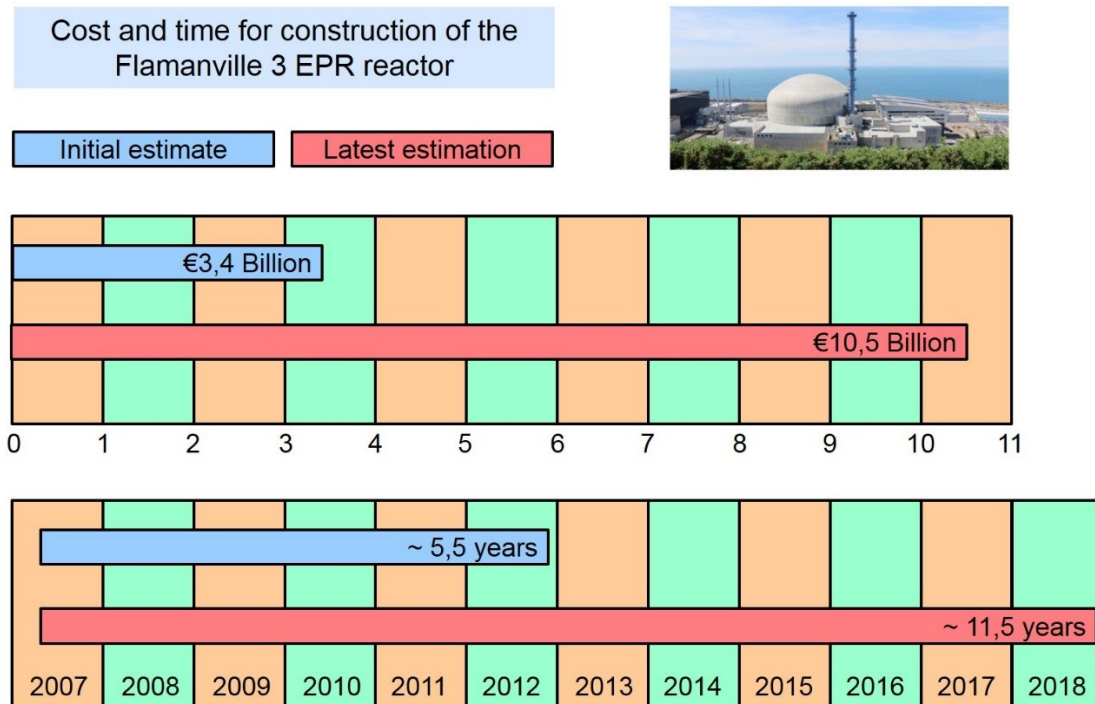


Hazard Pruning

Would a molten salt reactor really be cheaper?

It's understandable that some people find that difficult to believe, coming from a nuclear sector that has had so much trouble meeting its commitments, whether it be for construction time or the cost of nuclear power plants.



But a molten salt reactor is designed around a liquid fuel. It's a fundamentally different technology from the pressurised water reactors currently in use in all French nuclear power plants.

[According to Jean-Marc Jancovici](#), the cost of nuclear energy is 30% a "technical cost" [...] and 70% the "cost of caution" (what some might call the "cost of fear").

