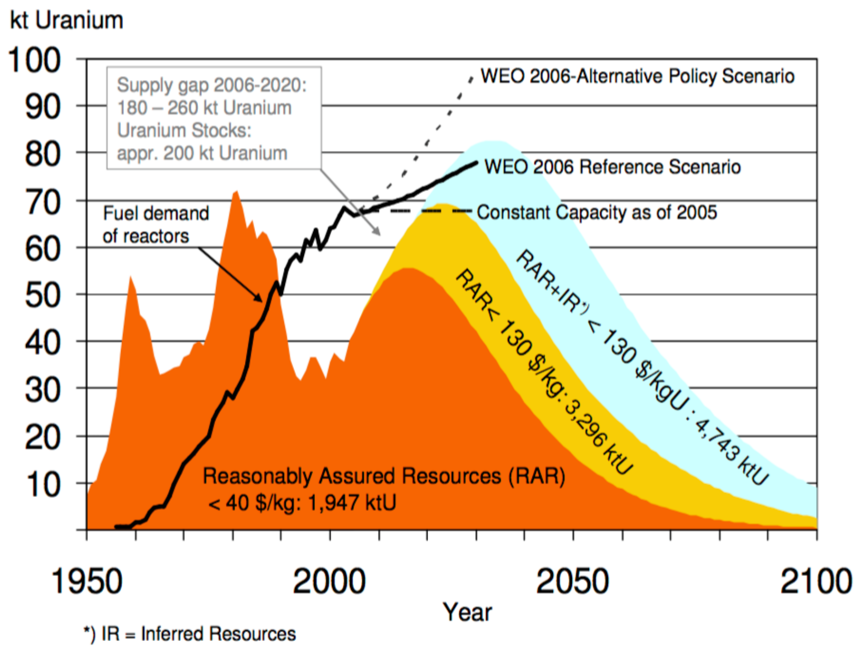
The original hope of breeder reactors was based partly on the belief that uranium was a scarce resource, so all of it had to be used, not just the fissionable isotope. This has turned out not to be the problem that was imagined. There is a lot of uranium, so the now old fashioned reactors can be fueled for a long time with enriched uranium. This is especially true because modern uranium enrichment using centrifuges is cheap. (That is part of the present proliferation problem.)

Just how much uranium there is and how long it will last, given that only 0.7% is fissionable, is a matter of some dispute. Part of the issue is due to the fact that ongoing burning of enriched uranium is a small part of the overall cost of a reactor. A commonly quoted number is that the present cost of uranium amounts to only 6% of the cost of electricity. This number could increase a lot without making the electricity unaffordable.

Estimates of how much uranium is available have varied widely. The subject of "Peak Uranium" even has its own Web page!

All estimates are unusual in that they refer to mined uranium that can be enriched for conventional reactor fuel. The result is that at the end of this process, a very large amount of depleted Uranium-238 will remain-99.3% of all that is mined. With breeder reactors, this depleted uranium would last a very long time.

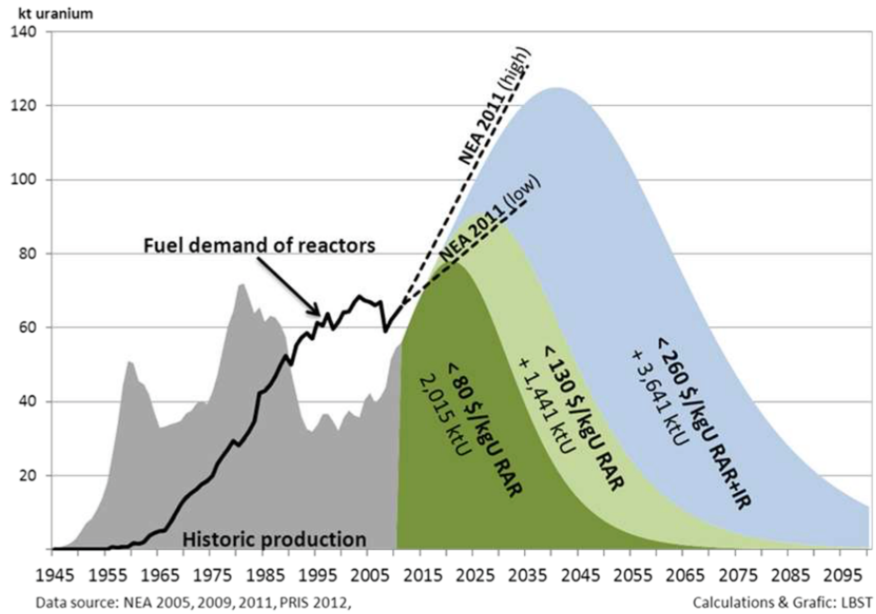
An early 2006 estimate by the German Energy Watch Group shows uranium running out in a few decades:



Estimates such as these all depend on the price of uranium, as is clear from the EWG plot here.

The EWG plot from their 2013 update is not much different--but notice that the high price uranium has gone to $260 per kilogram.

(There is about four times as much mineable thorium as uranium, but no working thorium reactors. So the price is not interesting now.)



