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General Comment

I hope the nuclear industry is borrowing from the Refining/Chemical Industry and will do HAZOP (HAZard and OPerability) and LOPA (Layers Of Protection Analysis Studies) and incorporate appropriate SILs (Safety Integrity Levels) into the design. In my opinion, if this had been done for Fukishima, that disaster could have been avoided. I am attaching some slides on the sodium cooled reactor types and Safety. The latter contain links to short videos on HAZOP, LOPA, AND SIL that are only a few minutes long and are well worth viewing.

My biggest concern for the sodium cooled reactors is that at some point in the process there is a heat exchanger that transfers heat from molten sodium to water/steam, with the steam used to turn turbines to generate electricity. I am concerned about process upsets that can lead to large rapid temperature swings in this exchanger (and the exchanger that extends through the hot and cold internal sodium pools). This can lead to tube failure and sodium coming into contact with water leading to an explosion.

In my own experience, I have seen exchangers fail due to upsets. This needs to be addressed in proper HAZOP, LOPA, and SIL studies.

I am attaching slides from courses I teach on Refining and Petrochemicals and Global Warming, Renewable Energy, and Decarbonization on the sodium cooled reactor and on Safety. I would be willing to discuss this further if contacted.

Attachments

Sodium Cooled Nuclear Reactors

Processes for Safe Process Design

Sodium-Cooled Nuclear Reactor

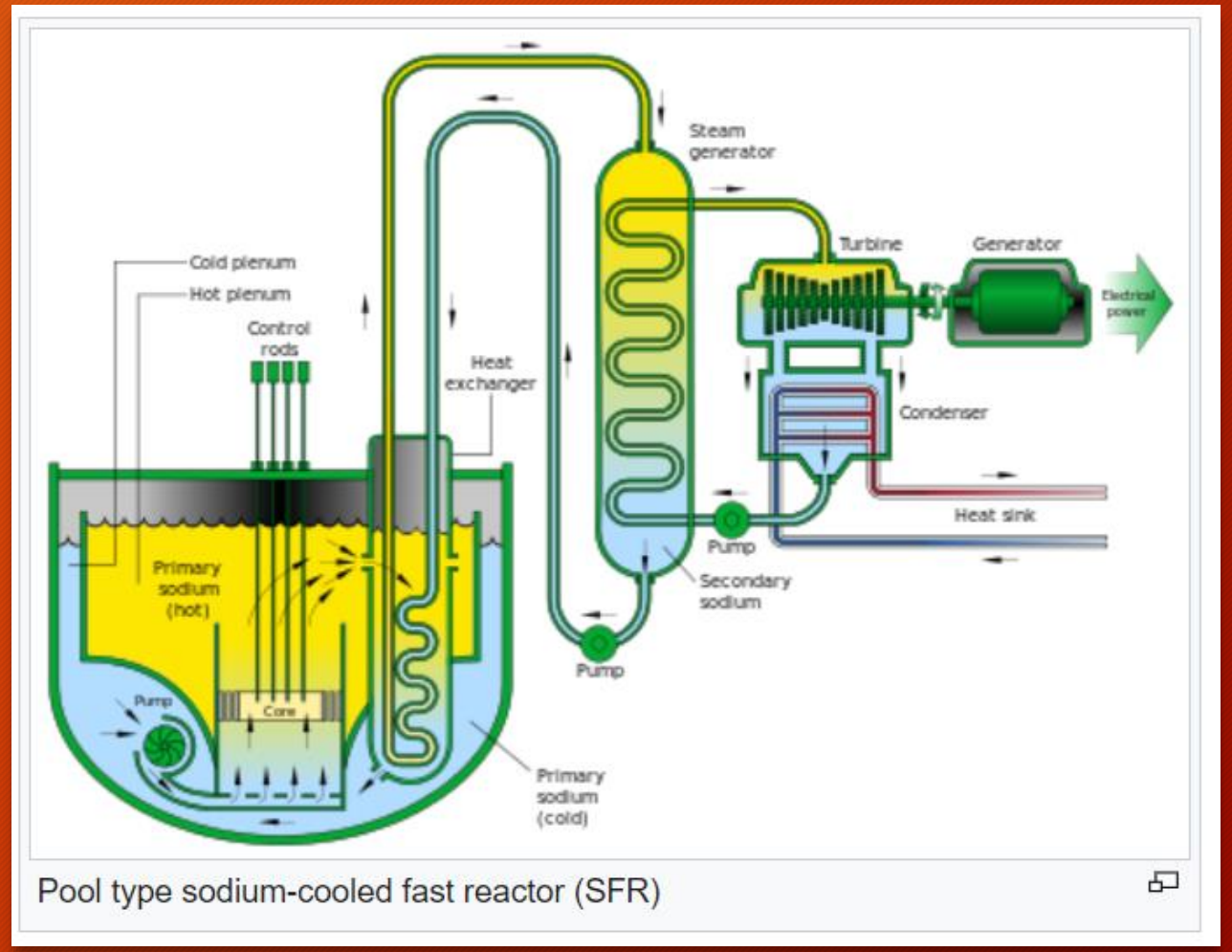