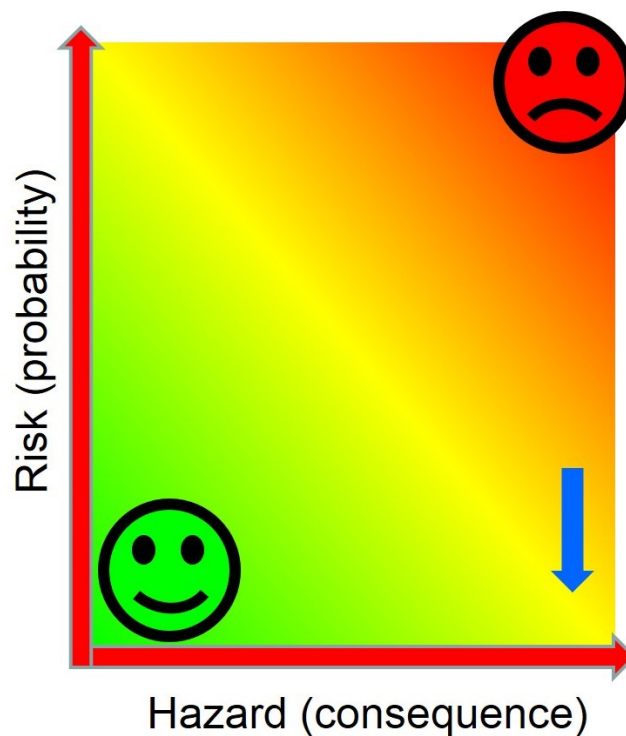
To work on this fear in a rational way, safety engineers use a tool called a "[fault tree](#)" to graphically represent possible combinations of events that would lead to an undesired outcome. The dialogue between a reactor vendor like [Framatome](#) and a safety authority is centred on this fault tree.

With 60 years of experience in the design, construction and operation of pressurised water reactors their fault tree is widely understood and documented, which is why the safety levels of these machines are excellent.

But it's a very big tree.

There is a fairly direct relationship between the size of the fault tree and the cost of the nuclear power plant. While the fundamental concept of the reactor has not changed for 60 years, experience and feedback from nuclear incidents and accidents has added new branches, twigs and leaves to the fault tree. And each leaf must be covered by at least one safety system, to ensure a very low probability of an accident, which increases the cost.

The current paradigm is that we have so much feedback from the pressurised water reactor that it is virtually impossible to change the concept. We have to live with the hazards that are intrinsic to that concept and work to reduce the risks. In the diagram below, that means following the blue arrow:



Let's go back to the example of the [EPR](#), which is a typical example of this paradigm. In a pressurised water reactor, losing the ability to cool the reactor is a serious malfunction which can result in a core meltdown. The cooling pumps that circulate pressurised water around the fuel assemblies must operate at all times. Sizable branches of the fault tree are dedicated to analysing the risks associated with this hazard.

What if we lose the power supply to the pumps?

- We start up a backup diesel generator to restore power.

And if the backup generator is down?

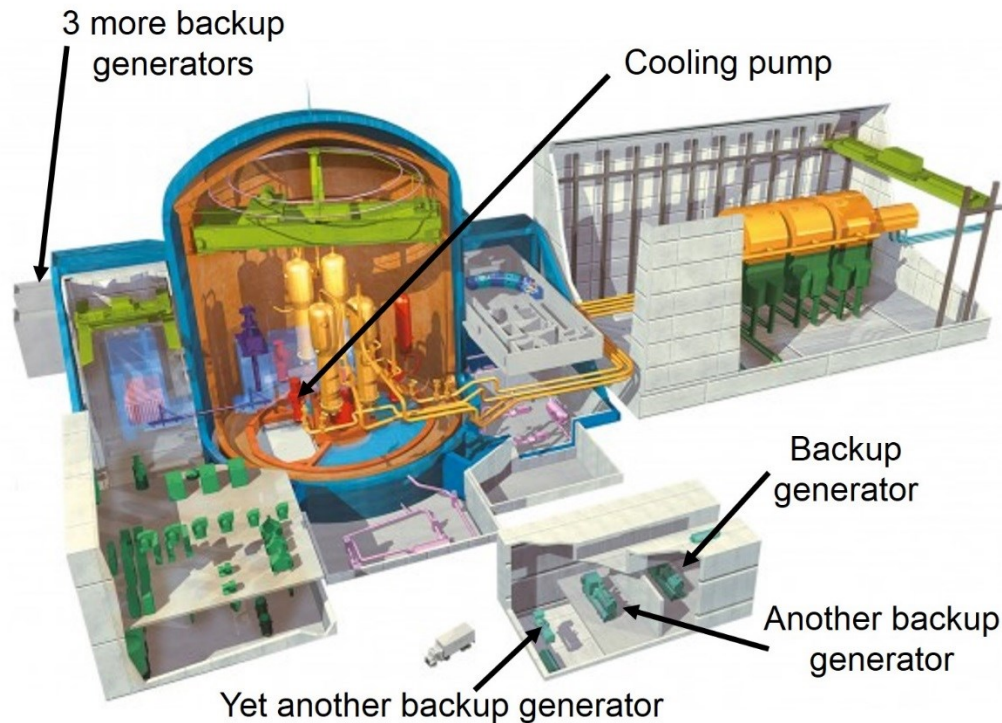
- Well, then there's another backup generator next to the first one.