It would be interesting to see the EWG projections for a uranium cost of $520 per kilogram. My reason comes from World Nuclear Association fuel cost estimates for 2015. If I scale them up to $520/kg then I get a uranium fuel cost of only 1.5 cents per kilowatt-hour, about 15% of what I pay for electricity now. [1]There is probably a lot of uranium available at this price. At present prices of around $100 per kilogram, enrichment costs are only about a third of the cost of fuel. So enrichment is not a major issue.

Given the amounts of uranium available, conventional reactors can be fueled for a long time, perhaps out beyond the latter half of this century. Beyond that, breeder reactors can continue to use already mined and stored Uranium-238.

There are widespread quite large estimates of the total amount of uranium available in the world. This is where an earlier estimate in this book comes from--that the total energy available from uranium is about a hundred times that of the energy available from all fossil carbon. Since fossil carbon has served us for about a hundred years, it is not unreasonable to suppose that, if it makes sense to do so, that breeder reactors could supply power for some thousands of years.

Chapter 7 Nonconclusion

It was not my intention in this book to come to a conclusion in the abstract whether or not nuclear power is a good thing or a bad thing.

It might be good at this point to recapitulate remarks in the preface. Eventually, later in this century, fossil carbon energy production will nearly cease, except possibly for minor production of liquid fuels. The question is what will replace lost fossil carbon energy.

Nuclear power is an option. We understand how to use this. Nuclear power already supplies a fifth of our electricity use. But plants are large and technologically complex--producing about a gigawatt of electricity per plant. An advantage of this is that, because of their size, nuclear power plants can be where needed. Maintaining public safety is essential and not a trivial task.

One possible observation that emerges from this book, and some of the references, is that our present application of nuclear power is probably not survivable if it is to have a future. In the U.S. we have a regulatory structure that, appears to have been captured by a for-profit industry. This industry, and its regulators, are largely inattentive to public safety. The prevailing view is that if the probability of a catastrophe is small, that is good enough. The possibility of an accident in the U.S. that could contaminate tens of thousands of square kilometers with radiation and completely destroy any future for nuclear power is very real. Claiming that the probability of this is small, obtained by an opaque calculation, is not good enough.

But other replacement energy options have still unknown problems of their own. Most of them--think of wind and solar energy--are intermittent and involve large land areas, energy storage and transmission of power over long distances. How they will interact with our power grid is largely unknown. Also, the number of energy units (wind turbines, etc.) needed to equal a present large power plant is enormous. We have essentially no experience with these issues on the huge scale that we will face in the decades ahead. If nuclear power can be made truly safe, it might be wise to keep our future energy options open and not give up on it.

Endnotes
Introduction

1. See the earlier book in this series, "The Rise and Fall of Fossil Carbon" and references there. The example of coal in Great Britain is sobering, presented in detail by David Rutledge. Only about a third of the supposedly accessible coal in place was ever extracted and there is now almost no coal production--a fossil carbon whose energy allowed the creation of the industrial revolution. What happened to U.K. coal presages what will happen in time to all our fossil carbon resources.

2. Rather than finding replacement energy, it might seem that we can drastically reduce our use of energy. This is unlikely. Already in the 19th century, we Americans used about a third as much energy per person as at present. Most European nations now use about half as much energy per person as we do, as you can easily check. Given the continental geography of our nation, our use of energy per person is likely to remain about what it is now, or slightly less if we conserve. The way for the nation as a whole to use significantly less energy is simple if unlikely to happen--fewer people.

3. Since we have built our industrial society over more than a century on fossil carbon energy, it is not unreasonable to suppose that uranium and thorium, if used completely up, would last for a few thousand years. The ratio in the text comes from the following estimate. Our recoverable fossil carbon resources, at the start of the industrial revolution, probably amounted to perhaps a trillion tons equivalent of oil. A crude estimate from the "Red Book" of recoverable uranium alone, at just above current prices, is around ten million tons. Multiplying by a factor of a million to get an equivalent energy in fossil carbon units would give ten trillion tons equivalent fossil carbon. Accounting for thorium at four times the amount of uranium would take us to an equivalent of fifty trillion tons of oil equivalent. This does not take account of low levels of uranium and thorium that can likely be mined, nor does it take account of uranium in seawater.

4. All delivered electric power amounts now to about an average 400 gigawatts. (Average meaning the total energy in joule units produced per year divided by the number of seconds in a year or joules per second or watts.) Roughly a hundred nuclear power plants deliver not quite 100 gigawatts of the total electric power. The rest--most of what we use-- is from coal and natural gas.
The *total* national average useful energy (after thermal and engineering losses) is about 40 exajoules (ten to the power 18 joules) per year or about 1300 gigawatts average power. If this were *all* to be replaced by electric power, we would need roughly three times the present value. Most of our nuclear power plants are very old. If we were to replace these over 20 years *and add an equal number of new ones*, making 200 nuclear plants in total, we would have to add ten plants per year on average. Even this number would probably leave us with not quite a quarter of our future electricity from nuclear power, after accounting for increased need.

