Simulation of a Nuclear Pressurised Water Reactor based Power Plant

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Disclaimer

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The sole purpose of this document is to provide a guide to the accompanying application.

Use the information contained at your own risk.

Contents

Acknowledgements

Whilst writing the associated application and preparing this documentation and various tutorial videos, I have managed to combine my hobby of computer programming and my years working at various power plants around the world for my own enjoyment and satisfaction.

Whilst I am happy of the outcome, I do realise that many features are missing or could be improved. It may be in the future I will take another look at this program and update/improve it further.

I would like to acknowledge the following people and/or programming utilities that both inspired me and allowed this program to be written.

Ernest Rutherford (the father of nuclear physics and New Zealand's greatest export) without who none of this would be possible.

Colin Tucker author of How to Drive a Nuclear Reactor (ISBN 978-3-030-33875-6) which was the trigger for me to write this application.

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RobbytheAtomicEngineer who was most helpful in suggesting new ideas/improvements and beta testing this software.

Power plant icons created by Freepik - Flaticon.

made with XOJO

Application files and this user guide can found on my webpage `https://richardspowergenerationpage.com`

Tutorial videos can be found on YouTube at `https://www.youtube.com/@RichardSmith-zc9zi`

Figure 1: Power plant icons created by Freepik - Flaticon

1 System Requirements

The current release version of this software for both Windows and macOS is NucSIM v1.38.0

1.1 macOS

Minimum System requirements macOS are;

- INTEL or ARM processor
- macOS 10.14 (Mojave)
- 3024 x 1964 pixel screen

1.2 Windows

Minimum System requirements Windows are;

- Windows 10 (build 1903+) or Windows 11
- 3024 x 1964 pixel screen

Note: Whilst the simulator program runs on Windows it was originally designed for macOS only. Therefore the experience of using this software is better on macOS with especially the update of graphic screens a bit slow on Windows machines. I will continue to try and rectify these issues but currently I recommend to use the macOS version of this software if possible.

2 Introduction

This simulation represents a rather basic model of a 3500MW (thermal) Pressurised Water Reactor with attached steam turbine for electrical power generation. Whilst it is more of a proof of concept to demonstrate what is easily possible with a small amount of programming effort it still may be of some use in educating non nuclear power plant operating staff. Actual plant staff training should be undertaken on a much more comprehensive/expensive simulator.

2.1 Glossary of Terms

U-235 Uranium-235 or U-235 is an isotope of uranium making up about 0.72% of natural uranium. Unlike the predominant isotope uranium-238, it is fissile, i.e., it can sustain a nuclear chain reaction.

U-238 Uranium-238 or U-238 is the most common isotope of uranium found in nature, with a relative abundance of 99%. Unlike uranium-235, it is non-fissile, which means it cannot sustain a chain reaction in a thermal-neutron reactor.

Enrichment Uranium enrichment removes some of the uranium-238 and increases the proportion of uranium-235. The uranium fuel pellets contained within each fuel rod in our reactor has been enriched to a level of 4%. i.e. it contains 4% U-235 and 96% U-238.

Fission is a reaction in which the nucleus of an atom splits into two or more smaller nuclei. The fission process often produces gamma photons, and releases a very large amount of energy even by the energetic standards of radioactive decay. This is covered more completely in section 3.2.

Chain Reaction When the Neutrons produced by a fission of the nucleus go on to cause fission in other U-235 nuclei then a Chain Reaction is established.

Fast Neutrons Neutrons release in the fission process are moving very quickly - approx. ten thousand miles per second. This makes it difficult for them to be captured by a U-235 nucleus and continue the chain reaction.

Slow Neutrons Neutron after they have been Moderated (Slowed down) by the Moderator (Water in this case) to a speed where they are much more likely to be captured by another U-235 nucleus and continue the chain reaction.

Thermal Neutrons Another term for Slow Neutrons.

Moderate Refers to slowing down the Fast Neutrons produced by fission of U-235 to a slower speed.

Moderator The medium used to slow the Fast Neutrons so that they become Slow Neutrons. In a Pressurised Water Reactor the Moderator is the deminerlised water that fills the primary circuit and the spaces between each fuel rod. Other reactor types can use graphite or heavy water as the Moderator material.

Reactivity is a measurement of change in the number of nuclear fissions within the reactor core from one moment to the next. If the number of fissions is increasing then we can say the reactor has a positive reactivity. Conversely if the number of fissions is decreasing then the reactor has a negative reactivity. This is covered more completely in section 3.3.

Boron The element Boron absorbs neutrons and is soluble in water so therefore by adjusting the concentrations of boron in the primary circuit we can control the reactor reactivity.

Diluting to reduce the boron concentration in the reactor primary circuit.

Borating to increase the boron concentration in the reactor primary circuit.

Neutron Poison Some of the fission products generated during nuclear reactions have a high neutron absorption capacity, such as xenon-135. Because this fission product poison removes neutrons from the reactor, it will affect the reactivity. The poisoning of a reactor core by these fission products may become so serious that the chain reaction comes to a standstill.

Gadolinium Newly loaded U-235 fuel has a high reactivity, whilst in fuel that is 18 months old the reactivity is greatly reduced. To ensure a flatter profile of the reactivity of the fuel over the time (approx 18 months) between reactor refueling a burnable poison is added to the fuel elements during manufacturing. The element Gadolinium is used and for the first 3 - 4 months it will absorb neutrons and therefore have a negative effect on reactivity, but in the process will be consumed and thereafter have no effect.

Mode The reactor has 5 operating modes as described below;

- **Mode 5** Cold shutdown - reactor is sub-critical with 0% power output and primary coolant average temperature < 95 degC.
- **Mode 4** Hot shutdown - reactor is sub-critical with 0% power output and primary coolant average temperature is > 95 degC and < 176 degC.
- **Mode 3** Hot standby - reactor is sub-critical with 0% power output and primary coolant average temperature > 176 degC.
- **Mode 2** Startup - reactor is critical with power output $< 5\%$
- **Mode 1** Power operations - reactor is critical with power output $> 5\%$

SCRAM Reactor Emergency Trip - The meaning of the term SCRAM in regards to Reactor Emergency Trip has a rather vague origin[1].

SLB Steam Line Break is an accident case in which the steam line leading from each steam generator through the containment vessel wall and to the steam turbine building suffers a fracture resulting in a large leakage of steam either into the containment vessel or the turbine building and a de-pressurisation of the affected steam generator.

LOCA Loss Of Coolant Accident is an accident case where the primary coolant leaks either due to a large fracture of primary circuit piping, small fracture of a pipe connected to the primary circuit of stuck open pressure relief valve.

[1] `https://en.wikipedia.org/wiki/Scram`

2.2 KKS

The KKS system (Kraftwerk-Kennzeichen-System in German or factory numbering system in English) is a classification system for the complete power plant and its components and provides a common language for the designer, the manufacturer and the user.

It is used at many power plants around the world to identify the various components, such as pumps, valves, pressure vessels, electrical supplies and instrumentation in a logical and standard manner.

KKS will be used throughout the accompanying software application and also within this user guide to identify plant components - so it is a good idea that you become familiar with it.

A typical KKS code for an item of plant machinery is as below;

01MAV10AP001

This is broken down as follows;

01 - Unit 1

MAV Can be further broken down into;

- **M** Main machine
- **A** Steam turbine
- **V** lubricant supply system

10 location of item within this system

AP Pump

001 First pump in this system at this location

So in summary the KKS code 01MAV10AP001 refers to the Unit 1, main steam turbine lubricating pump. If two lubricating pumps are fitted in parallel then the other can be referred to as 01MAV10AP002 or even 01MAV11AP001.

In addition to M referring to Main machine, the following codes are also used in this simulation;

A - Grid and distribution systems

B - Power transmission and auxiliary power systems

G - Water supply and disposal

J - Nuclear heat generation

K - Reactor auxiliary systems

L - Steam, water, gas cycles

M - Main machine sets

P - Cooling water system

Q - auxiliary systems

U - Buildings

Also other than AP for pump, the following equipment keys are also used;

AA - valve, damper, etc

AC - heat exchanger

AE - Turning, driving, lifting and slewing device

AN - Compressor units, fans

AP - Pump units

AV - combustion equipment

BB - Storage equipment (vessels, tanks)

CE - Electrical variables (current, voltage, power, frequency)

CF - flow rate

CK - time

CL - level

CP - pressure

CS - velocity, speed

CT - temperature

CY - vibration

GH - Electrical and instrument installation units (cubicles, boxes)

GS - Switchgear equipment

GT - Transformer equipment

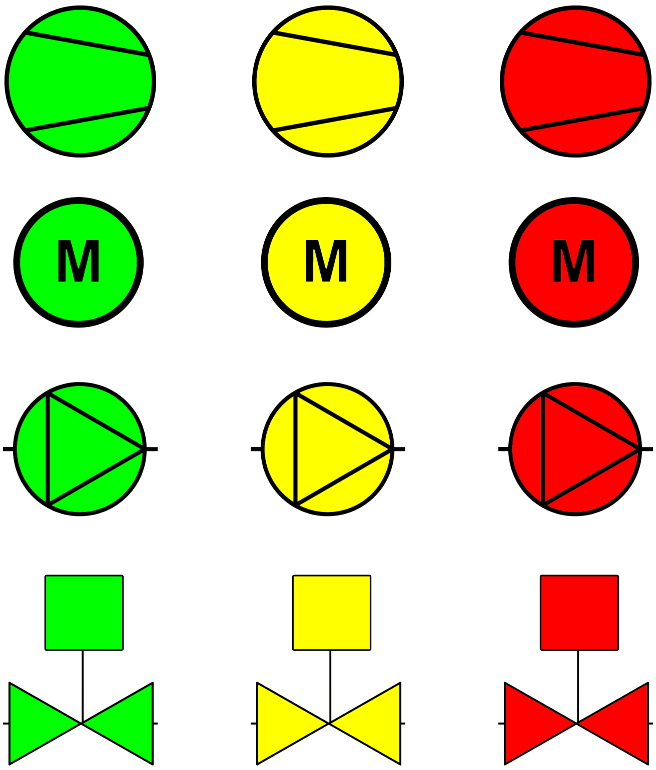
A complete list of KKS codes used in this simulation is provided in appendix A.

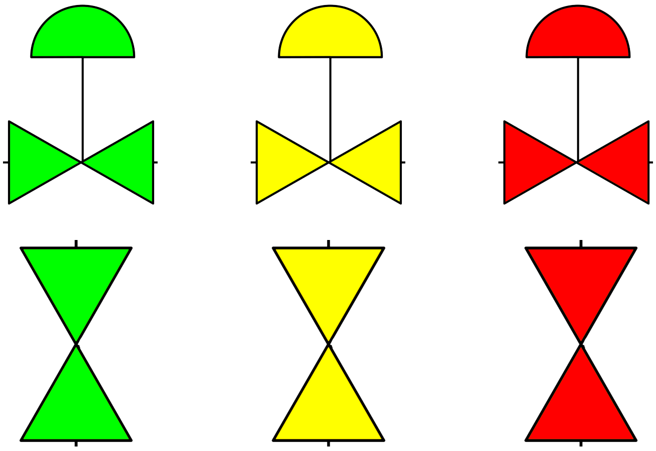
For further information on the KKS coding system please search on-line.

2.3 Open/Close, On/Off conventions

When using a screen to represent physical action in the real world, we must agree on a standard to clearly show when a valve is open or closed, or even in fault. For this simulation the colour RED is used to show that a valve is OPEN or that a pump/fan/motor is running. Conversely the colour GREEN means that a valve is CLOSED or that a pump/fan/motor is shutdown.

If the pump, motor, circuit breaker is coloured YELLOW, then is in in fault and will need resetting.





whilst above the colour RED indicated that a valve is OPEN for instance, when it comes to electrical system it is the opposite (i.e. a RED circuit breaker indicated it is closed.

It is better then not to think about if an item of equipment is OPEN or CLOSED, etc, but better to think of it being In Service and Out of Service.

Therefore if an item of plant (Pump, motor, valve or circuit breaker) is In Service it will be shown in RED, whilst if Out of Service it will be shown in GREEN.

3 Nuclear fission

3.1 Atoms

Atoms are the basic particles of the chemical elements. An atom consists of a nucleus of protons and generally neutrons, surrounded by an electromagnetically bound swarm of electrons. The chemical elements are distinguished from each other by the number of protons that are in their atoms. For example, any atom that contains 11 protons is sodium, and any atom that contains 29 protons is copper. Atoms with the same number of protons but a different number of neutrons are called isotopes of the same element.

Atoms are extremely small, typically around 100 picometers across. A human hair is about a million carbon atoms wide. Atoms are smaller than the shortest wavelength of visible light, which means humans cannot see atoms with conventional microscopes. They are so small that accurately predicting their behavior using classical physics is not possible due to quantum effects.