And if both suffer from a common fault?

- A third backup generator, manufactured by another supplier, is installed next to the other two.

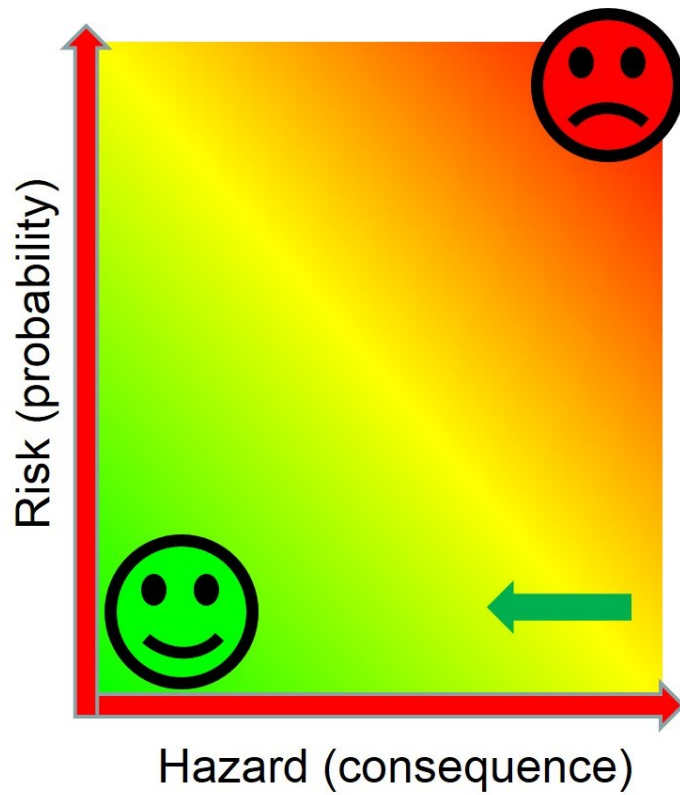
And if the building containing the generators is damaged or destroyed (by a flood, plane crash, terrorist explosion etc.)?

- In another building on the other side of the plant, there are 3 more backup generators.