5. At present, there is an interesting website that discusses just how these pressure vessels--often eight inches thick--were made. Check http://atomicpowerreview.blogspot.com for details. We will see later on that it is possible to make a different kind of fission reactor that does not need such a thick and high pressure vessel.

6. Large container ships, carrying a few hundred thousand tonnes, now largely use something called "bunker fuel", the last residue of oil refining. It is cheap now, even at a tenth of all oil, but without oil it will go away. These ships will continue for a time with natural gas power but even that will be minimal by 2100. It is no accident that the largest and fastest purely wind powered ships of the nineteenth century were small, less than a twentieth the carrying capacity of a modern container ship. There is just not enough power in sea winds alone to drive a large container ship at the speeds of a modern fuel engine. This is not to say that large wind powered ships are impossible but that, as a century ago, there will be a limit to their size and carrying capacity.

7. "The Replacement Energy Problem" goes into process heat in some detail. Low temperature heat, as that from a CHP plant, is useful for heating buildings. Heat at a much higher temperature is needed for industrial processes. The difference is often ignored, but may be important.

8. I am thinking here of the "European Power Reactor" (EPR), not radically new--just an evolutionary design, that is now being constructed in various places at much greater difficulty and cost than originally estimated. The EPR will reappear when I discuss modern safer reactor designs.

Chapter 1-Some Nuclear Physics

1. The energy to break up a hydrogen atom into a proton and an electron is the electric "binding energy" of the atom. The atomic units of energy are small, just as atoms are small. It is the "electron volt" and about 14 electron volts of energy are needed to pull apart the proton and electron in a hydrogen atom.

2. In the language of the "standard model" of particles and their interactions, the fact that neutrons are heavier than protons is due to the slight mass difference of certain of the elementary quarks inside the neutron and proton. This mass difference arises from the arbitrary strength of the coupling of these quarks to the Higgs field of the standard model. This strength is one of the many arbitrary parameters of the model, not determined by any fundamental principle.

3. You might wonder how it is possible to get a bunch of positively charged protons close together. They should fly apart, since the electric force causes like charges to repel one another. The nuclear force is attractive for both protons and neutrons, so it can balance out the electric force that causes protons to repel one another. But it only acts when the neutrons and protons are close together and it is not actually strong enough to create a nucleus of protons alone. (No such

stable nucleus exists.) The neutrons are essential for the nuclear force to work so as to create the nuclei of the atoms we know, with their mixture of protons and neutrons.

4. Uranium -238 decays to radioactive Thorium-234 plus the nucleus of the helium atom He-4; the decays go on from there, producing many of the radioactive elements that the Curies discovered over a hundred years ago in uranium ore. Uranium-235 decays to Thorium-231 plus He-4; about half of any amount of Uranium-235 decays this way in about 0.7 billion years. The decays continue on from Thorium here as well. This is not where natural thorium comes from. Most thorium in nature is Thorium-232; half of any amount of it decays in about 14 billion years--about the age of the universe--to Radium-228 plus, again, He-4. Radium, the first discovery by the Curies, itself also decays and further decays go on from there. It is mostly the later decays that produce the radioactivity of ores of uranium and thorium Neither Uranium-238 nor Thorium-232 are, by themselves, very radioactive because of their long lives.

5. The light elements that make up most of the earth have about as many neutrons as protons--nitrogen and oxygen are examples. The line of protons versus neutrons bends up gradually until the ratio changes from 1:1 to about 3:2 This turns out to be important. If a Uranium-235 nucleus breaks up into two more-or-less equal pieces, they *also* have a neutron to proton ratio of 3:2--but the light stable elements have a ratio smaller than this. So these fragments have too many neutrons and are very unstable. (This is still so even though the Uranium-235 fission releases some of its neutron excess as free neutrons.)

Chapter 2-Pressurized and Boiling Water Reactors in the U.S.

1. There are many sources of reactor information on the Web and on the site of our Nuclear Regulatory Commission. If you can tolerate the high physics load, I think that the best is the MIT Open Courseware http://ocw.mit.edu/courses/nuclear-engineering/22-312-engineering-of-nuclear-reactors-fall-2015/ “Engineering of Nuclear Reactors”, by Jacopo Buongiorno.

2. The image in the text is from the report “WASH-1250” (1973). It is available from nrc.gov and after over fifty years it remains the best place to start understanding reactors and safety. It does require some background, but not much. I like this image because it omits many complex components in detailed engineering designs but keeps the essential features of a BWR.

3. The uranium enrichment in a pellet might be from the natural 0.7% U-235 to about 4%. Before they are loaded into a reactor, the pellets are not very radioactive. For fun, I once borrowed an unused pellet. The gamma radiation level was in the ballpark of a few microcuries. This is typical of the radiation level of physics demonstration sources--i.e. negligible per pellet. A *used* pellet just after removal from a reactor might have a radiation level of hundreds or more Curies.

4. The pellets are contained in tubes and the tubes make up an assembly. Here is an image of an assembly from WASH-1250. There are, of course, lots of assemblies in a reactor core because a lot of water has to flow easily thru the core. The water even boils inside the core.