1

References

- Wikipedia, Sodium-cooled fast reactor
  Sodium-cooled fast reactor – Wikipedia
- TerraPower, GEH introduce Natrium, 01 September 2020
  TerraPower, GEH introduce Natrium : New Nuclear - World Nuclear News (world-nuclear-news.org)
- The Guardian, Bill Gates and Warren Buffett to build new kind of nuclear reactor in Wyoming, June 2021
  Bill Gates and Warren Buffett to build new kind of nuclear reactor in Wyoming | Bill Gates | The Guardian

Pool Type Sodium-Cooled Nuclear Reactor – How it works

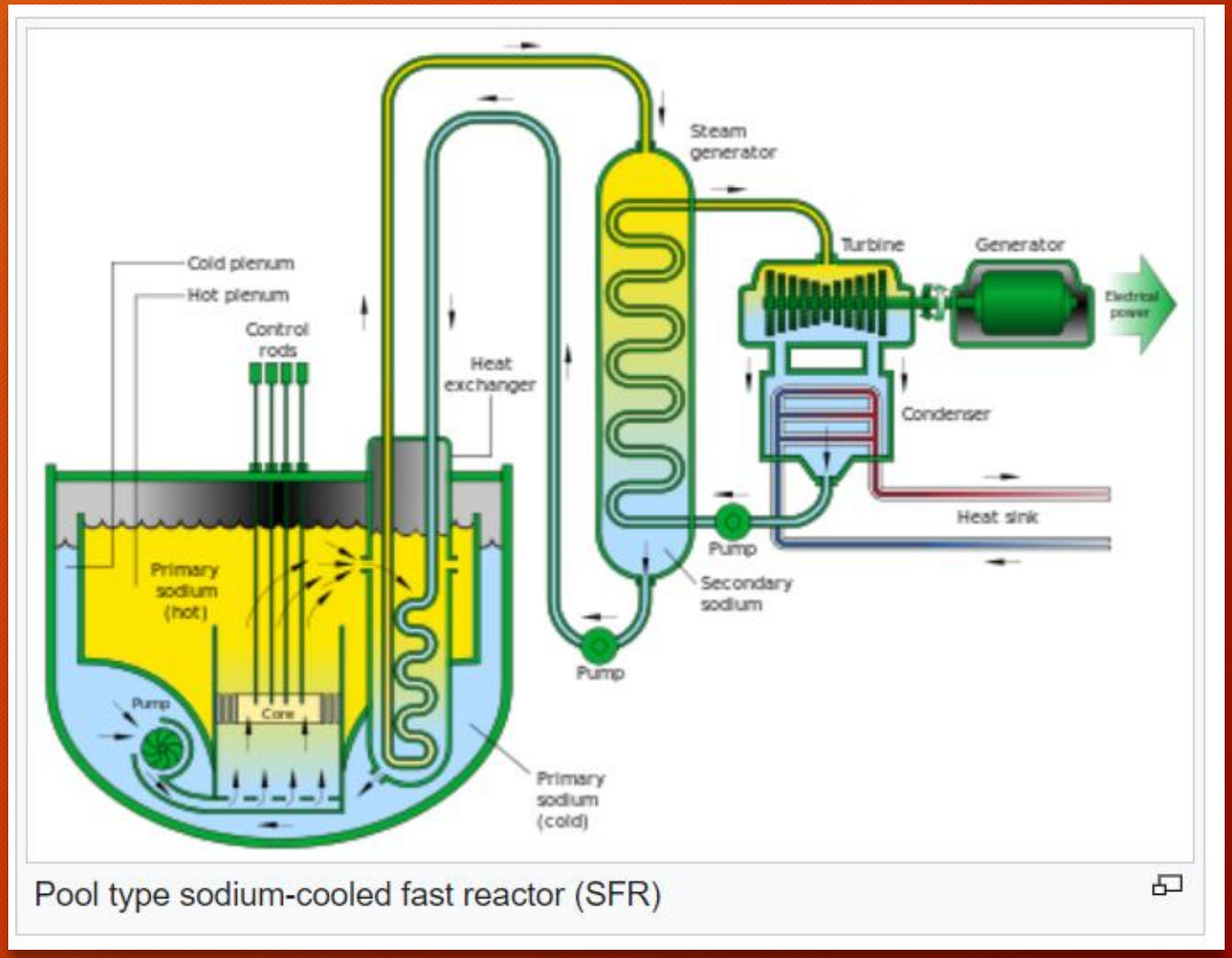
- Source Wikipedia
  Sodium-cooled fast reactor - Wikipedia
- The control rods containing uranium are lowered into the primary pool.
- Heat released by the nuclear reaction melts the sodium in the primary pool.
- Heat is transferred from the hot pool to the cold pool through the surface area of the cold plenum, which causes the sodium in the cold pool to melt.
- Heat is transferred to melt and heat sodium in a heat exchanger that extends through the hot pool to the cold pool.
- Sodium is preheated in the bottom of the exchanger by the cold pool. This also cools sodium returned to the cold pool from the external steam generator heat exchanger.
- Sodium from the external exchanger is further heated as it passes through the hot pool.
- Heat is transferred from the sodium in the steam generator to water to generate steam.
- The steam turns turbines to generate electricity.
- The tubes in both internal and external exchangers can undergo considerable temperature change, especially during upsets. Can this lead to tube failure?