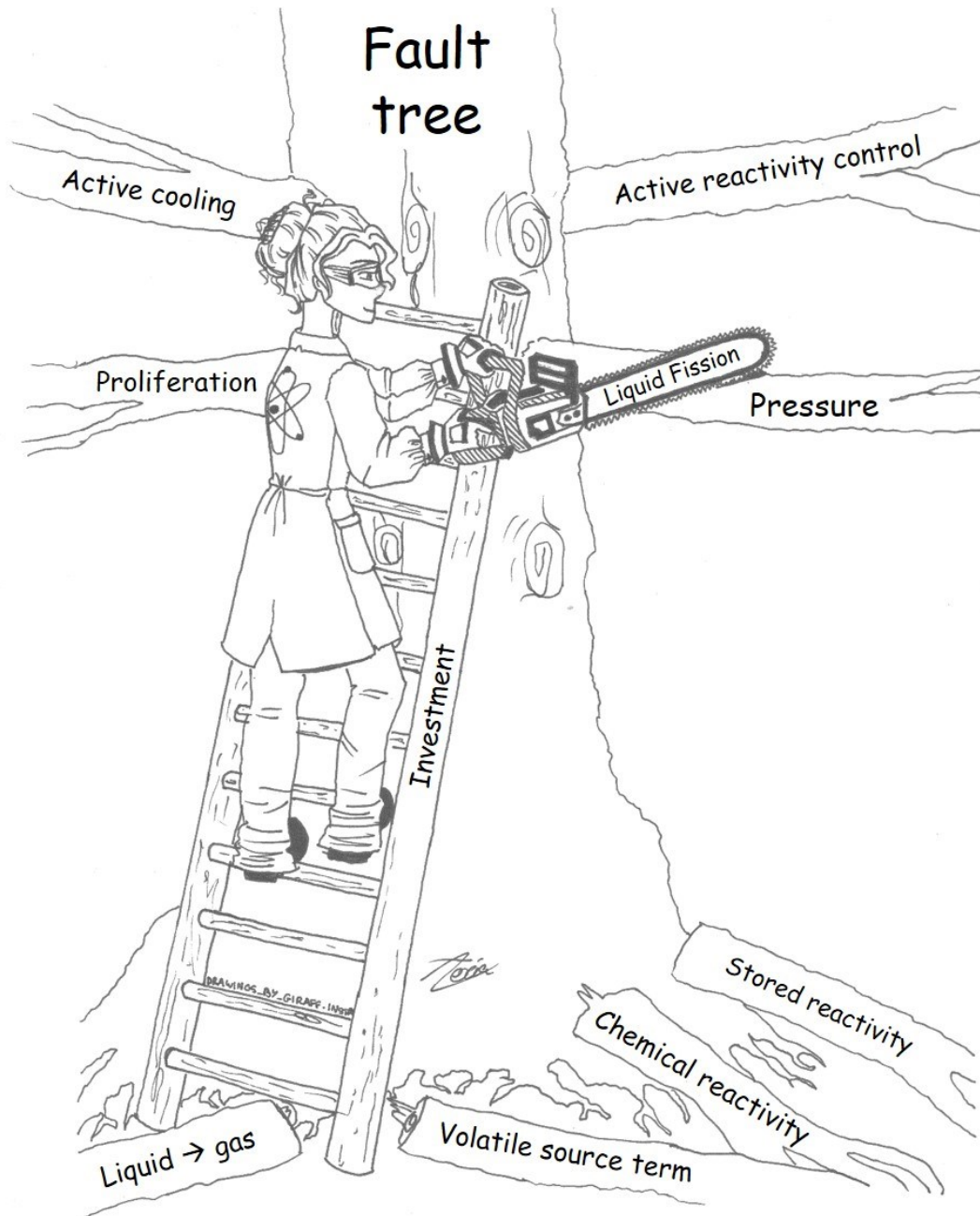


It's pretty easy to see that the redundancy in this strategy is a strong driver of complexity, cost and time to design, license, construct and commission. Following the blue arrow means increasing the cost.

Atomic architects who are at work designing molten salt reactors have a different paradigm. To reduce power plant costs, the design can be simplified by reducing or eliminating hazards.



With a liquid fuel, a whole bunch of tools, ideas and elegant and ingenious solutions are available that are simply impossible to implement when the fuel is a solid. When we follow the green arrow we tend to reduce cost, by pruning the fault tree:



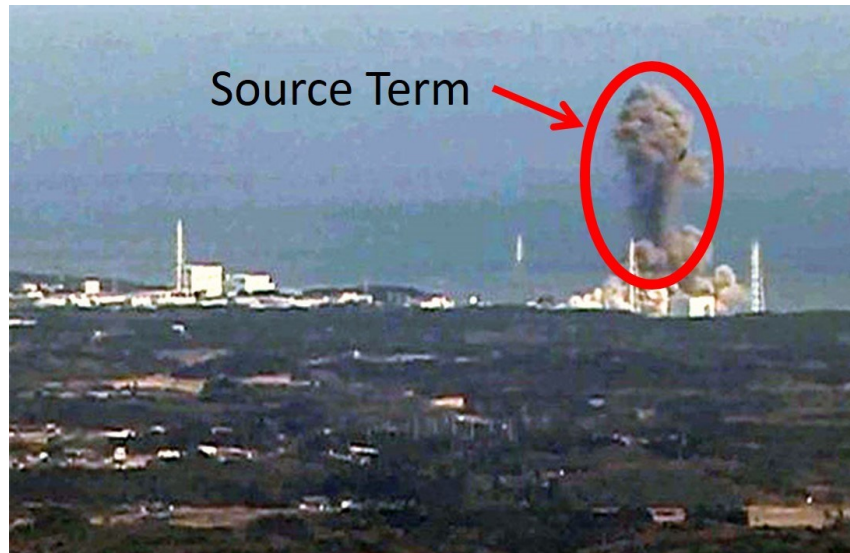
Pressure

In a pressurised water reactor, an enormous amount of potential energy is stored in the form of hot water under pressure. If suddenly released, this presents the hazard of turning into steam and propelling radioactive material into the environment. The accumulation of fission product gases in fuel tubes represents a second pressure hazard.

In a molten salt reactor, the liquid fuel is at atmospheric pressure. These hazards are eliminated.

Volatile source term

The source term – the types and amounts of radioactive or hazardous material released to the environment following an accident - represents different hazards depending on its physical state.



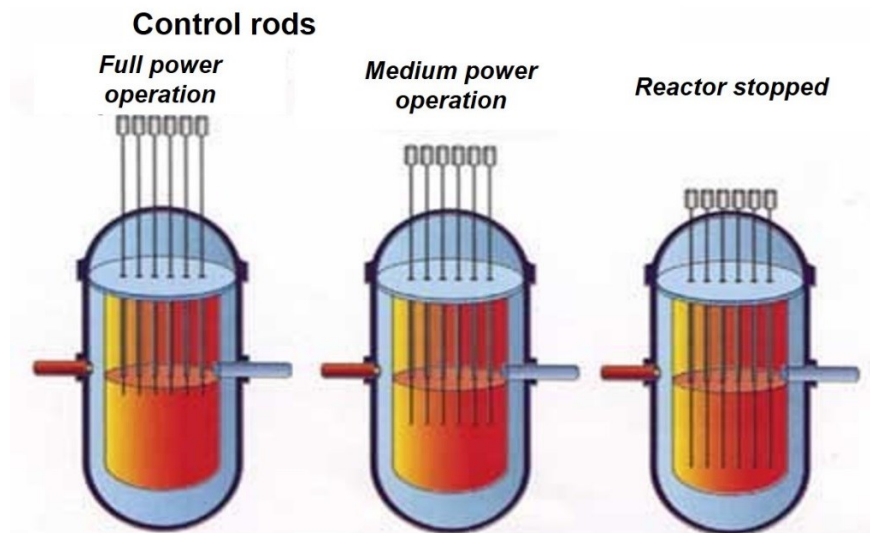
Radioactive isotopes that are solids or liquids will not go far in the event of an accident. But those that are gases can be dispersed in the atmosphere in a radioactive cloud capable of contaminating large areas.

In a conventional solid oxide fuel some fission products that pose a risk to human health, such as Caesium and Iodine, are [volatile](#) - they exist in the gaseous state.

In a molten salt fuel these isotopes are chemically confined by the [ionic liquid](#), with a [vapour pressure](#) close to zero. The amount of volatile source term is reduced by a factor of about one million. The hazard that contributes the most to the "fear" of nuclear energy is virtually eliminated.

Active reactivity control

In a pressurised water reactor, the power is controlled using control rods that absorb neutrons.