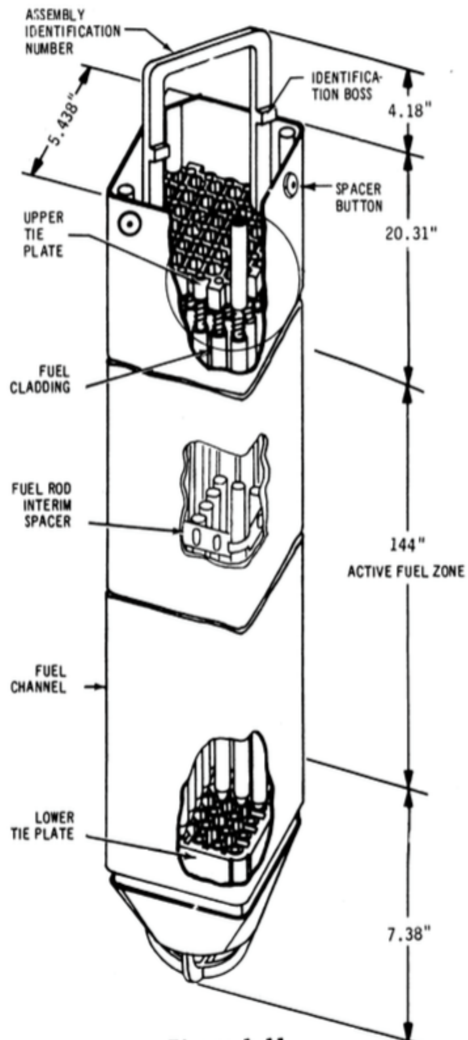


Figure 1-11
BWR Fuel Assembly

5. The whole BWR reactor vessel can look quite complicated, with its core in the lower part, the steam cleaning part in the top and the core control rods emerging from the bottom. The control rods do not actually come out of the pressure vessel, just the attached rods that allow them to move in and out of the core. You can find a number of images on the Web; this one is from oece-nea.org.

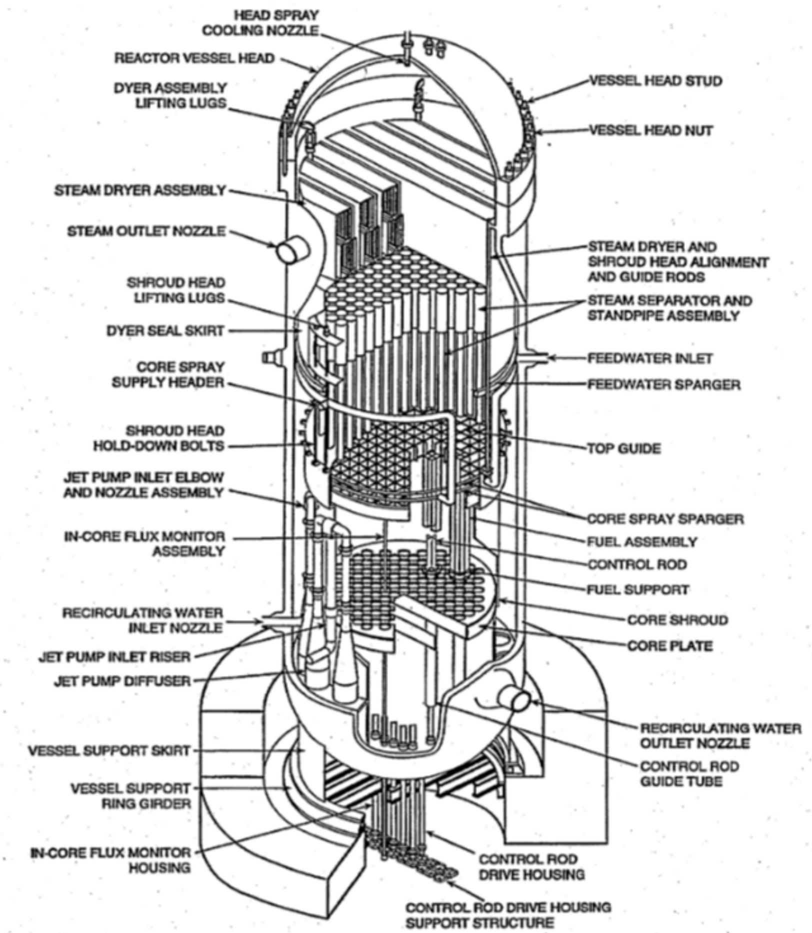


Figure 6.1-2 Reactor Vessel (BWR/3 or BWR/4)