More than 99.9994% of an atom's mass is in the nucleus. Protons have a positive electric charge and neutrons have no charge, so the nucleus is positively charged. The electrons are negatively charged, and this opposing charge is what binds them to the nucleus. If the numbers of protons and electrons are equal, as they normally are, then the atom is electrically neutral as a whole. If an atom has more electrons than protons, then it has an overall negative charge, and is called a negative ion (or anion). Conversely, if it has more protons than electrons, it has a positive charge, and is called a positive ion (or cation).

The electrons of an atom are attracted to the protons in an atomic nucleus by the electromagnetic force. The protons and neutrons in the nucleus are attracted to each other by the nuclear force. This force is usually stronger than the electromagnetic force that repels the positively charged protons from one another. Under certain circumstances, the repelling electromagnetic force becomes stronger than the nuclear force. In this case, the nucleus splits and leaves behind different elements. This is a form of nuclear decay.

Atoms can attach to one or more other atoms by chemical bonds to form chemical compounds such as molecules or crystals. The ability of atoms to attach and detach from each other is responsible for most of the physical changes observed in nature. Chemistry is the science that studies these changes[2].

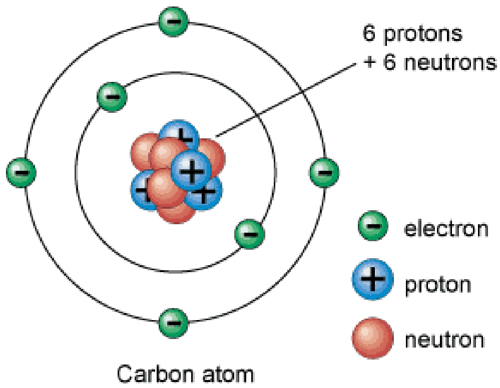


Figure 2: Diagram of a Carbon atom

3.2 Fission

Nuclear fission is a reaction in which the nucleus of an atom splits into two or more smaller nuclei. The fission process often produces gamma photons, and releases a very large amount of energy even by the energetic standards of radioactive decay.

For heavy nuclides, it is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). Like nuclear fusion, for fission to produce energy, the total binding energy of the resulting elements must be greater than that of the starting element.

[2] `https://en.wikipedia.org/wiki/Atom`

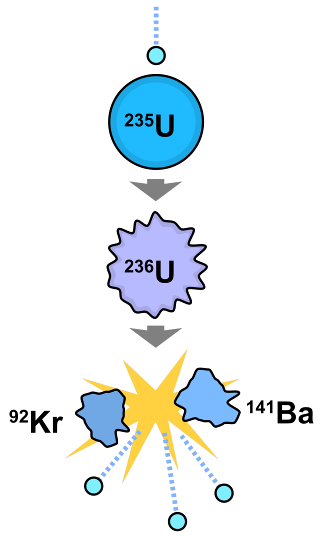


Figure 3: Fission of U235

Induced fission reaction
A neutron is absorbed by a uranium-235 nucleus, turning it briefly into an excited uranium-236 nucleus, with the excitation energy provided by the kinetic energy of the neutron plus the forces that bind the neutron. The uranium-236, in turn, splits into fast-moving lighter elements (fission products) and releases several free neutrons, one or more "prompt gamma rays" (not shown) and a (proportionally) large amount of kinetic energy[3].

Fast and Slow Neutrons
When a fission event occurs the neutrons liberated are travelling a high speed (they are Fast Neutrons). This speed is so high that their chances of being captured by another fuel atom and causing a further fission event is exceedingly small.

We need to slow down (Moderate) these Fast Neutrons to increase the chance of further fission events.

In a PWR (Pressurised Water Reactor) the water in the primary circuit purpose is to circuit the heat received from the fuel to the steam generators, but it also acts as a Moderator within the reactor to slow each Neutron down.

Chain Reaction
As shown above, neutron-induced fission generates extra neutrons which can induce further fissions in the next generation and so on in a chain reaction. The chain reaction is characterized by the neutron multiplication factor k, which is defined as the ratio of the number of neutrons in one generation to the number in the preceding generation. If, in a reactor, k is less than unity, the reactor is subcritical, the number of neutrons decreases and the chain reaction dies out. If $k > 1$, the reactor is supercritical and the chain reaction diverges. This is the situation in a fission bomb where growth is at an explosive rate. If k is exactly unity, the reactions proceed at a steady rate and the reactor is said to be critical. It is possible to achieve criticality in a reactor using natural uranium as fuel, provided that the neutrons have been efficiently moderated to thermal energies." Moderators include light water, heavy water, and graphite.

[3] https://en.wikipedia.org/wiki/Nuclear_fission

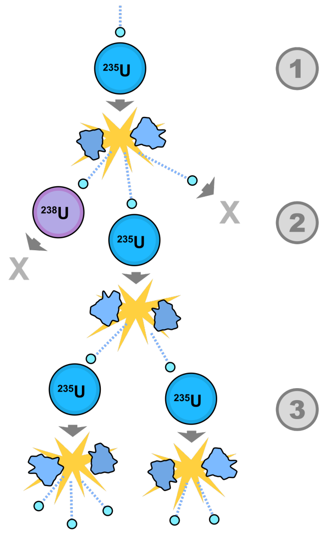


Figure 4: Chain reaction

A schematic nuclear fission chain reaction.

1. A uranium-235 atom absorbs a neutron and fissions into two new atoms (fission fragments), releasing three new neutrons and some binding energy.

2. One of those neutrons is absorbed by an atom of uranium-238 and does not continue the reaction. Another neutron is simply lost and does not collide with anything, also not continuing the reaction. However, the one neutron does collide with an atom of uranium-235, which then fissions and releases two neutrons and some binding energy.

3. Both of those neutrons collide with uranium-235 atoms, each of which fissions and releases between one and three neutrons, which can then continue the reaction.

The number of fissions occurring every second at full load (3500MW thermal) is approximately;

109,375,000,000,000,000,000

3.3 Reactivity and Criticality

Reactivity is a measurement of change in the number of nuclear fissions within the reactor core from one moment to the next. If the number of fissions is increasing then we can say the reactor has a positive reactivity. Conversely if the number of fissions is decreasing then the reactor has a negative reactivity.

If there is no change in the number of fissions from one moment to the next then reactivity is zero.

A 1% change is reactivity is called a change of 1 Nile (A Nile is not an SI unit but is a commonly used term for change in reactivity). However a 1% change of reactivity would have a rather large impact on the power output of your reactor, therefore a more common term would be the milliNile which is a 0.01% change in reactivity.

Within the reactor many variables contribute to the total value of reactivity. Some have a positive effect on reactivity, whilst others a negative effect, but for the reactor to be under control the positives and negatives must be almost equal. Factors affecting reactor total reactivity are as follows;

Fuel (+ve effect) A new load of fuel rods will give a positive reactivity of approximately 18 Niles. As the fuel is used then this will decrease and after 1 year of continuous operation be at approx. 12 Niles and after 18 months will be less than 4 Niles.

Protection Rods (-ve effect) Each protection rod (2 in this reactor) has an effect on reactivity of approximately -2 Niles.

Control Rods (-ve effect) Each Control Rod (4 in this reactor) has an effect on reactivity of approximately -1 Nile each. Total effect on reactivity when all Protection and Control rods are inserted into the reactor core is -8 Niles. Note that the effect of each rod on reactivity is not linear, with the effect tapering off at each end of the rods travel.

Boron (-ve effect) Boron concentrations in the primary circuit can be varied so as to control the reactor reactivity. This can be with a large dose of boron, maybe >3000 ppm to ensure a large shutdown safety margin when maintenance is required or with a changing concentration to control reactor load increase/decrease. Each 1 ppm change in boron concentration will give a change of 7 milliNiles., however note that this is not a completely linear effect with higher concentrations of boron having a progressively lower impact. If boron concentration is increased the reactivity will be negative (+1 ppm boron = -7 milliNiles), whilst conversely if boron concentration is decreased then reactivity will be positive (-1 ppm boron = +7 milliNiles).

Fuel Temperature Coefficient - FTC (-ve effect) At zero load this will have a value of near 0 Niles, but as the load increases and the temperature of the uranium fuel pellets also increase it will have a negative effect of reactivity. At full load we can expect a total effect of -0.4 Niles.

Moderator Temperature coefficient - MTC (-ve effect) Also at zero load the effect will be near 0 Niles, but as with the Fuel Temperature Coefficient as the load increases the value of MTC will become more negative. A difference however is that the concentration of boron in the primary circuit will also effect the MTC. When the fuel is new and boron concentration is high the effect of MTC will be almost zero across the full reactor load range. As fuel ages and loses reactivity and less boron is required in the primary circuit the effect of MTC will become increasingly negative at high reactor load.

Neutron Poisons (-ve effect) Some of the fission products generated during nuclear reactions have a high neutron absorption capacity, such as xenon-135. Because this fission product poison removes neutrons from the reactor, it will affect the reactivity. The poisoning of a reactor core by these fission products may become so serious that the chain reaction comes to a standstill.

Xenon-135 in particular tremendously affects the operation of a nuclear reactor because it is the most powerful known neutron poison. The inability of a reactor to be restarted due to the buildup of xenon-135 (reaches a maximum after about 10 hours) is sometimes referred to as xenon precluded start-up. The period of time in which the reactor is unable to override the effects of xenon-135 is called the xenon dead time or poison outage. During periods of steady state operation, at a constant neutron flux level, the xenon-135 concentration builds up to its equilibrium value for that reactor power in about 40 to 50 hours. When the reactor power is increased, xenon-135 concentration initially decreases because the burn up is increased at the new, higher power level. Thus, the dynamics of xenon poisoning are important for the stability of the flux pattern and geometrical power distribution, especially in physically large reactors.

Because 95% of the xenon-135 production is from iodine-135 decay, which has a 6- to 7-hour half-life, the production of xenon-135 remains constant; at this point, the xenon-135 concentration reaches a minimum. The concentration then increases to the equilibrium for the new power level in the same time, roughly 40 to 50 hours. The magnitude and the rate of change of concentration during the initial 4 to 6 hour period following the power change is dependent upon the initial power level and on the amount of change in power level; the xenon-135 concentration change is greater for a larger change in power level. When reactor power is decreased, the process is reversed[4].

Burnable Neutron Poison (-ve effect) When the nuclear fuel load is new it provides a very high positive reactivity (approx. 18 Niles). To ensure that the plant can be maintained in a shutdown manner after refuelling and also the plant started in a safe manner we must counteract this positive reactivity with a greater negative reactivity. The Protection and Control rod contribute -8 Niles only so therefore we need more than -10 Niles of reactivity from the Boron concentration in the primary circuit to ensure the reactor does not start up by itself.

The problem with this is that high concentration of Boron can promote corrosion of the pipe material in the primary circuit, reactor vessel and Steam Generator vessels, so we need counteract the weal acidic properties of boron by dosing an alkali, typically lithium hydroxide. This alkali if dosed at very high levels can also lead to corrosion of the stainless pipework of the primary circuit. So therefore it is best to avoid the situation of dosing high levels of boron and lithium hydroxide altogether.

A solution is to introduce a burnable neutron poison (something that provides a negative reactivity) to the system, but which is only needed during the early months of reactor operation whilst the fuel reactivity is still high. If we add the element Gadolinium into the fuel rods during manufacturing it will act as this poison.

Gadolinium in the fuel rods will provide approx. -3.5 Niles of reactivity when new, but this will decrease over a few months and after 5-6 months its effect will be zero.

Void Coefficient (-ve effect) A void can occur within the primary circuit due to excessive temperatures causing localised boiling of the primary coolant. As steam does not moderate the fast neutrons nearly as well as water does this will have a negative effect on reactivity. Note - not all reactor designs will have a negative void coefficient (e.g. Chernobyl reactor design had a positive void coefficient and that contributed to Unit 4's destruction) [5].

Axial Power Shape Ideally we would like the nuclear chain reactions to occur evenly across and from top to bottom of the core, however inserting control rods can distort this ideal axial power shape. Any deeply inserted rods will distort the core power distribution forcing the lower half of the reactor core to contribute more of the reactor load and the upper half less which can lead to a fuel rod experiencing higher than design temperatures in the lower core. As fuel cladding temperature rises with reactor load the margin for exceeding this is less at higher loads than at lower. It is therefore important to ensure a good axial power shape the higher we go in reactor load and this is why we aim to operate at these higher loads with the control rods all but fully withdrawn.

[4] https://en.wikipedia.org/wiki/Neutron_poison
[5] https://en.wikipedia.org/wiki/Void_coefficient

4 PWR basics

A pressurized water reactor (PWR) is a type of light-water nuclear reactor. PWRs constitute the large majority of the world's nuclear power plants (with notable exceptions being the UK, Japan, India and Canada).