When we want to increase the reactivity we raise the control rods. Fewer neutrons are absorbed and the chain reaction accelerates. When we want to reduce the reactivity or stop the reactor we lower the control rods. It's an active control system, driven by mechanisms, by software and by humans. A failure can put the reactor in an unstable state and cause a [criticality accident](#).

A molten salt reactor is a [homeostatic](#), self-regulating system, where reactivity control is managed passively, without control rods. As the temperature of the fuel increases, the liquid expands. Each atom is now a little further from all the others, and the probability of fissioning a heavy nucleus decreases, so reactivity and power also decrease. When the temperature drops, the fluid contracts and the power increases. The laws of physics are in charge.

Active cooling

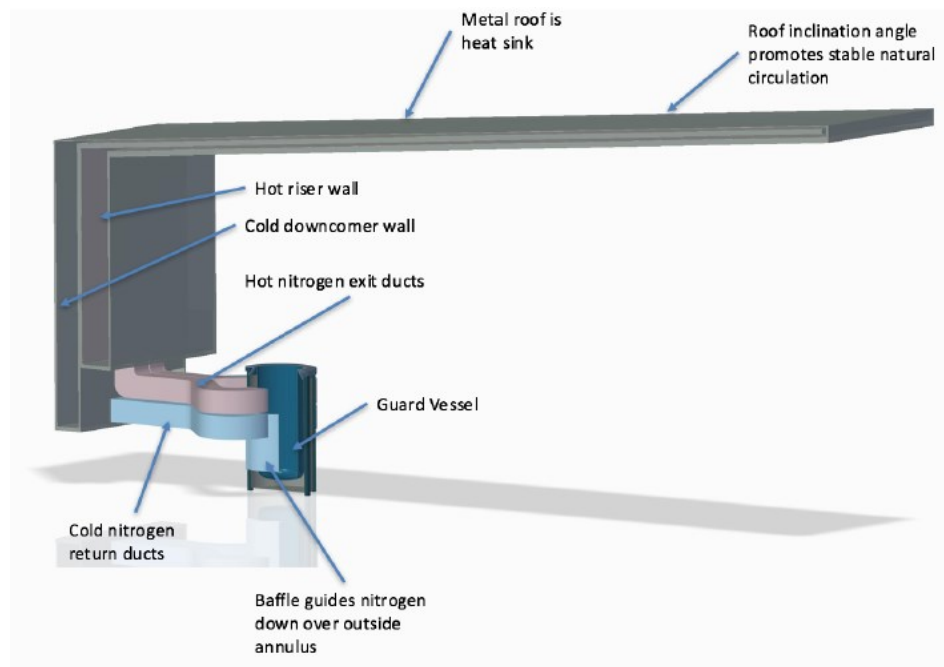
In all nuclear reactors, heat is generated in two ways:

1. The fission of heavy nuclei, which generates two smaller atoms called fission products (about 89% of the heat produced)
2. The decay of radioactive fission products (the remaining 11%)

Fission can be stopped at any time. In a pressurised water reactor for example, the control rods are dropped into the core and 2 seconds later all fission has stopped. But it's impossible to stop

the fission products decaying. In a solid fuel, decay heat is conducted through the material of each pellet, and then conducted through the cladding into the cooling water. It's crucial to get rid of the heat otherwise the temperature can rise and the fuel pellets can melt, hence the importance of the cooling pumps in a pressurised water reactor to ensure active cooling, and the backup generators mentioned above to ensure that the pumps always keep running.