6. One type of PWR--reactor pressure vessel and steam generators from WASH-125 looks like this:

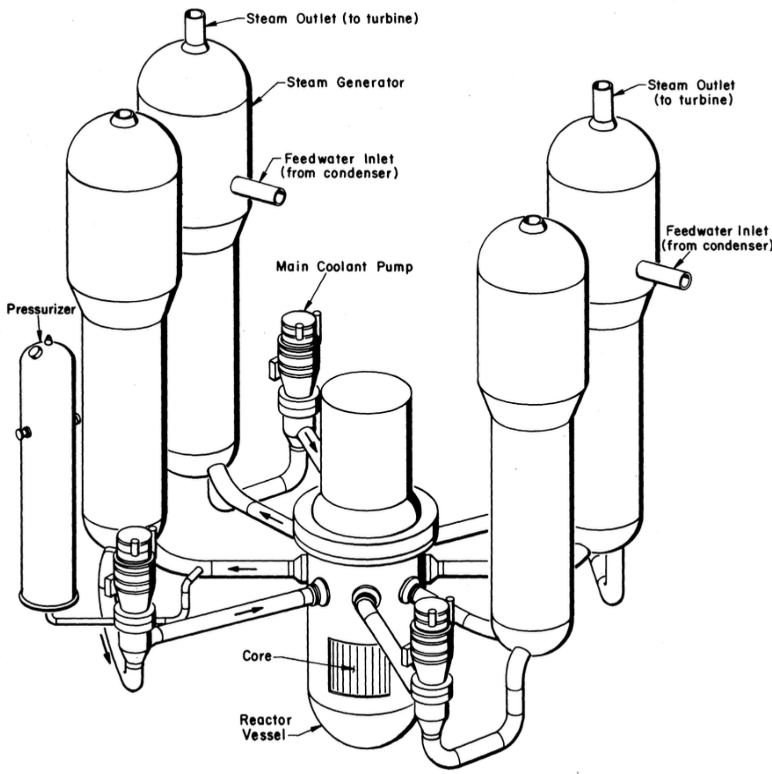


Figure 1-2.

--there is a lot more “hardware” outside the actual reactor pressure vessel than for a BWR.

Chapter 3-Accidents and Radiation Dangers

1. There is a long history of U.S. assessments of possible nuclear power accidents. The first attempt was called WASH-1400 and a more recent one by the Nuclear Regulatory Commission is NUREG-1150. Both can be found on the Web. There have been and will continue to be many more studies.

2. My version of the accident here is taken largely from “The Kemeny Report” , prepared six months after the accident. Because of that, it is somewhat incomplete. But it remains the best because it is so well written. Another early report is the “Rogovin Report” to the NRC; I will use a figure from this report. Both are available on the Web.

3. I am not sure if this very detailed Spectrum report, by is available or not; I got my PDF copy from my university library. The diagram of the TMI-2 plant in this report is not quite the same as that in the “Rogovin Report”.

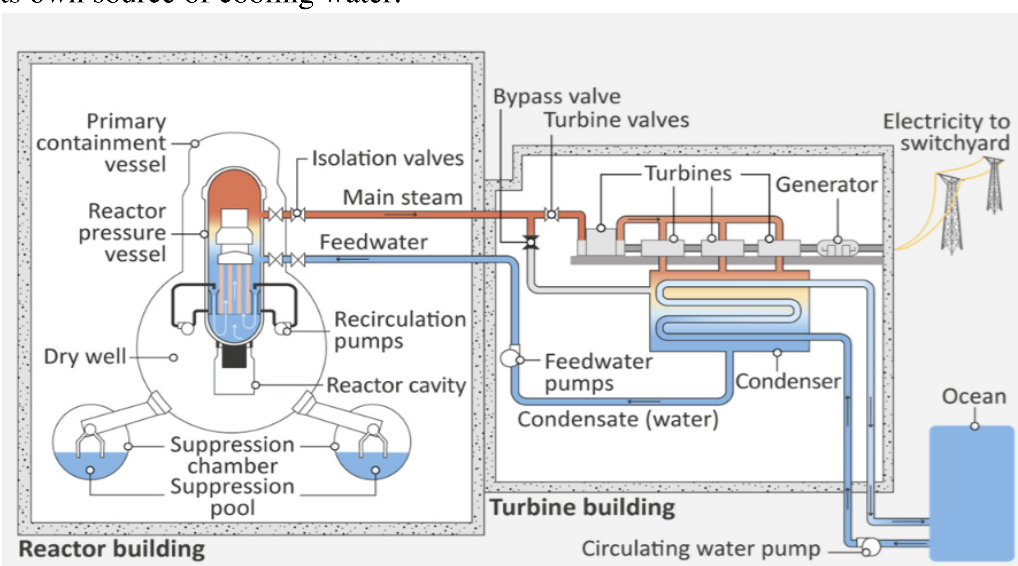
4. When a reactor core “melts”, it does not melt all at once and melting is not all that happens. Early on, the water in the pressure vessel reacts chemically with the now overheated metal of the

core structure to produce dangerous levels of hydrogen gas. Later, the core support structure actually does melt. Only much later do the uranium dioxide fuel pellets melt. At this point, their load of really dangerous radioactive elements is released. A confusing property of this process is that quite early on there is a release of radioactive noble gasses. These gasses do not interact chemically and can be released to the environment. Their release is not good, but it is also not harmful to the public if an accident does happen. The real danger is the elements inside the fuel pellets.

5. The NRC response to the official Kemeny Report was detailed in a *very* hard to find report, NUREG-1355. Perhaps unintentionally it shows how the NRC and its allies avoided implementing the two main and important recommendations of the report--recommendations that were put at the beginning of the Kemeny report and very carefully argued.