In a PWR, water is used both as a neutron moderator and as coolant fluid for the reactor core. In the core, water is heated by the energy released by the fission of atoms contained in the fuel. Using very high pressure (around 155 bar) ensures that the water stays in a liquid state. The heated water then flows to a steam generator, where it transfers its thermal energy to the water of a secondary cycle kept at a lower pressure which allows it to vaporize. The resulting steam then drives steam turbines linked to an electric generator. A boiling water reactor (BWR) by contrast does not maintain such a high pressure in the primary cycle and the water thus vaporizes inside of the reactor pressure vessel (RPV) before being sent to the turbine. Most PWR designs make use of two to six steam generators each associated with a coolant loop.

The pressurized water reactor (PWR) generating system described in this document is a triple circuit unit. The three circuits are called the primary, the secondary and the tertiary.

The primary circuit includes the reactor vessel, the pressurizer, and four closed reactor coolant loops connected in parallel.

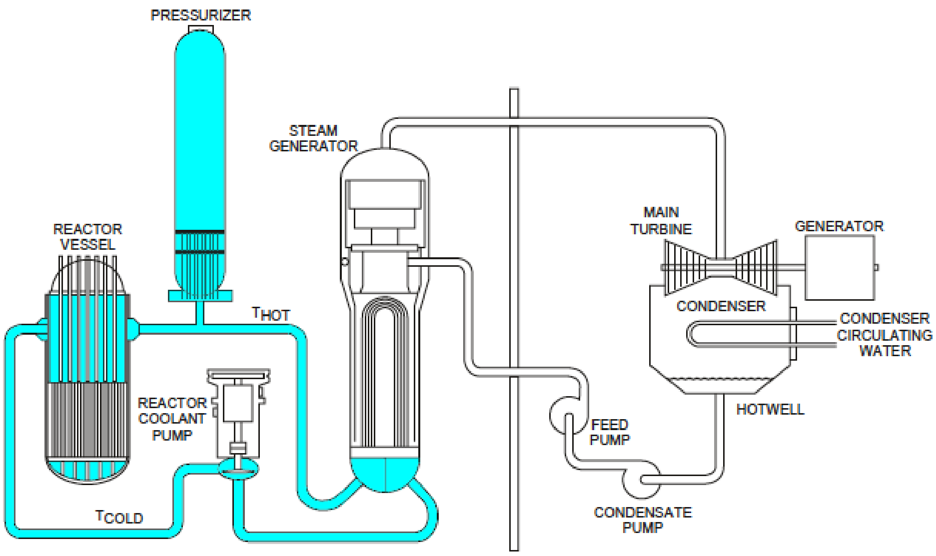


Figure 5: Primary (Reactor) circuit of a Pressurised Water Reactor (Light blue)

The secondary circuit includes the steam system, the high and low pressure turbines, and the condensate and feedwater system. The secondary systems together are sometimes referred to as the power conversion system. The sole function of the power conversion system is to generate electricity.

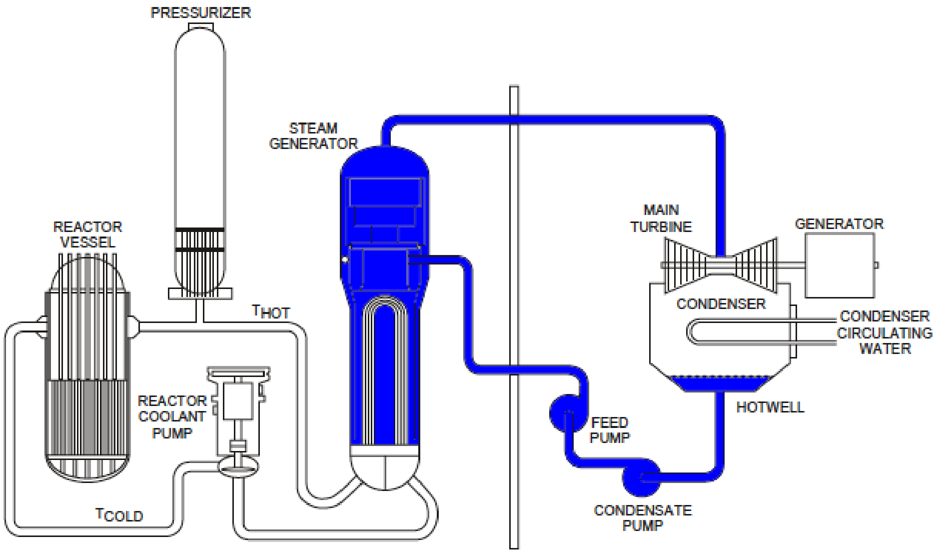


Figure 6: Secondary circuit of a Pressurised Water Reactor (Dark blue)

The tertiary circuit includes the cooling water system for removing heat from the turbine condenser and providing cooling to various heat exchangers within the primary and secondary circuits.

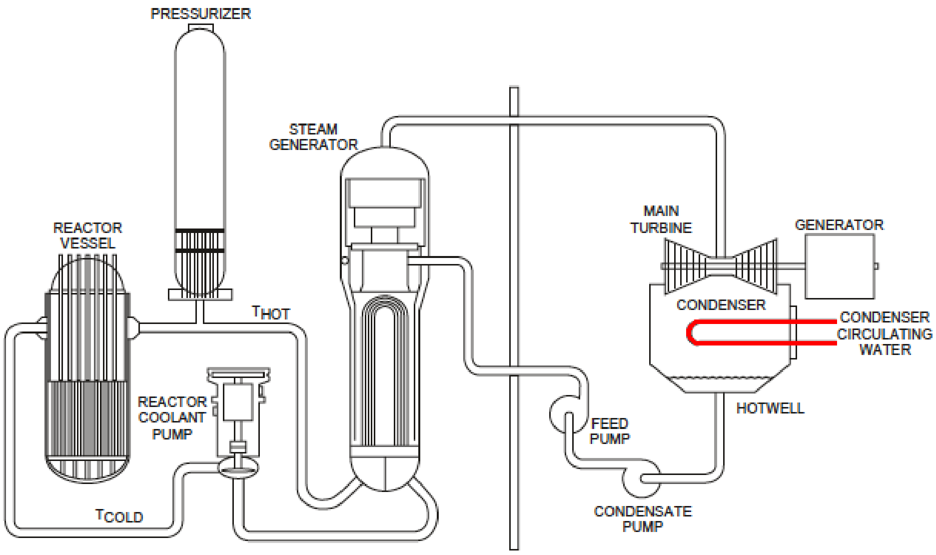


Figure 7: Tertiary (Condenser Cooling Water) circuit of a Pressurised Water Reactor (Red)

The primary cycle is located entirely inside the containment building. This building is designed to act as a shield to minimize the exposure of plant personnel to radiation. In addition, the design of the containment structure prevents or minimizes the release of radioactive material to the environment during normal operation or under an accident condition.

This design reduces the amount of radioactive material transferred to the power conversion system components. By minimizing the amount of radioactivity transferred to the secondary circuit, the potential exposure of plant personnel is reduced, and any potential releases of radioactive material to the atmosphere are minimized.

5 Components

5.1 Primary Circuit

The primary circuit includes the reactor vessel, the pressurizer, and four closed reactor coolant loops (steam generators) connected in parallel. These items and associated connecting pipework contain approximately 180 tons of deminerlised water dosed with Boron.

Other items connected to the primary circuit and installed within the containment vessel include the Chemical and Volume Control System, the Refuelling Water Storage Tank (RWST), pressuriser relief tank, Cold leg safety accumulators, Safety injection pumps and Containment vessel sump.

5.1.1 Reactor vessel

The reactor vessel and its internals contain the heat source for the nuclear steam supply system in the form of the fuel assemblies in the core area. The cladding of the fuel assemblies provides the first barrier to the release of fission products to the environment. The fuel assemblies are supported and held in alignment by the internals packages within the reactor vessel. Additionally, the internals packages provide flow paths for the coolant to remove the heat from the fuel and distribute it to the coolant loops for circulation.

The reactor vessel is comprised of a flanged cylinder, made of welded rolled plates or ring forgings, welded to a hemispherical bottom and a removable, flanged and gasketed, hemispherical upper head. The vessel is designed to provide the smallest and most economical volume required to contain the core, core support structures, control rods, and flow directing members of the internals packages. The control rod drive mechanisms and incore temperature instrumentation supports are attached to the reactor vessel head. The bottom of the vessel contains penetrations for the incore nuclear instrumentation.

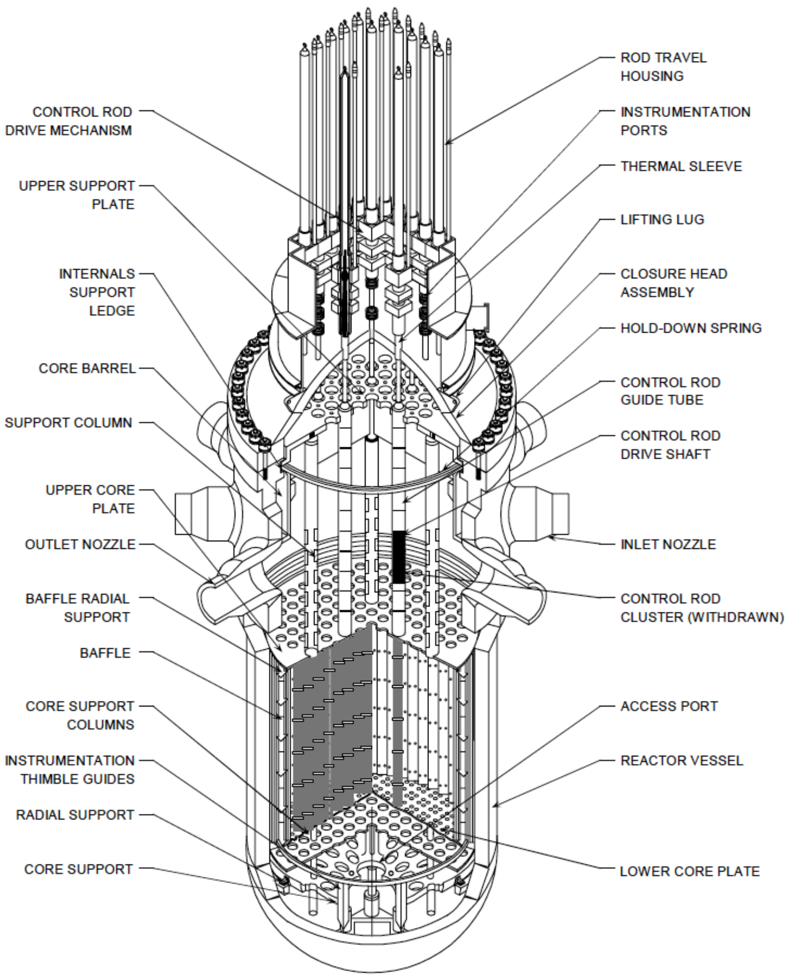


Figure 8: Reactor Vessel

Inlet and outlet nozzles are located in a horizontal plane below the reactor vessel flange but above the top of the fuel assemblies. Coolant enters the reactor vessel through the inlet nozzles and flows down the annulus between the vessel wall and the core barrel of the core support structure, then turns at the bottom and flows up through the core to the outlet nozzles. All reactor vessel internals are supported from the internals support ledge, which is machined into the reactor vessel flange.

Fuel Assemblies All fuel assemblies are mechanically identical, open cage assemblies. Each fuel assembly consists of 264 fuel rods, 24 guide thimble tubes, and 1 instrumentation guide thimble supported and aligned by grid assemblies and top and bottom nozzles in a 17 × 17 fuel rod array. The instrumentation guide thimble is located in the center position and provides a channel for the insertion of an incore neutron detector dry guide thimble if the fuel assembly is located in an instrumented core position. The instrumentation guide sheath is open at the bottom and closed at the top to prevent core bypass flow.

Fuel Rods Each fuel rod consists of uranium dioxide ceramic pellets which are placed inside a slightly cold worked zircaloy-4 tube. The tube is then plugged and seal welded at both ends to encapsulate the fuel.

Control Rod Drive Mechanisms The control rod drive mechanisms are electromechanical devices used to position the rod cluster control assemblies (control rods) in the reactor core. Each is capable of withdrawing or inserting a control rod in discrete increments (steps) or holding it at a constant position. Tripping (scramming) is accomplished by simply de-energizing the mechanisms and allowing the control rods to fall by gravity into the core.