Pool type sodium-cooled fast reactor (SFR)

Pool Type Sodium-Cooled Nuclear Reactor - Concerns

- Source Wikipedia
  Sodium-cooled fast reactor - Wikipedia
- First concern was what happens when sodium freezes during upsets
  - This can safely be handled by pulling control rods, and then reinserting them.
  - Heat generated by the inserted control rods will remelt the sodium.
- Three pools shown
  - In containment vessel, outer “cool” pool (1) is pumped past the control rods where it picks up heat to become the “hot” pool (2).
  - External pool loop (3) in the steam generator circulates to the internal heat exchanger and transfers heat to generate steam for turbines generating electricity.
- What about upsets in the external heat exchanger loop?
  - Sodium can still freeze in the external loop including heat exchanger and piping? How would that be remelted after upset?
  - Thermal shock or loss of steam side pressure could cause severe tube vibration and rupture, leading to water coming in contact with sodium.
  - If water gets in contact with sodium, BOOM!!!
- The latest reactor build in France has huge cost overruns and required a lot of rewelding due to poor construction practice that cannot be tolerated.

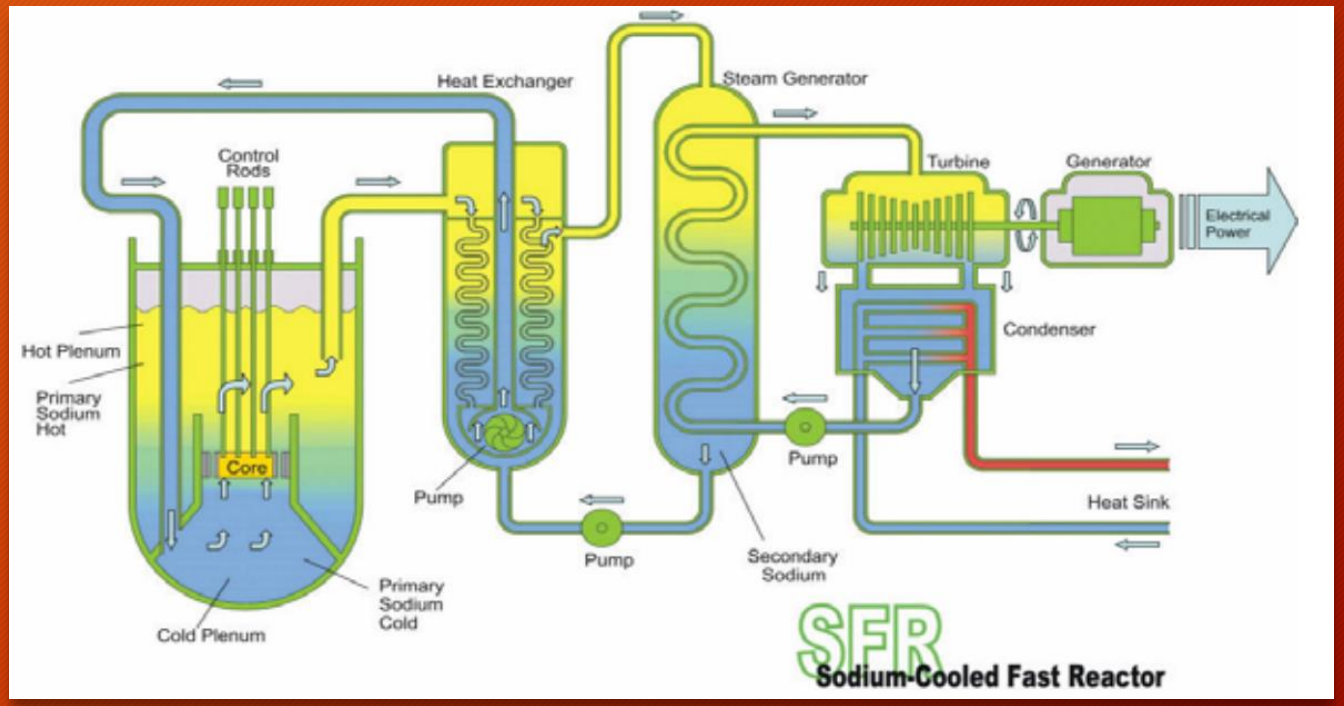


Pool type sodium-cooled fast reactor (SFR)

Difference between pool and loop designs

- Source Wikipedia
  Sodium-cooled fast reactor – Wikipedia

- The two main design approaches to sodium-cooled reactors are pool type and loop type.