6. We still do not know enough about the accident. There are a number of reports as of 2011-2012. The most often quoted is the report of the international atomic energy agency, IAEA-Pub1710, available on the Web. Another is by the Institute of Nuclear Power Operators, INPO-11-005 from November 2011, the year of the accident itself. I happen to like the report "Fukushima-Unfallablauf und wesentlich Ursachen" by Christoph Pistner from 2013; I don't know of an English version. This last has the advantage that it is written by one person with a single clear viewpoint and includes useful diagrams. (The IAEA report also has good diagrams) A recently updated report is that by the World Nuclear Association; there is also a Wikipedia timeline entry. Both are available on the Web.

7. As a reminder, here is the IAEA diagram of this early generation of BWRs, without the emergency core cooling parts; notice that the "Primary Containment Vessel" is small, but it does contain its own source of cooling water:



8. A nuclear power plant closer to the earthquake, the Onagawa plant, also shut down without incident after the earthquake. It withstood a 13 meter tsunami water flood, but that was because it was constructed on land 14.8 above sea level, with a tsunami protective front embankment. This height was chosen by the plant operator, a different company than TEPCO, because of historical tsunami height estimates. (The height was increased after the earthquake and tsunami of 2011, partly because the earthquake caused the land to drop by one meter compared to sea level.) The seawater cooling pumps survived, again because of the construction design. See the brief Wikipedia article on Onagawa. There is a very detailed IAEA report, IAEA-2012, "IAEA Mission to Onagawa…", which is mainly concerned with the earthquake, since the tsunami had little effect. In some ways, the IAEA Onagawa report is more interesting than the Fukushima reports because of its focus on earthquake damage. One of the many strange features of the Fukushima plant is that the original land height was above the actual 2011 tsunami level. The land was cut down to 10 meters above sea level as part of the plant construction.

9. It may seem odd at this point that the operators thought that they had six hours, given my earlier estimate and the TMI-2 accident timeline. Both those times were short. This difference is because the containment of the Fukushima reactors had extra cooling water and systems to run this through the pressure vessel. It would take time for this extra water to boil off as described in the next note.

10. The emergency cooling system for reactor 1, the oldest and smallest, was passive. High pressure steam from the reactor ran thru cooling pipes in a large vessel of water. The steam was condensed and returned by gravity to the reactor. This system would eventually boil off the water used to cool the steam, in about 8 hours. The vessel could, in principle, be refilled--given electric power. This system also needed working valves, since it was normally off. Reactors 2 and 3 had more power and used a different emergency cooling system, where reactor steam drove a turbine that pumped water from the reserve inside the containment vessel into the reactor. These systems did partially work, but were not effective enough to prevent the cores from becoming uncovered.

11. This number is for the flooding of reactor 2, from a TEPCO report.

12. There are some key reports by the World Health Organization, mainly the "Health Risk Assessment" available on the Web. The dose estimate here is from that document and WHO's "Fukushima Five Years On".

13. Cancer deaths are estimated using something called the "Linear No Threshold" model, assuming that the death rates can be obtained by extrapolating death rates at high dose to the very low doses at Fukushima. There is no convincing evidence that this extrapolation is correct and it has been questioned for many years. It is well known that there are mechanisms by which skin cells protect the organism from cancer due to ultraviolet radiation DNA damage. It is not unreasonable that there are mechanisms that protect the organism from radiation damage to its DNA. A 2005 report, "The debate on the use of the linear no threshold for assessing the effects of low doses" jointly by the French Academy of Sciences and Medicine summarizes where things

stand. They conclude that, at least on average, there may well be a threshold with little or no radiation effect below about thirty times the level of background radiation (below about 100mSv in modern units, where mSv stands for "milliSieverts"). This would cover almost all exposure at Fukushima. I got the report thru my university--I do not know if there is a public version.

14. A microcurie is 37000 nuclear disintegrations per second or 37000 "Becquerel" due to the radioactive *source*. The *absorbed* radiation by a person is measured in the "Sievert" unit used in the proceeding note. In this unit, all of us get about 3 milliSieverts dose per year from the environment. Despite Wikipedia, media stories routinely mix these up.

15. It seems to be not well enough appreciated that an annual absorbed dose, measured a meter above the ground, that is quite low (tens of mSv, possibly a harmless level) can mean a *ground* contamination that is unacceptably high--not a place that we would want to live if it was likely that we could pick up the radioisotopes on clothes or food. I would not regularly buy vegetables from land that had even a one microcurie per square meter Cesium-137 contamination. However, I would likely buy such vegetables just once. (As a physics demonstration, I like to drink tea out of a Fiesta ware cup with a uranium glaze, the overall cup radioactivity amounting to a few microcuries. But it does not leach into the tea, as I show with a geiger counter. Numbers do matter.)

16. There is an excellent summary by the Union of Concerned Scientists, "Preventing an American Fukushima". My view is that our NRC has been grossly negligent and that an accident at this level could happen here. The arguments against such an accident are not dissimilar to arguments in Japan against high tsunami seawalls and protection of backup generators, fuel and DC batteries. After a disaster, everybody knows what *should* have been done.