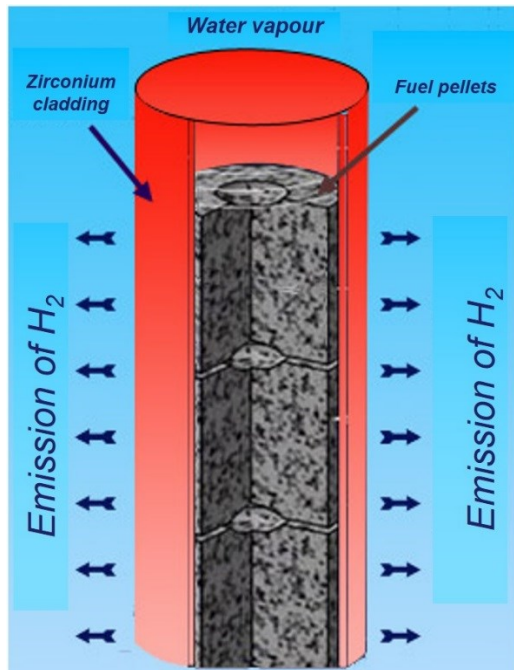
A liquid fuel benefits from the physical mechanism of convection to transport the heat produced by the fission products to the walls of the reactor, where it can be removed by passive systems that require no human involvement.



The passive heat removal system in Terrestrial Energy's IMSR reactor.

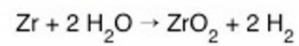
Chemical reactivity

In a nuclear reactor the materials used can be a source of hazards. The solid fuel pellets in a pressurised water reactor are surrounded by cladding made from zirconium alloy, a material which brings many advantages to the reactor design. But if the fuel pins are not cooled properly, water in contact with them can react chemically with the zirconium, [releasing hydrogen](#):



$$T > 900^{\circ} \text{C}$$

Zirconium oxidation



- *Emission of Hydrogen*
- *Cladding damage*
- *Volatile isotope leakage*

To manage this hazard, EPR reactors are equipped with combiners, capable of converting the hydrogen back into water, a system that increases the cost of the reactor.

It's worth mentioning sodium cooled fast reactors here. Sodium is an attractive material for reactor physics, but it presents major (read expensive) challenges in the management of its chemical reactivity:



Reaction of [sodium](#) with water

But in your kitchen you can find that same sodium, combined with another reactive element – chlorine, [in ionic form](#).

It is precisely because salts are composed of very reactive elements that when combined with an [ionic bond](#) they form substances which are extremely chemically stable.

Proliferation

People who sell double glazing no longer speak about "anti-intrusion" glass, preferring the term "delayed intrusion". If a burglar really wants to break your window, he will do it if he has enough time.

[Nuclear proliferation](#) is a similar story – it's impossible to totally eliminate the hazard of fissile material being acquired for military or terrorist purposes. This branch of the fault tree cannot be cut off completely, but it can be pruned down if we make things extremely tedious for an organisation with such intentions.

Molten salt reactors have several attributes that would reduce this hazard:

- They can be powered by fuels with impurity levels that are discouraging to criminals.
- The fuel in the reactor is protected by the intense radiation coming from the fission products.
- Fuels can be "denatured" with natural uranium.
- If online reprocessing is used, the waste can include no fissile material.
- If the thorium-uranium fuel cycle is used, the fissile material is protected by the highly radioactive daughter isotopes of Uranium-232.
- It is not necessary to use highly enriched uranium

Stored reactivity

Solid fuels are typically loaded into a pressurised water reactor for a 12 to 18 month period. To ensure full power operation at the end of this period, the run must be started with a store of excess fissile material. Without the control rods, at the beginning of the run the reactor would be in a state of supercriticality.