- In the pool type, the primary coolant is contained in the main reactor vessel, which therefore includes the reactor core and a heat exchanger. The US EBR-2, French Phénix and others used this approach, and it is used by India's Prototype Fast Breeder Reactor and China's CFR-600.
- In the loop type, the heat exchangers are outside the reactor tank. The French Rapsodie, British Prototype Fast Reactor and others used this approach.



Safe Design Processes and Chemical Safety Board Videos

Safe Design Processes and Link to the Chemical Safety Board (CSB) Site

- HAZard and Operability Study HAZOP
  https://www.youtube.com/watch?v=6AqtX8oCpKI
- Layers of Protection Analysis (LOPA)
  https://www.youtube.com/watch?v=L3kQ9DKHS5A
- Safety Integrity Level (SIL)
  https://www.youtube.com/watch?v=Af-CbZ7aTCY
- Project Risk Assessment with examples
  https://bigpicture.one/blog/project-risk-assessment-examples/#:~:text=A%20risk%20matrix%20gives%20you,occurs%20(y%2Daxis).

- Chemical Safety Board Main Site
  https://www.csb.gov/
  - BP Deepwater Horzon Macando Well Blow Out
    https://inspectioneering.com/videos/2014-07-05/4925/csb-safety-video-deepwater-hor
  - C5-C6 Isom Unit Explosion BP Texas City Refinery
    https://www.youtube.com/watch?v=VCcN4SQkb9A
  - **Tesoro Refinery Fatal Explosion and Fire (Reformer Heat Exchanger Failure)**
    https://www.youtube.com/watch?v=8vPaQYM-tWs

What is a HAZOP?

- HAZOP stands for hazard and operability study. It's purpose is to identify and assess risk through a creative and collaborative process based on the collective knowledge of a multi-disciplinary team where there is a facilitator whose function is to guide the team to achieve high quality decisions.