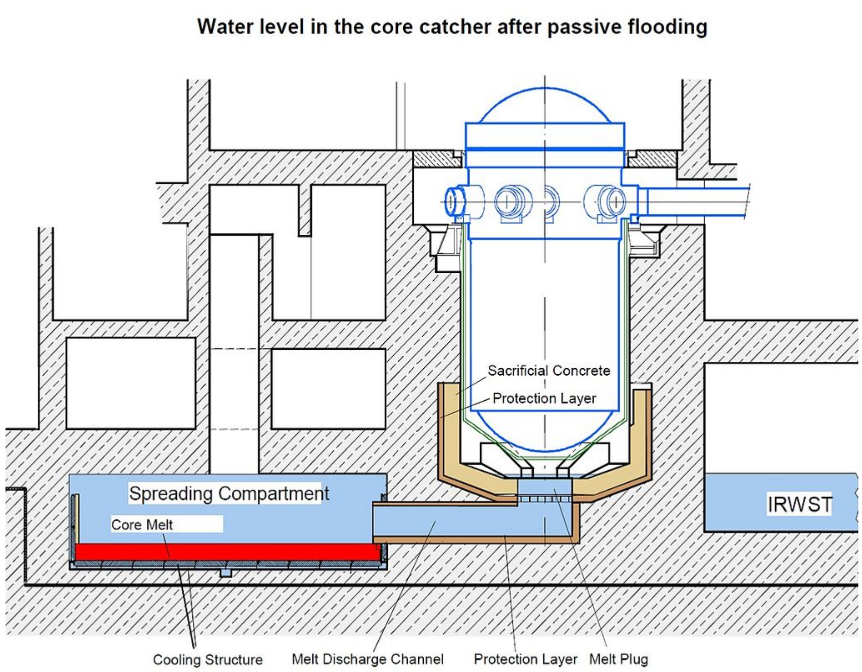
Chapter 4-Safer Reactors

1. Passive filtered vents were proposed by Jan Beya and Frank von Hippel in the 1980's after TMI, but never to my knowledge implemented in the U.S. They vents are now commercial and can be retrofitted. The company "Areva", among others, sells them. Existing ones cost about $20-$30 million and can reduce radioactive emissions by about a factor of a thousand if the containment is full of radioactivity and is at dangerous pressure. Of course, they cannot help if the containment itself is so hugely damaged that it leaks radioactivity directly into the environment. The original filter, called a "scrubber", was installed at an English reactor over fifty years ago at the insistence of the physicist Cockcroft; it worked to reduce radioactive emissions when a fuel fire later broke out. My interest in filtered vents is because I live 40 miles from a "Fukushima" GE Mark I reactor that has no such passive filtered vent; that reactor is now 45 years old and is running on a license extension to age 60.

2. There is an IAEA report on the post-Fukushima safety rules, "Safety of Nuclear Power Plants:Design".

3. There are several EPR reactors, by the French company Areva, now under construction. I want to discuss this reactor design despite the present problems that Areva is having with the construction. The biggest engineering problem is due to the defective metallurgy of part of the pressure vessel. Other problems seem to be due to bad project management. Whether the problems can be fixed, I do not know. In any case, the design principles are important.

4. Core catchers are not a crazy idea. The physics of core catchers is not complicated; the engineering of them is *very* complicated. The underlying idea is, very crudely, the following. Imagine a spherical mass of molten core a day or so after shutdown. It would be about two meters in diameter and the surface would be about the temperature at which steel melts. (I used black body radiation to get this, so it is only a crude estimate.) The temperature, in Kelvin units, would drop very roughly proportional as the one-fourth power of the heat power divided by the surface area. If the core material is diluted with low density stuff, the area would be bigger and the temperature less. If this molten stuff is spread out in a layer, the area would be even bigger and the temperature even less. The core material plus whatever dilutes it would soon be below the melting temperature of the catcher, particularly if the catcher were lined with something that only melted at a very high temperature. Of course, the catcher would have to be cooled; in time the core material would develop a crust and then even solidify. This happened at the TMI accident. Here is an image of the EPR design, showing spread out core material, from a German article https://de.wikipedia.org/wiki/Areva_EPR:



The German Wikipedia article contains many details.

5. The only source for this information that I found is at www.rosatom.ru; the report there has a diagram of the core catcher for the VVER-1200 series. Here is a picture of the steel outer pot:

6. I got my information from a Westinghouse document, “Coping With Station Blackout” from April, 2011. I will refer to it again.

7. A good overall criticism of the design of both the AP1000 and the ESBWR has been given by the Union of Concerned Scientists, “Nuclear Power in a Warming World”, 2007, Chapter 6.

8. This may be asking for too much, but it would be a good thing anyway.

9. There is a Westinghouse report, mentioned earlier, “Coping with Station Blackout” from 2011 that states that the onsite backup generators will work and can be used. There seems to be claims elsewhere that even if *all* onsite AC power is lost, portable generators can be brought to the site. Of course, this depends on their availability and on transportation. The statement in the report that AC can be available by using inverters powered by DC batteries does not make sense to me. The plant power demands of DC and AC are surely totally different in scale.