Control rods are made from an alloy of 80% silver (Ag), 15% indium (In), 5% cadmium (Cd)

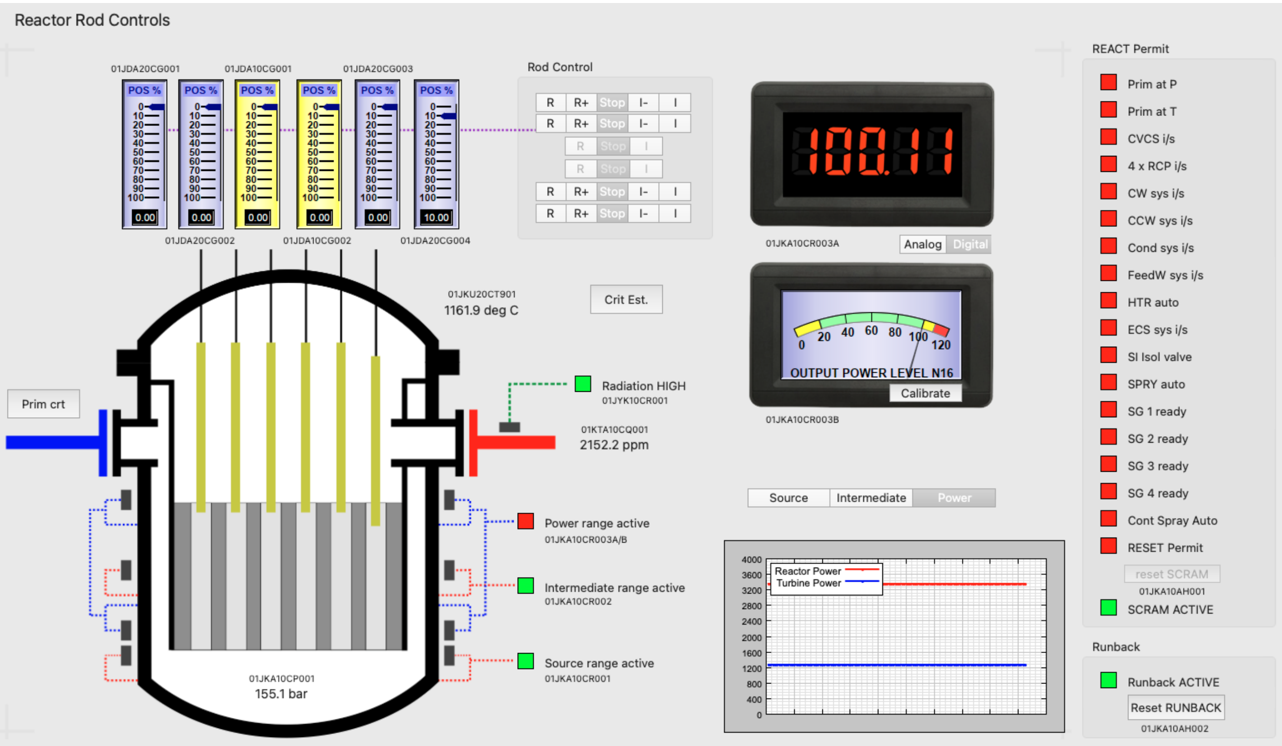


Figure 9: Reactor Rod Control page screenshot

5.1.2 Steam Generator

The steam generators are vertical shell-and-U-tube heat exchangers in which energy from the hot pressurized reactor coolant is transferred to the secondary coolant to produce dry, saturated steam. The steam generator provides the boundary between the radioactive primary system and the non-radioactive secondary system.

A cutaway diagram showing the construction of a steam generator may be found on Figure 11.

The steam generator is designed to produce saturated steam with less than 0.25% percent moisture by weight under the following conditions:

1. Steady-state operation at up to 100% of full load steam flow, assuming that the water level in the steam generator is at program,

2. Ramp load changes at a maximum rate of 5% per minute in the range from 15 to 100% full power steam flow, and
3. Step load changes of 10% of full power between 15 and 100% full power steam flow.

The steam generator is constructed of carbon steel, with all surfaces in contact with reactor coolant made from or clad with appropriate corrosion resistant material. Construction and operation of both the primary (reactor coolant) and secondary (steam) sides of the steam generator are described in the following paragraphs.

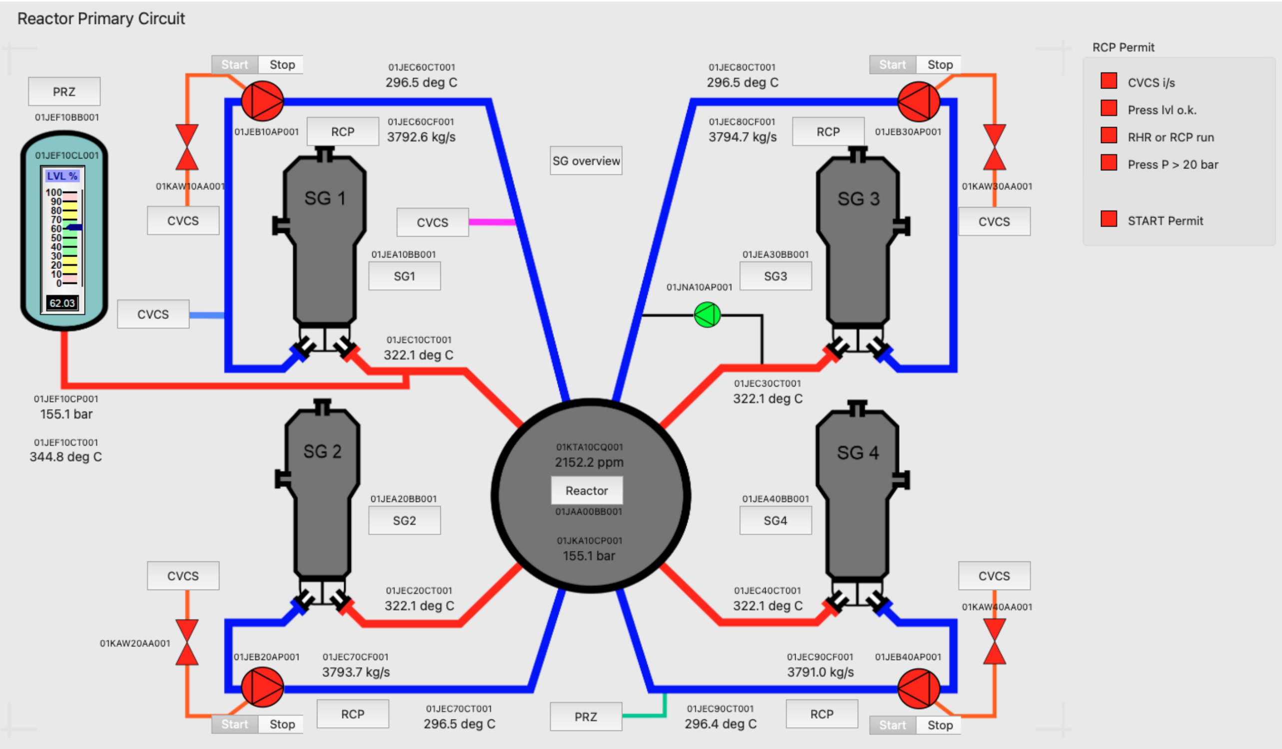


Figure 10: Reactor Primary Circuit page screenshot

Primary (Reactor Coolant) Side

Reactor coolant enters and leaves the steam generator through nozzles in the bottom hemispherical head. The head is divided into inlet and outlet chambers by a vertical partition (divider) plate which extends from the bottom of the tubesheet to the bottom hemispherical head. Bolted, gasketed manways are provided for access to both the inlet and outlet sides of the bottom hemispherical head.

The tubesheet and the heat transfer tubes form the boundary between the primary and secondary systems. The tubes and the divider plate are manufactured of Inconel. The primary side of the tubesheet is clad with Inconel while the interior surfaces of the hemispherical head and the nozzles are clad with austenitic stainless steel. After the tube ends are seal welded to the tube sheet, they are roller expanded for the full depth of the tubesheet cladding. This is done to prevent the leakage of the high pressure reactor coolant from the primary side to the lower pressure secondary side.

Secondary (Steam) Side

The secondary side of the steam generator will be discussed in the Secondary Circuit section.

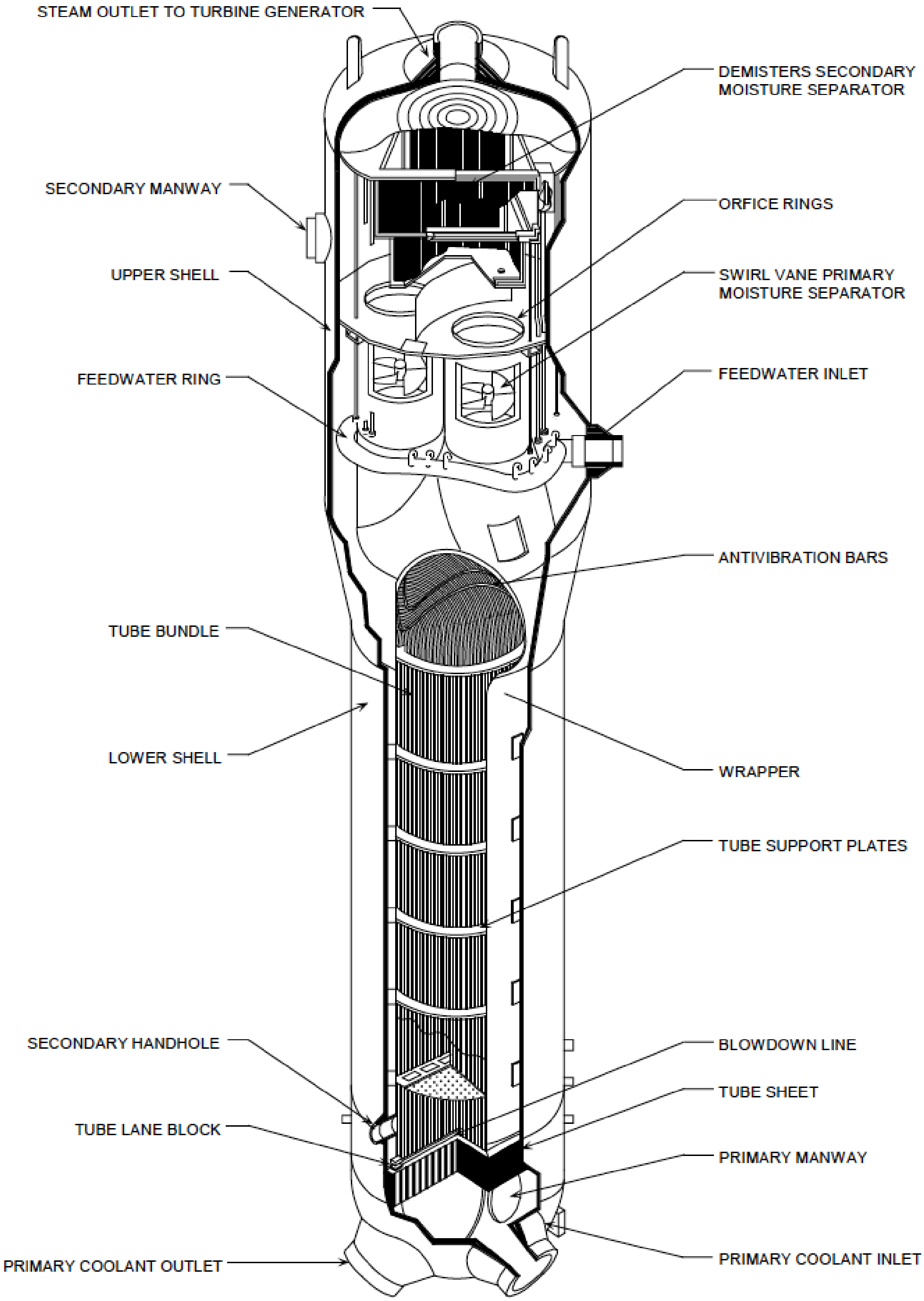


Figure 11: Steam Generator cutaway sketch

5.1.3 Reactor Coolant Pumps

The reactor coolant pumps provide forced-circulation water flow through the core sufficient to ensure adequate heat transfer from the fuel rods within the reactor core to the Steam Generators.

To ensure adequate core cooling after a loss of electrical power to the RCPs, each pump is designed with a flywheel that is attached to the top of the pump motor. If the reactor trips on a loss of flow due to a loss of power to the reactor coolant pumps, the flywheels will extend the coast-down time to maintain adequate heat transfer capability and help establish natural circulation flow. Power to the reactor coolant pump motors is from the non-vital station service power and cannot be supplied from the emergency diesel generators. The RCPs are capable of operation without mechanical damage at speeds of up to 125% of normal speed.