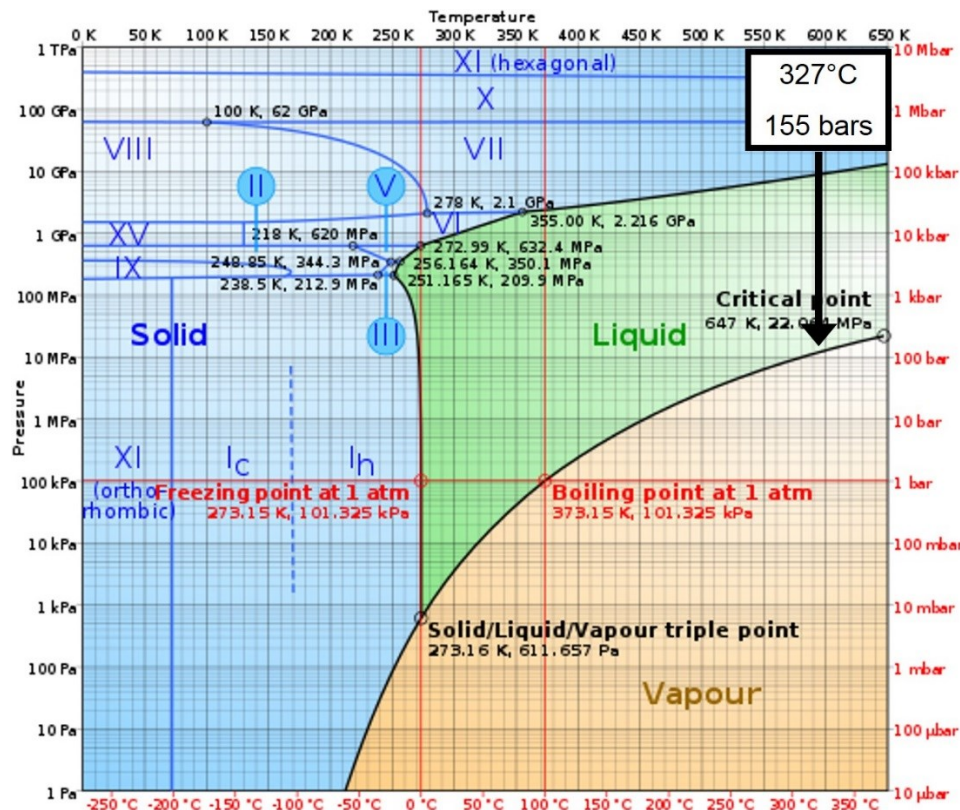
During the run the chain reaction is [poisoned by Xenon-135](#), a gaseous fission product that gobbles neutrons and can cause power fluctuations. This gas is produced inside the solid fuel, and remains locked into its structure. Excess reactivity needs to be provided to compensate for the reactivity lost due to absorption of neutrons by the Xenon.

In a liquid fuel, gaseous fission products such as Xenon remove themselves from the fuel by forming bubbles which rise to the surface of the liquid. Also, many designs allow fissile material to be added during a run. The hazard of stored reactivity at the beginning of the run can be greatly reduced.

Liquid → gas

When producing energy, higher temperatures mean better power conversion efficiencies. Pressurised water reactor designers dream of raising their operating temperatures by a few degrees to extract more useful megawatts of nuclear power from their systems.

But the water in these reactors must remain in the liquid state, otherwise the system is put in a dangerous condition. In the temperature / pressure diagram below, you have to avoid getting too close to the line between the green and orange regions.



One way to get away from this limit line is to increase the pressure (for example, an EPR reactor operates at 155 bars). But more pressure means more hazard and thicker, more expensive plumbing. The poor designer is being pulled in all directions at once:

- Increase the temperature for more value!
- Lower the pressure to reduce the cost!
- Not too close to the limit to maintain the safety margin!

Operating at atmospheric pressure, the fuel in a molten salt reactor is typically at a temperature of around 700°C, so the power conversion efficiency increases from 33% to 45~50%. The safety margin is much greater since the molten salts have a boiling point typically around 1400°C.

Working at the concept level to eliminate or reduce hazards, instead of reducing the risks of a known concept, is a new paradigm for nuclear energy. The [atomic architects](#) who have made this paradigm shift are already in dialogue with regulators - in Canada, China, the United States and elsewhere, but not in France. Constantly on the lookout for the best compromise between [value, cost and time](#), liquid fission helps them to prune down their fault trees, for an easier dialogue with regulators, and safer and cheaper nuclear energy.

John Laurie, <http://fissionliquide.fr/>

February 2018

Fault tree illustration: Alexia Laurie