10. Doubts about keeping a molten core inside the pressure vessel can be found in a report of the French IRSN from July, 2015. The problem is that the intense decay heat of the fuel might be confined to a molten fuel layer in the general mess of molten material from the core. This layer would then melt through the side of the pressure vessel. The experiments that have been done were small scale and don’t directly apply to the AP1000.

11. There is an unusually detailed description of the reactor in a GE-Hitachi document, “The ESBWR General Description Book”

12. I got this material from a GE-Hitachi paper "Response to an Extended Station Blackout" by Barrett and Marquino.

13. There is an obvious problem designing a filtered vent for newer reactors with small containments and core catchers. A sudden overpressure of the containment--due to rapid steam production, for example--could be difficult to release thru a filter. Both the vent and the filter would have to deal with high pressures and large volumes of steam and radioactivity.

Chapter 5-Some Future Reactors

1. I will refer here to breeder reactors. Another use of fast neutron reactors is to burn up the heavy and long lived isotopes, such as plutonium, made in present power reactors. These fast reactors are often called "burners", as they destroy fissionable material rather than making it. To burn the fissionable material, it has to be extracted from spent reactor fuel, by "reprocessing". An advantage is that this extraction leaves behind the usual lighter fission products. These have relatively short half lives and mostly decay away after a century or two rather than the much longer time for the heavier plutonium-like isotopes.

2. It is possible in principle to breed fissionable fuel in a reactor but never extract the fuel--instead burning it in place. That way the reactor is never opened, it just creates and burns its own fuel from either uranium or thorium. It has to be started off with some fissionable material, of course. (Otherwise there would be no neutrons to breed new fissionable fuel.) No reactor of this type has ever been built.

3. The U.S. IFR line of development is described in a very readable book, "Plentiful Energy" by Charles E. Till and Yoon Il Chang, who had key roles in the IFR development. Much of my discussion in the text is taken from this book, which I recommend. (Besides the EBR-I and EBR-II, several other Argonne fast neutron reactors were used in the development of the IFR concept.) The actual IFR effort ran from 1984 to 1994 when it was very unwisely killed by the Clinton administration, a move somewhat similar to the termination of renewable energy work by the Reagan administration. Future energy research and prototype development in the U.S. has proceeded by starts and fitful ends. Much of the knowledge needed to develop complex systems is in the collective understanding of the people involved, not in books or computer programs. We tend to abandon both projects and people in a very inopportune way.

4. There have been many criticisms of fast neutron reactors. It is not clear to me how well these criticisms will hold up when we have to cope with a very low fossil carbon future. For example: cancelling U.S. breeder reactor programs in the 1990's did not reduce the proliferation of nuclear weapons--diplomacy did that to some extent; a number of breeder reactors have succeeded, their technical problems overcome; the risks of liquid sodium coolant is not clearly a fatal problem; at least the EBR-II was a passively safe reactor, although not all designs are clearly as safe. To my mind, the biggest problem facing these reactors is the need for very large scale reprocessing of

radioactive material and fuel fabrication and the question of how these facilities are to be dealt with when their useful life is over. Past reprocessing plants have been very messy and expensive to clean up.

5. The history can be followed in “The EBR-II Story” from Nuclear News, Catherine Westfall, 2004. This is possibly the best written and very short account of the design of a breeder reactor, the EBR-II. The Argonne director who led the early breeder reactor program was Howard Zinn. The EBR-II director was Leonard Koch, and there is an Argonne authorized report by him titled “Experimental Breeder Reactor II” with many details.

6. The diagram in the text of the BR-600 is from I Piero, “Russian Nuclear Power Program”

7. It is not appreciated just how easy it is to make enough plutonium for a few bombs per year. The North Korean reactor that did this was a carbon dioxide cooled graphite reactor that could be fueled with natural, not enriched, uranium. It was only about a 20 megawatt thermal reactor--really small by current standards. Reprocessing fuel to get plutonium on this small scale has been understood for decades. The only subsequent technical problems are ensuring that the plutonium is mainly Plutonium-239 with few other isotopes and getting the bomb implosion to work properly. Eventually North Korea did this. Only worldwide diplomatic pressure can restrict this sort of proliferation.

8. You can read about the Oak Ridge reactor program in “An Account of Oak Ridge National Laboratory’s Thirteen Nuclear Reactors” (2009), ONRL/TM2009/181. I am only interested in the molten salt reactor program.

Chapter 6-Uranium and Thorium Supply

1. My estimate comes from the following WNA table, leading, according to them, to a present fuel cost estimate of about 0.5 cents per kilowatt-hour

Uranium:	8.9 kg U_3O_8 x $97	US$ 862	46%
Conversion:	7.5 kg U x $16	US$ 120	6%
Enrichment:	7.3 SWU x $82	US$ 599	32%
Fuel fabrication:	per kg (approx)	US$ 300	16%
Total, approx:		US$ 1880	