The reactor coolant pump is a vertical, single-stage, centrifugal pump designed to pump large volumes of reactor coolant at high temperatures and pressures. A cutaway of a typical reactor coolant pump is shown on

Figure 12. The pump consists of three sections from bottom to top:

1. The hydraulic section consists of the inlet and outlet nozzles, casing, flange, impeller, diffuser, pump shaft, pump bearing, thermal barrier and thermal barrier heat exchanger.
2. The shaft seal section consists of the number one controlled leakage seal and the numbers two and three rubbing face seals. These seals are located within the main flange and seal housing.
3. The motor section consists of a vertical, squirrel cage, induction motor with an oil lubricated double Kingsbury thrust bearing, two oil-lubricated radial bearings, and a flywheel with an anti-reverse rotation device and appropriate support equipment.

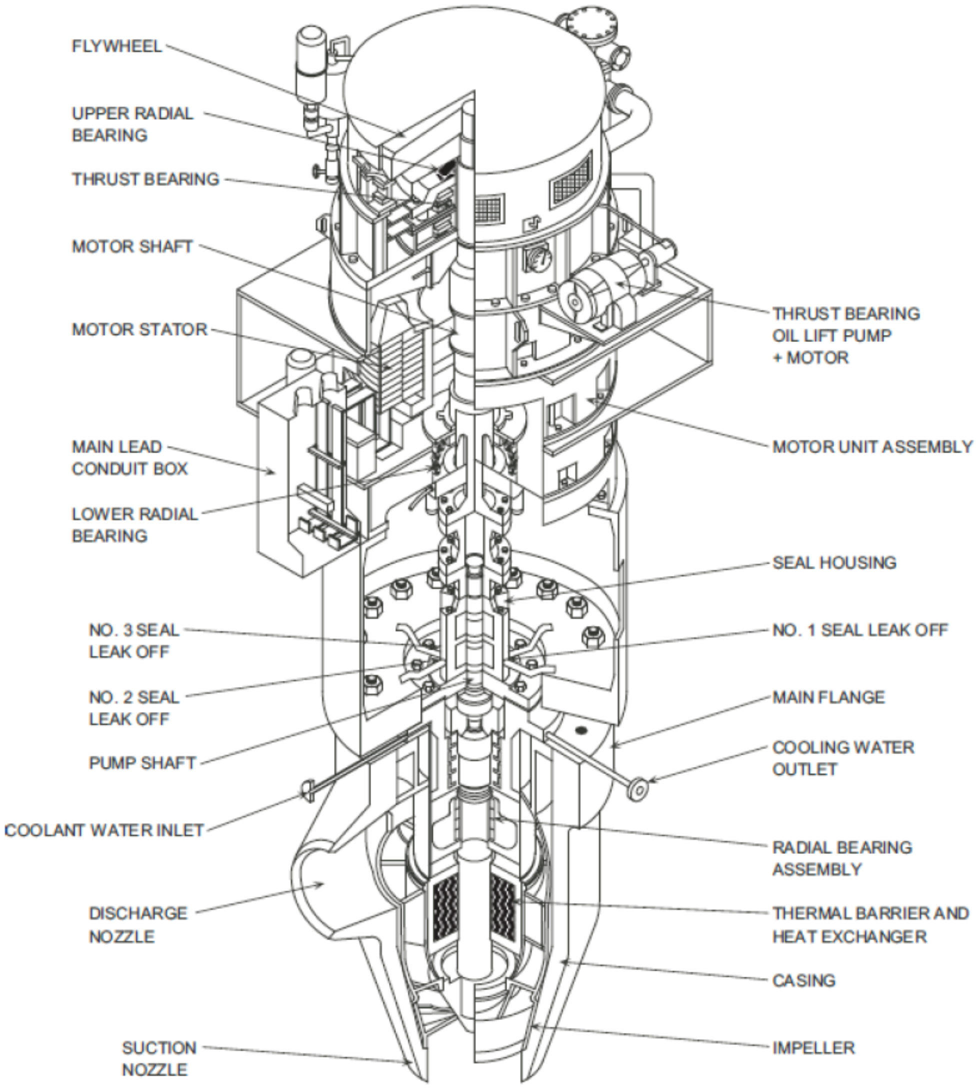


Figure 12: Reactor Coolant Pump

5.1.4 Pressuriser

The pressurizer is a vertical, cylindrical vessel with hemispherical top and bottom heads, constructed of manganese-molybdenum alloy steel, and clad with austenitic stainless steel on all surfaces exposed to reactor coolant water. Electrical heaters are installed through the bottom head of the vessel, while the spray nozzle, relief, and safety valve connections are located in the top of the vessel.

The pressurizer has four basic functions:

1. Pressurizing the RCS during plant heatup,
2. Maintaining normal RCS pressure during steady state operations,

3. Limiting pressure changes during RCS transients to within allowable values and,

4. Preventing the reactor coolant system pressure from exceeding its design pressure value of 172 bar.

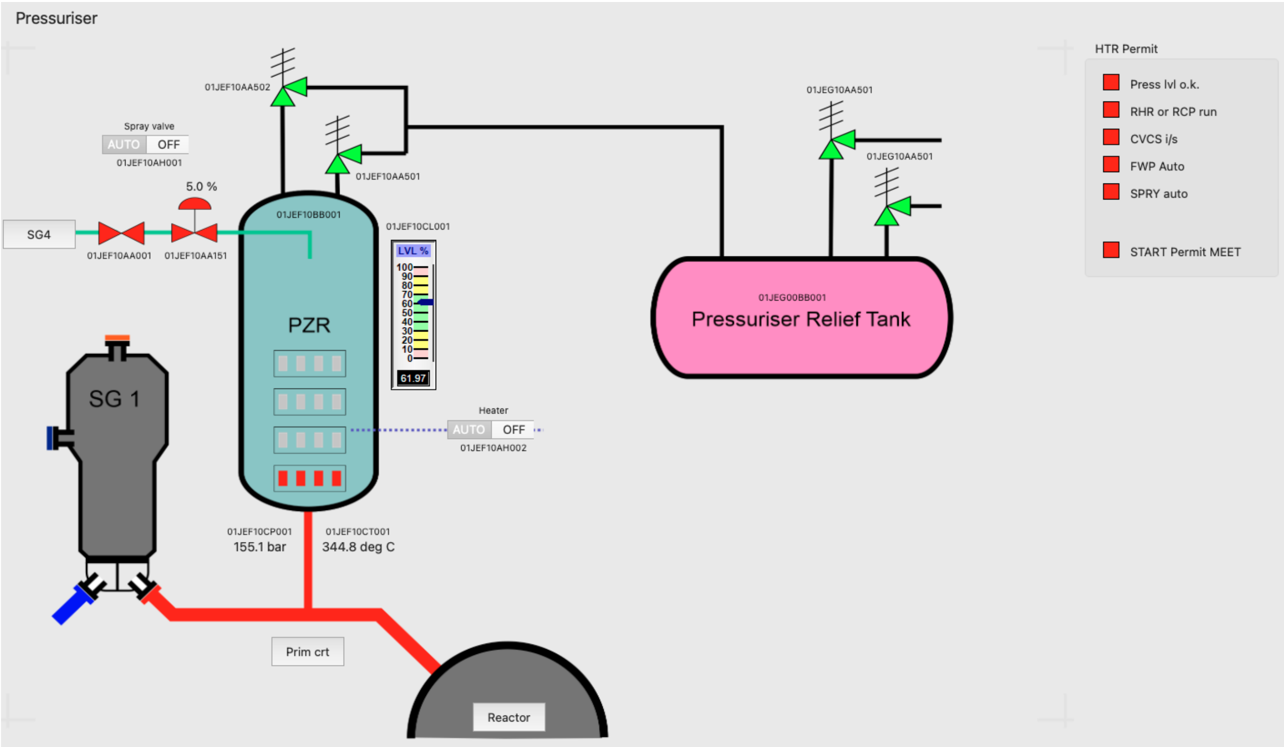


Figure 13: Pressuriser page screenshot

During normal operations, the pressurizer is maintained at saturation conditions by electrical heaters. Under saturation conditions, each temperature has a corresponding saturation pressure. At nominal full power conditions, approximately 60 percent of the pressurizer volume is saturated water, with the remaining 40 percent saturated steam.

The pressurizer is connected to a loop hot leg by the surge line. Since the RCS (except for the pressurizer) is a hydraulically solid system, the pressure in the pressurizer will be maintained throughout the system.

If the RCS were operated completely full of water any change in temperature of the reactor coolant would produce unacceptably large changes in pressure due to the density change of the coolant. Therefore, the pressurizer is attached to the reactor coolant system to provide a surge and makeup volume to accommodate these density changes.

To understand how the pressurizer maintains RCS pressure, consider the volumetric difference between water and steam. At normal system operating temperatures, water is approximately six times as dense as steam. Therefore, as the water is heated by the pressurizer electrical heaters to produce steam, a factor of six volume change occurs. For example, boiling one cubic foot of water would produce six cubic feet of steam. Since the volume in the pressurizer which is available for steam is fixed by the pressurizer level control system, the density of steam must increase. This increase in density produces a pressure increase in the RCS. Conversely if steam is condensed, a factor of six density reduction occurs, which results in a reduction in pressure. The steam inside the pressurizer respond in a manner similar to an ideal gas (pressure is proportional to density).

During steady-state operations a small number of heaters are energized to make up for ambient heat losses. The small amount of subcooled liquid which is continuously circulated from the RCS via the spray line bypass valves promotes mixing and aids in chemistry control.

Many transients affecting pressure are caused by changes in the reactor coolant temperature. Temperature changes produces changes in coolant density, which force water into (insurge) or out of (outsurge) the pressurizer.

In the case of an increase in RCS temperature, the expansion of the coolant produces an insurge into the pressurizer. This insurge compresses the steam "bubble" resulting in an increase in steam density and a corresponding increase in pressure. If the pressure increases by a predetermined amount, the pressurizer pressure control system modulates the spray valves to admit relatively cool water to the steam space to condense some steam. This reduces the density of the steam and limits the pressure increase.

If the RCS temperature decreases, the contraction of the coolant produces an outsurge from the pressurizer. This is accommodated by an expansion of the steam bubble and a corresponding decrease in steam density and pressure. As the pressure decreases, some of the saturated water in the pressurizer will flash to steam to help maintain system pressure. If pressure decreases to a predetermined value, the pressurizer pressure control system will energize additional electrical heaters to boil more water and return pressure to normal.

If the RCS pressure increases towards the design limit, power-operated relief and self-actuating code safety valves open. These valves release steam from the steam space of the pressurizer and thereby limit the overpressure condition.

The volume of the pressurizer is greater than, or equal to, the minimum volume of steam and water combination which satisfies all of the following requirements:

1. The combined saturated water volume and steam expansion volume is sufficient to provide the desired pressure response to programmed system volume changes.
2. The water volume is sufficient to prevent the heaters from being uncovered during a step load increase of ten percent of full power.
3. The steam volume is large enough to accommodate the insurge resulting from a 50 percent reduction of full load with automatic rod control and full steam dump capacity without the water level reaching the high level reactor trip set point.
4. The pressurizer does not empty following a reactor trip with a turbine trip.
5. The steam volume is large enough to prevent water relief through the safety valves following a loss of load with the high pressurizer water level initiating a reactor trip.
6. A safety injection signal will not be activated following a reactor trip and turbine trip.

Pressurizer Heaters
The electrical heaters installed in the pressurizer are replaceable, direct-immersion, tubular-sheath type heaters with hermetically sealed terminals. They are located in the lower portion of the pressurizer vessel and maintain the steam and water contents at equilibrium conditions. There are 78 heaters installed for a total capacity of 1794 kW. The heaters are broken down into two groups, the proportional heater group consists of 18 heaters for an output of 414 kW and the backup heater group consists of 60 heaters for an output of 1380 kW. The heaters are capable of raising the temperature of the pressurizer and its contents at approximately 30 degC/hr (although this has been sped up considerably in this simulation).

Pressurizer Spray
Spray water is injected into the steam volume of the pressurizer through a spray nozzle located in the top of the vessel. Automatically controlled, air-operated valves with remote manual overrides are used to control pressurizer spray from two loop cold legs. A small continuous flow (5% valve opening) is provided to reduce the thermal stresses and/or thermal shock to the pressurizer spray penetration and spray nozzle inside the pressurizer when the spray valves open. In addition, this flow helps maintain uniform water chemistry in the pressurizer to that of the reactor coolant system.

Temperature sensors with low temperature alarms are provided in each spray line to alert the operator of insufficient bypass flow. The layout of the spray line piping to the pressurizer forms a water seal which prevents steam buildup back to the spray valves. The maximum spray flow rate is selected to prevent the pressure in the pressurizer from reaching the operating set point of the PORVs, following a 10 percent step decrease in power.