Steps of a HAZOP

1. Identify the risk by asking what can cause a hazardous event by thinking of specific process deviations.
   - Deviations are key word driven, such as:
     - High Temperature; Low Temperature;
     - High Pressure; Low Pressure;
     - High Level; Low Level;
     - High Flow; Low Flow; No flow
2. Describe the consequences and assign a severity level.
3. Assess the probability of the cause.
4. Evaluate the risk based on the severity and probability without any safeguards. Look up your matrix to categorize the risk by locating the risk based on the probability and the severity.
5. Assess the risk with safeguards.
6. Make a decision to accept the risk or make a recommendation to reduce the risk.

What is a LOPA?

- LOPA stands for Layer of Protection Analysis.
- It is a method applied to high-risk scenarios where risk needs to be reduced.
- LOPA is a process for allocating appropriate safeguards proportional to the risk to achieve acceptable risk tolerance for specific consequences.

Steps of a LOPA

1. Identify a single consequence to analyse.
2. Understand your company's tolerable frequency for the consequence.
3. Assess the probability of the initiating events.
4. Identify independent protection layers and assign a risk reduction factor.
5. Calculate the expected frequency of the consequence scenario.
6. Decide if risk is acceptable based on the tolerable frequency.
7. Determine if additional safeguards are needed to reduce the risk to meet the tolerable frequency.

What is a SIL?

- SIL stands for Safety Integrity Level
- It is a way to measure a Safety Instrumented Function (SIF)
- A SIF is a combination of sensor(s), logic solver, and final element(s) that detect a hazard and bring the process to a Safe State.

Example of a SIL

- A pressure sensor detects high pressure in a vessel
- Control computer logic closes a valve (element) to stop flow into the vessel to prevent overpressure to bring the vessel to a Safe State.
- After this SIL is added to the design, the steps of a LOPA (Layers of Protection Analysis) are repeated to determine if an acceptable risk and estimated frequency of vessel rupture is achieved.
- If not, another SIL must be added, such as a relief valve (element).
- A relief valve set pressure is chosen, such that it opens automatically below the vessel design pressure without the need for computer control logic, i.e., the logic is built into the relief valve.

What is a SIL level?

- The SIL level defines the safety reliability range.
- The Safey Reliability Range can be expressed as the Probability of Failure on Demand (PFD), or the Risk Reduction Factor (RFD), which is the inverse of the PFD.
- As additional SIL's are added, their RFD's are multiplied until an acceptable overall RFD is achieved that meets a company's goals based on its Risk Matrix.
- Adding SIL's cost money for hardware and maintenance. Thus, SIL's are only added until an acceptable overall RFD is achieved.

SIL	Reliability	PFD	RRF*
1	90.00 – 99.00%	0.1 – 0.01	10 to 100
2	99.00 – 99.90%	0.01 – 0.001	100 to 1000
3	99.90 – 99.99%	0.001 – 0.0001	1000 to 10000
4	>99.99%	0.0001 – 0.00001	10000 to 100000

What is a Risk Matrix?

- A Risk Matrix gives you a quick view of project risks and their consequences' severity (impact). You use it to allocate ratings for each risk based on two intersecting factors:
  - The likelihood (or probability) of a risk to occur (x-axis).
  - The impact (or severity) if a risk occurs (y-axis).
- Risks can include risks of injury or death, risk of financial loss, and risk to company reputation.

Example of a Risk Matrix

What is a Risk Assessment Form?

- A risk assessment form tabulates identified risks, their likelihood, their impact, risk ranking (likelihood x impact), and suggested response (action).

Example of a Risk Assessment Form

Risk assessment form

RISK	LIKELIHOOD	IMPACT	RISK RATING	RESPONSE (ACTION)
Absence of warning signs on the heavy machinery can cause severe accidents	3	4	12	Warnings signs must be placed and explained to the employees.
Water leakage can cause injuries due to falls (bruises, broken limbs)	1	3	3	Equip employees with slip-resistant boots and place "Wet floor" warning signs.
Noise level coming from the quipment is above acceptable criteria and can cause hearing loss and stress	2	4	8	CE markings must be requested for equipment. Noise level must be checked. The level must not be higher than 85 dBA.
Non-qualified machinery operators with insufficient experience can cause injuries and fatalities	2	5	10	Qualifications of the operators must be checked.
Electrical leakage can cause severe accidents and fatalities	5	5	25	Wiring of equipment must be inspects before each use. Damaged or frayed electrical cords must be replaced immediately. Enforce safe work practices every time electrical equipment is used.