The pressurizer spray lines and valves are sized and located to provide adequate spray using the differential pressure between the surge line connection in the hot leg and the spray line connection in the cold leg as the driving force. The spray line inlet connections extend into the cold leg piping in the form of a scoop so that the velocity head of the reactor coolant loop flow adds to the spray driving force.

Pressurizer Power-Operated Relief Valves
The pressurizer power-operated relief valves are used to limit the primary pressure on transients in order to avoid a reactor trip on high RCS pressure and lifting of the code safety valves. The pressurizer PORVs are also used to remove the heat from the core if no other methods of heat removal are available.

The failure of the pressurizer power-operated relief valves is present in several accident sequences which lead to core damage. There are two general failure modes for the relief valves. First, the failure of the power-operated relief valve(s) to shut when required leads to the need for recirculation cooling of the reactor, and the subsequent failure of the recirculation mode of the emergency core cooling system results in core damage. The second failure is the failure to open when required for the purpose of initiating bleed and feed cooling for the reactor. This failure of heat removal results in core damage.

Probable causes of a loss of the power-operated relief valves are :

1. Failure of the PORVs to open on demand,
2. Failure of the block valve to shut to isolate a stuck open relief valve, or
3. Failure of the power supply to the PORVs.

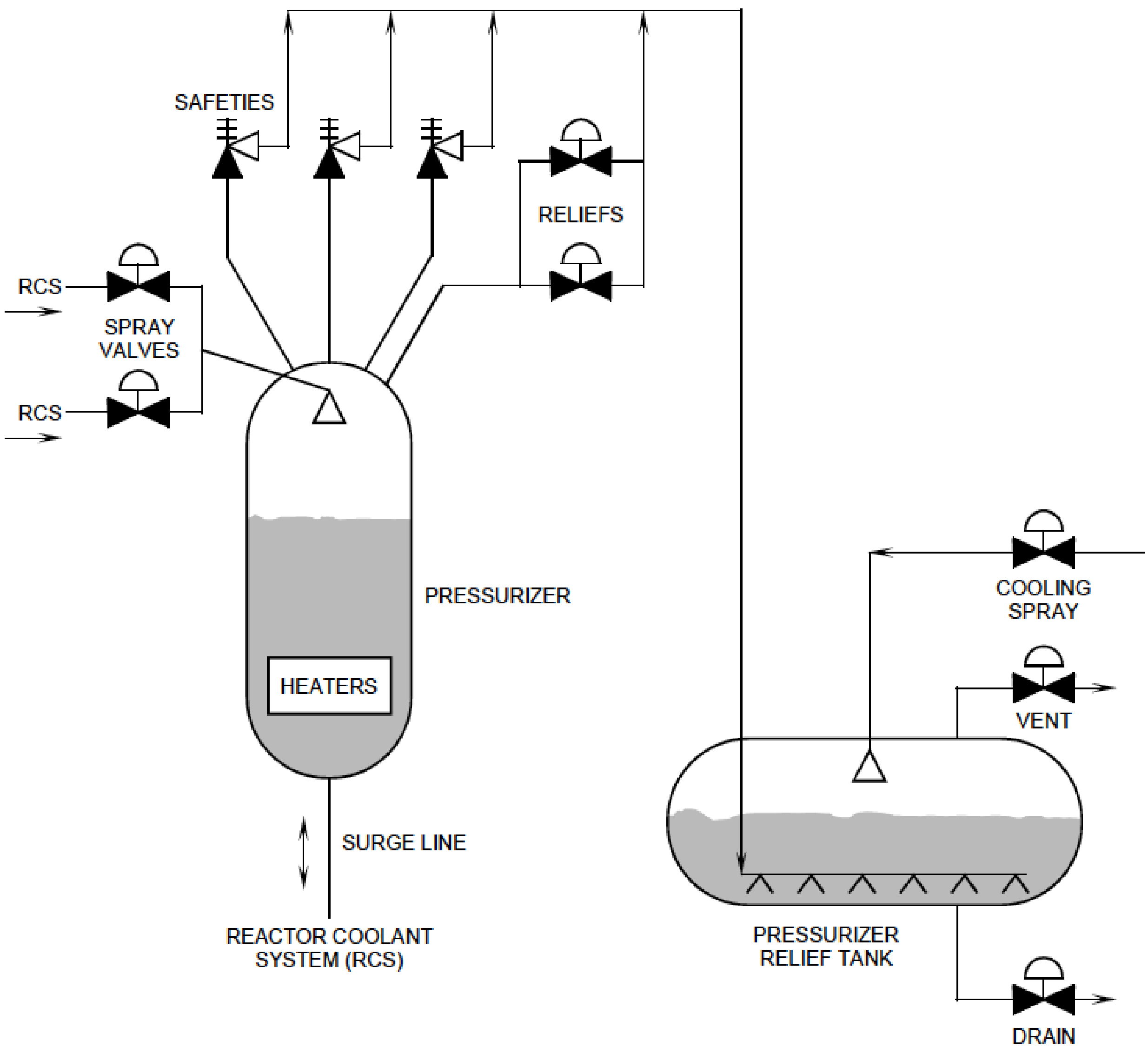


Figure 14: Pressuriser arrangement diagrammatically showing heaters, spray valves and PORV (safeties) which vent to Pressuriser Relief Tank

5.1.5 Chemical and Volume Control System (CVCS)

The chemical and volume control system purpose is to:

1. Adjust the reactor coolant boric acid concentration,
2. Maintain the proper water inventory in the RCS in conjunction with the pressurizer level control system,
3. Provide seal water flow to the reactor coolant pump shaft seals,
4. Add corrosion inhibiting chemicals to the reactor coolant,
5. Purify the reactor coolant in order to maintain it within its design activity limits,
6. Provide borated water for emergency core cooling,
7. Process reactor coolant for the reuse of boric acid and reactor makeup water in the boron recovery system,
8. Degasify the reactor coolant, and
9. Provide a means of emergency boration of the reactor coolant.

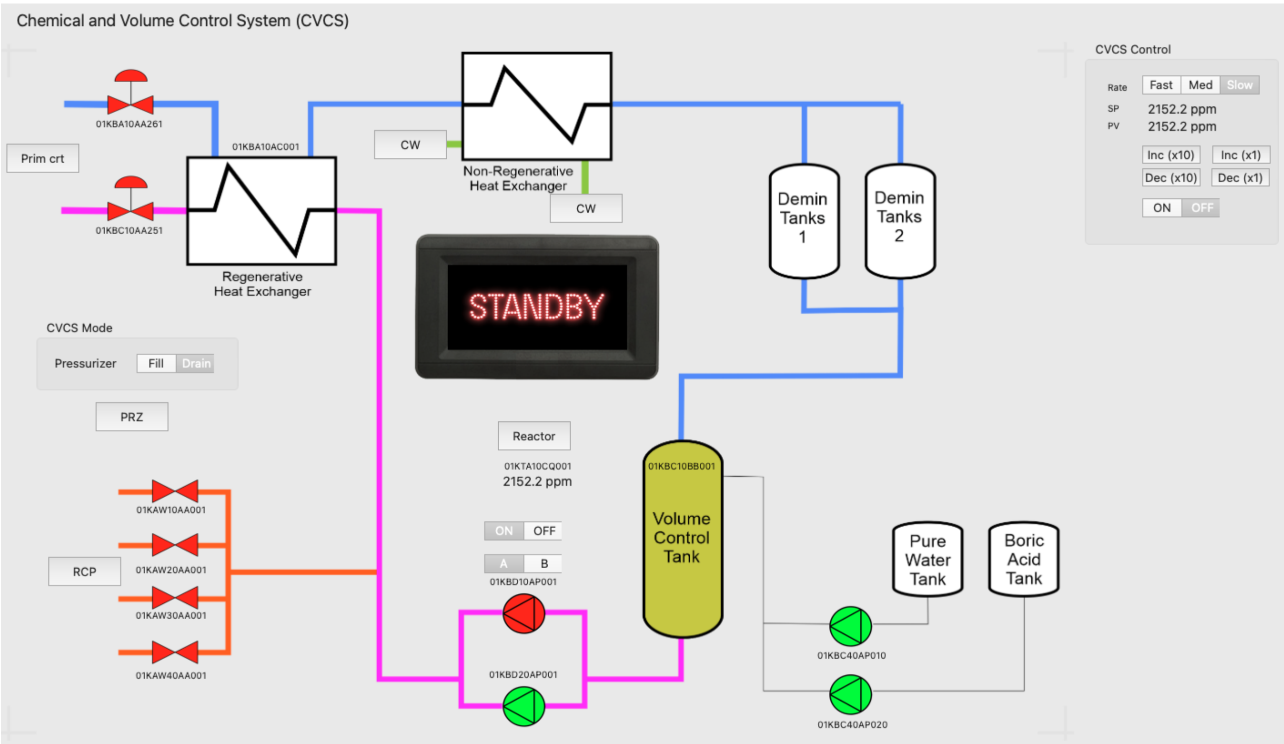


Figure 15: Chemical and Volume Control System page screenshot

Charging Pumps

Two charging pumps are installed in the system to provide charging flow to the RCS. All parts in contact with the reactor coolant are fabricated of austenitic stainless steel or other materials of adequate corrosion resistance. The centrifugal pump seals are provided with leak-offs to collect reactor coolant leakage before it can escape to the atmosphere.

The charging flow rate is determined by the pressurizer level control system. Control of the flow rate from each centrifugal charging pump is controlled by varying the position of a modulating valve (01KBC10AA251) on the discharge of the centrifugal pumps.

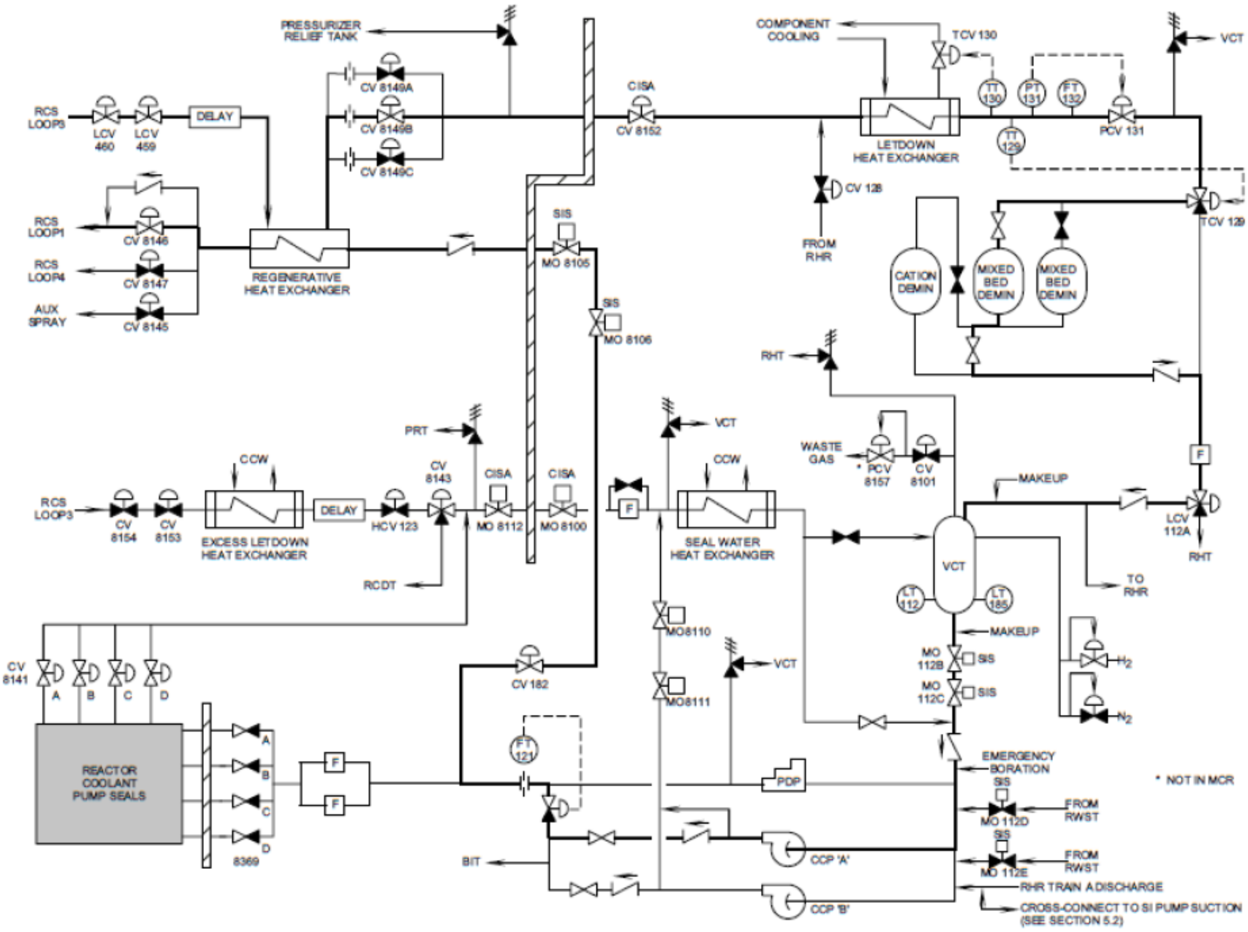


Figure 16: Typical CVCS layout for PWR. This has been simplified considerably for our simulation

5.1.6 Containment vessel

The purposes of the containment vessel are as follows:

1. Provides a barrier to prevent the escape of radioactivity during normal and accident conditions,
2. Provides protection against internally and/or externally generated missiles,
3. Provides biological shielding during normal and accident conditions, and
4. Provides Seismic Category I supports for the reactor coolant system (RCS) and its associated support systems.

The containment completely encloses the reactor and the RCS, and serves to prevent the inadvertent release of radioactive fission products to the atmosphere. The containment also provides biological shielding during normal operations and during the unlikely event of a loss-of-coolant accident (LOCA).

Several different types of containments have been developed for PWR applications, and almost all are premised on the use of the containment structure to contain the large volume of high pressure, high temperature steam-water mixture that would result from a LOCA or a Steam Line Break (SLB) inside the containment. After a LOCA or a SLB, the pressure and temperature inside the containment will increase to a peak level, and then decrease as the containment support systems are activated.

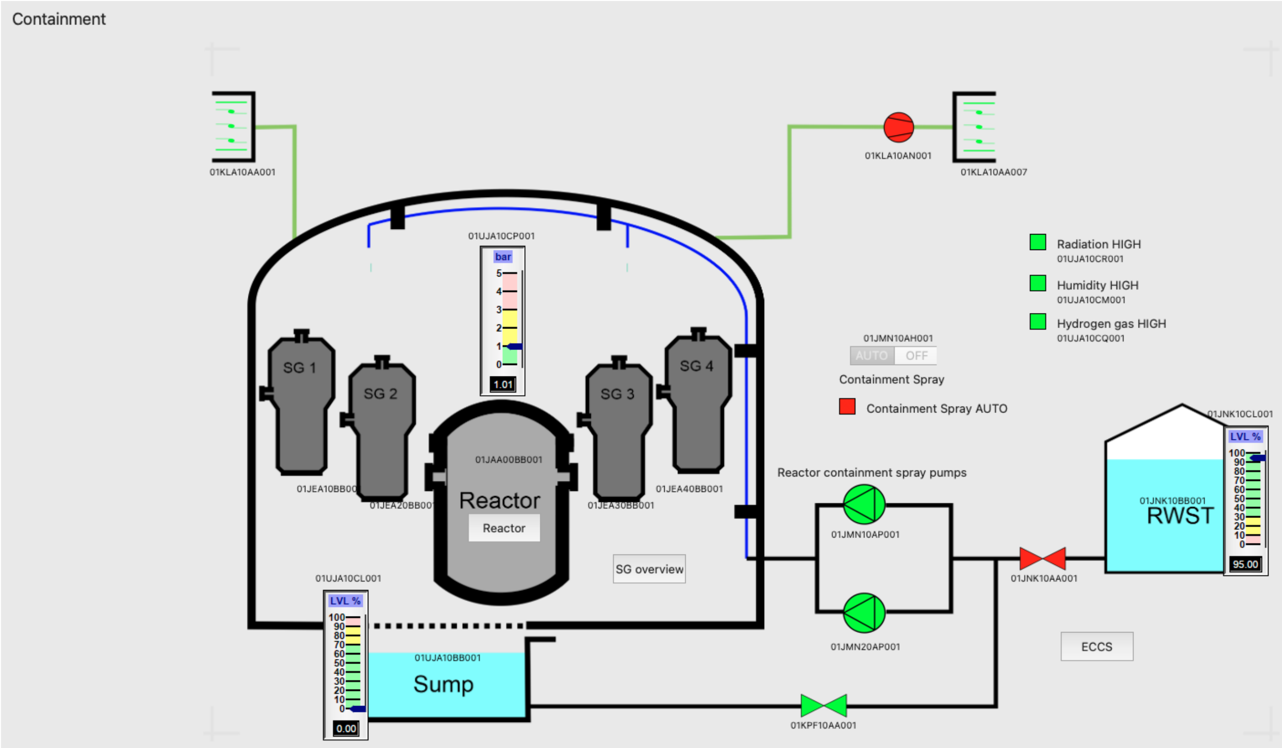


Figure 17: Containment vessel page screenshot

The containment structure must be shown to be functionally available for the life of the plant. From the viewpoint of design, the containment design must consider the following loadings:

1. Pressure and temperature transients that occur as the result of a design-basis accident (DBA).
2. Thermal loads, such as the temperature gradient through the containment wall, during normal and transient conditions.
3. Dead loads consisting of the weight of the concrete wall, dome, base slab, internal concrete, and machinery, and other permanent load-contributing stresses.
4. Live loads, which consist of snow loading, movable equipment loads, and other loads which vary with intensity and occurrence.
5. Earthquake loads, such as those associated with the operating basis earthquake (OBE) and the safe shutdown earthquake (SSE).
6. Wind and tornado loads, with consideration given to missile impingement.
7. Hydrostatic loads based on the worst-case flood conditions with a water level significantly above mean sea level.
8. External pressure loads based on a maximum differential pressure, inside to outside, on the containment.
9. Pre-stressing loads, considered in all loading combinations.
10. Pressure test loads up to 1.15 times the design pressure.

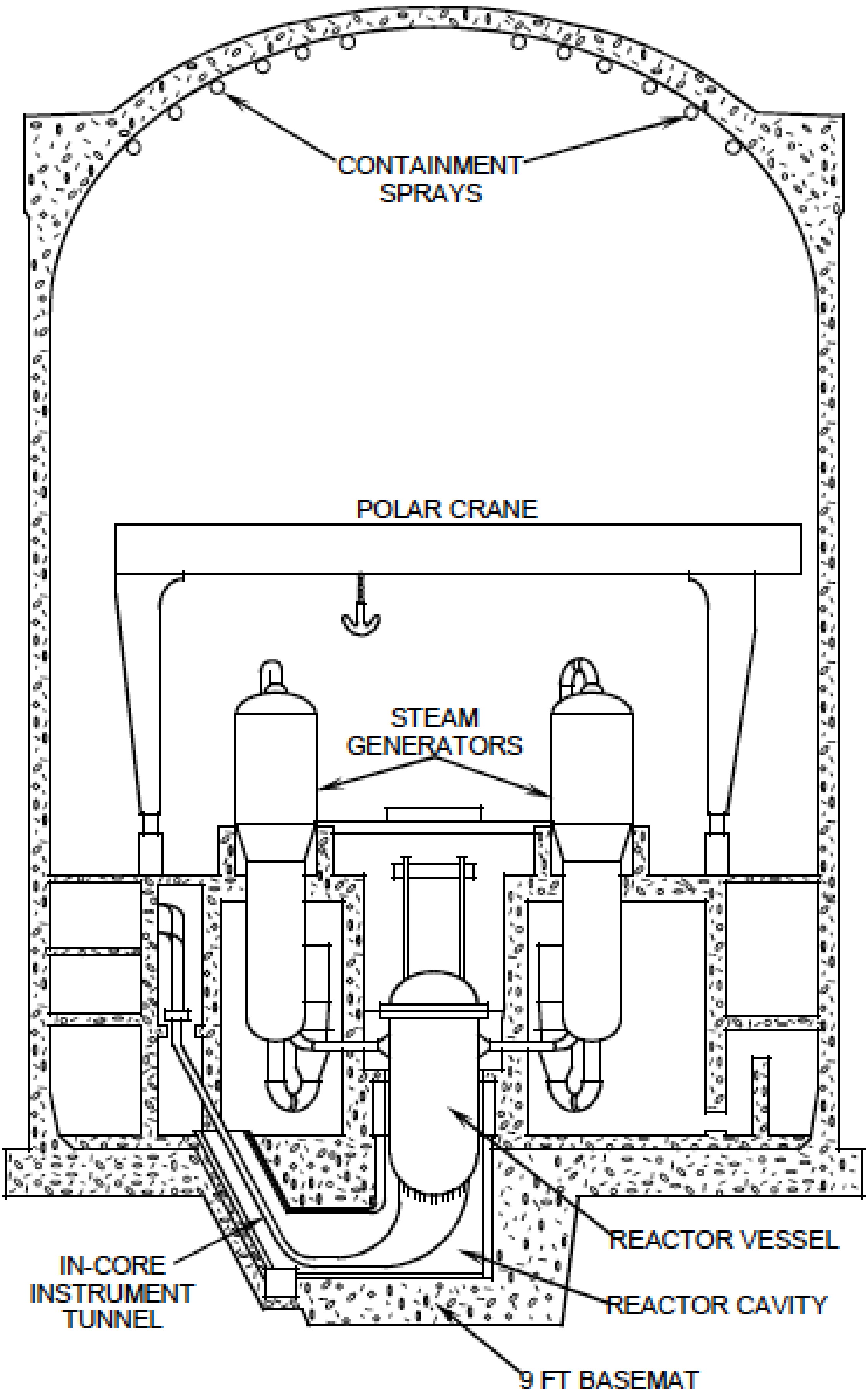


Figure 18: Sectional view of Containment vessel

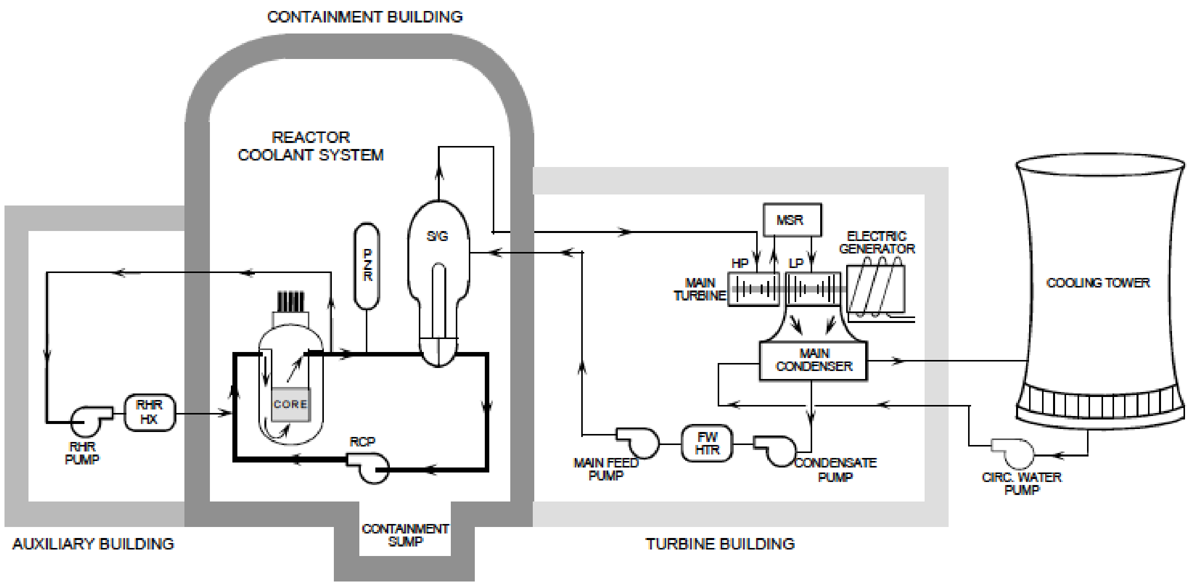


Figure 19: Basic layout of reactor components per building

Sump
The containment recirculation sump is a large collection reservoir designed to provide an adequate water supply to the ECCSs and containment spray system during recirculation modes of operation. The water collected in the sump is reactor coolant lost through an RCS pipe break as well as water that has been injected from the RWST into the RCS and then through the pipe break. Sump design features limit the size of debris that can enter the recirculation flowpaths and ensure an adequate net positive suction head (NPSH) for the containment spray and RHR pumps.

Containment Ventilation Systems
The purposes of the containment ventilation systems are as follows:

- To control the temperature and pressure of the containment during normal operations to maintain operability of the containment and associated equipment,
- To provide localized area ventilation for equipment inside containment, and
- To provide cleanup of the containment atmosphere for limited personnel access while at power, and for continuous access while shutdown.

Containment Spray Pumps
The spray pumps are vertical, single-stage centrifugal pumps. Each spray pump delivers a design flow equal to 100 percent of the heat removal capability necessary to maintain the pressure in the containment below its design maximum. The design discharge pressure of each pump is sufficient to continue at rated flow with the RWST almost empty, against a head equivalent to the sum of design containment pressure, the elevation head of the uppermost nozzle, and the line and nozzle pressure losses.

Containment Pressure Instrumentation
The atmospheric pressure within the containment vessel is monitored on a continuous manner as any increase would be an indication of a leak from the primary or secondary circuits. This pressure is displayed on instrument gauge 01UJA10CP001 and if the value reaches the HIGH HIGH level ($>$ 3 bar) it will cause an automatic isolation of the containment ventilation system and start both Containment Spray Pumps to reduce any pressure buildup.

Containment Radiation and Humidity Monitors
Humidity is another important instrument to indicate a leak from the primary or secondary circuits as any water at such high pressures will flash off to steam thus increasing containment humidity levels. High humidity is indicated by instrument 01UJA10CM001.

Radiation within the containment vessel is also monitored as this will clarify if the leak is from the primary or secondary circuit. Primary water is radioactive and this instrument 01UJA10CR001 will indicate if high levels detected.

Containment Hydrogen Analysis System (CHAS)
Hydrogen in the containment vessel is another value we are interested in as any leakage from the primary circuit will be detectable on instrument 01UJA10CQ001.

Additionally if the worst happens and a major reactor meltdown does occur then the intense heat in the reactor will cause a reaction between the steam and the zircaloy cladding of the fuel elements releasing large amounts of hydrogen gas. This system will detect this and also the containment vessel is usually fitted with a device (catalytic recombiner) to absorb hydrogen to prevent an explosion.

5.1.7 Refuelling Water Storage Tank (RWST)

The RWST is a very large (438,000-gal capacity) seismically qualified tank containing borated (greater than 2000-ppm) water. The tank contents are used to fill the refuelling cavity for refuelling operations and to provide water for ECCS and containment spray system operation. During normal operation, the RWST is always aligned through open isolation valves to the suctions of the safety injection, RHR, and containment spray pumps.

The minimum water volume (428,000 gal) and boron concentration required by the RWST technical specification ensure:

1. Sufficient coolant to support ECCS operation during the injection phase,
2. Sufficient water volume in the containment recirculation sump to support continued ECCS and containment spray system operation during the recirculation phase, and
3. Maintaining core subcriticality following a LOCA.

5.1.8 Pressuriser Relief Tank (PRT)

The PRT collects, condenses and cools the steam discharged from the pressurizer safety and power-operated relief valves. The tank is maintained approximately three quarters full of water with a nitrogen cover gas. Steam is discharged through a sparger at the bottom of the tank below the water level. This condenses and cools the steam by mixing it with water that is near containment ambient temperature.

Discharge from a number of smaller relief valves located in systems inside or outside of the containment are also piped to the pressurizer relief tank. The design of the PRT is based on the requirement to condense and cool a discharge of pressurizer steam equal to 110 percent of the volume above the zero power pressurizer water level set point (25%). This tank is not designed to accept a continuous discharge from the pressurizer.

5.1.9 Emergency Core Cooling System

The purposes of the emergency core cooling systems are as follows:

1. Emergency core cooling systems:
   - Provide core cooling to minimize fuel damage following a LOCA, and
   - Provide additional shutdown margin following a steam line break accident.
2. Cold-leg accumulators (passive system):
   - Rapidly refill the reactor vessel downcomer and bottom plenum and begin to reflood the core following a large LOCA.
3. High head injection system (active system):
   - Provides high pressure, low volume safety injection for small to intermediate sized LOCAs, and
   - Adds negative reactivity and makes up for reactor coolant contraction by injecting borated water into the reactor coolant system (RCS) following a steam line break.
4. Low head injection system (active system):

- Provides low pressure, high volume safety injection to complete the reflooding of the core following a LOCA, and
- Provides a flowpath and heat sink for long-term core cooling following a LOCA.

As listed above, the emergency core cooling systems consist of one passive system and two active systems.

The passive system (accumulators) consists of large volume tanks of borated water pressurized with nitrogen. The pressure in the passive system is less than that of the RCS. Following an accident, when RCS pressure decreases below tank pressure, the borated water is injected.

The active systems (high, and low pressure injection systems) consist of several pumping systems capable of varying discharge pressures and flow rates. Each of these systems does not start until it receives an accident initiation signal (a safety injection actuation). Once started, these systems inject borated water into the RCS as the RCS pressure decreases below the discharge pressures of the system pumps.

The ECCSs are designed to cool the reactor core and provide additional shutdown capability following initiation of the following accident conditions:

1. Loss of coolant from the RCS in excess of the normal makeup capability,
2. Steam generator tube rupture, and
3. Pipe break in the main steam system.

The emergency core cooling systems provide reactor shutdown capability for the accidents listed above by means of chemical poison (boron) injection.

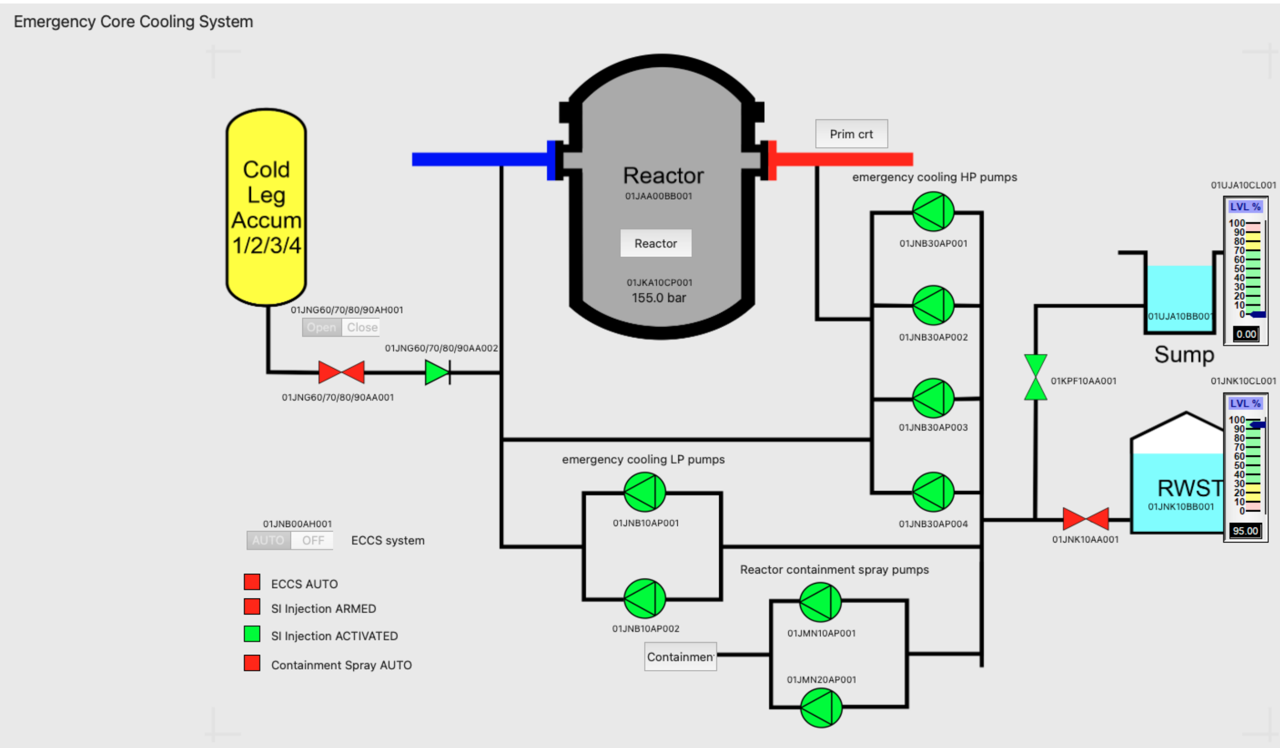


Figure 20: Emergency Core Cooling System page screenshot

5.1.10 Safety Injection pumps

High Head Injection System
To provide initial core cooling in response to smaller LOCAs, the high head injection system provides high pressure, low volume injection from the RWST and consist of 4 pumps (01JNB30AP001/002/003/004). In response to a steam line break, the injection of borated water from the RWST adds negative reactivity and makes up for reactor coolant contraction.

Low Head Injection System

The low head injection system is designed to provide low pressure, high volume injection from the RWST to the four RCS cold legs for large RCS pipe breaks up to and including the design-basis LOCA, in which the RCS pressure decreases to containment pressure in a relatively short period of time. It consists of 2 pumps (01JNB10AP001/002). In addition, the system provides long-term core cooling following a LOCA via the recirculation and cooling of water collected in the containment recirculation sump.

When the RWST has emptied to the low-level setpoint, the suctions of the Low Head Injection pumps are automatically realigned to the containment recirculation sump for recirculation of the sump water to the RCS.

A safety injection actuation signal initiates the following actions in the Emergency Core Cooling system:

1. START emergency cooling LP pumps (01JNB10AP001/002).
2. START emergency cooling HP pumps (01LNB30AP001/002/003/004).
3. Once RWST supply of highly borated water is at a low level automatically CLOSE valve 01JNK10AA001 isolating RWST tank and OPEN valve 01KPF10AA001 to allow water accumulated in the containment sump to be used for further cooling of the reactor.

If a LOCA (Loss of Coolant Accident) has occurred then other systems, such as the Cold Leg Accumulators would have actuated first on a drop in primary circuit pressure and also the Containment spray pumps would have started on detection of increased pressure int he containment vessel.

5.1.11 Cold Leg Accumulators

The accumulators are pressure vessels containing borated water and pressurized with nitrogen. During normal operation each accumulator is isolated from the RCS by two seated check valves in series. Should the RCS pressure fall below the accumulator pressure, the check valves unseat, and borated water is immediately forced into the RCS by the expansion of the nitrogen volume.

One accumulator is attached to each of the cold legs of the reactor coolant system. The accumulator discharge penetration into each cold leg and the downstream check valve in each accumulator discharge pipe are shared with the intermediate and low head injection systems. The accumulators are passive components, since mechanical operation of the swing disc check valves is the only action required to open the injection path from each accumulator to the core via the cold leg.

The accumulator tank volume is approximately two thirds full of borated water; the remaining volume is filled with nitrogen at a pressure greater than 600 psig. The boron concentration (approximately 2000 ppm) is about the same as that of the RWST contents. The technical specification limits on accumulator water volume and nitrogen cover pressure ensure that the discharge from three accumulators is sufficient to rapidly refill the reactor vessel downcomer (the annular space between the vessel and the core barrel) and vessel bottom plenum and to begin reflooding the core so that core damage is limited following a design-basis LOCA. The entire contents of the fourth accumulator are assumed to be completely lost via the RCS pipe break during the blowdown phase of the LOCA and are thus unavailable for core cooling. The boron concentration limits ensure that sufficient negative reactivity is added to maintain post-LOCA subcriticality and ensure acceptable post-LOCA containment recirculation sump pH values.

Accumulator Check Valves
Each accumulator check valve is designed with a low pressure drop configuration with all operating parts contained within the body. The disc is permitted to rotate, providing a new seating surface after each valve opening. Each valve has a test connection on its upstream side to permit leakage testing. Design considerations and analysis which assure that leakage through both check valves in an accumulator injection line does not impair accumulator availability are as follows:

1. During normal operation each downstream check valve is seated with an approximate differential pressure of 1650 psid across the disc. Since the valve remains in this position except for testing or when called upon to function, and is not, therefore, subject to the abuses of flow operation or impact loads caused by sudden flow reversal and seating, it does not experience significant wear of the moving parts, and hence it is expected to function with minimal leakage.
2. When the reactor coolant system is being pressurized during the normal plant heatup operation, each check valve is tested for leakage as soon as there is a stable differential pressure of about 100 psi or more across the valve. This test confirms the seating of the disc and whether there has been an increase in

leakage since the last test. When the leakage testing is completed, the discharge line motor-operated isolation valves are opened, and the RCS pressure increase is continued. There should be no increase in leakage with further RCS pressurization, since increasing the reactor coolant pressure increases the seating forces on the valve discs and decreases the probability of leakage.

3. The accumulators can accept some in-leakage from the RCS without an effect on availability. In-leakage would require, however, that the accumulator water volume be adjusted according to technical specification requirements. An accumulator level alarm is provided as an added safeguard against excessive accumulator in-leakages.

5.1.12 1, 2, 3 or 4 Steam Generators

Our plant has 1 reactor vessel where the heat is generated from nuclear fission and 4 steam generators to transmit this heat from the primary circuit to the secondary circuit. But why 4 steam generators.

We could have just employed 1 steam generator to take the entire heat load from the reactor vessel, however this steam generator would need to be vary large. Having 1 very large steam generator has a few downsides.

1. It would be a very large pressure vessel and hence very expensive to manufacture.
2. It would also be difficult to fit into the containment vessel and difficult to repair if required.
3. It would be very difficult to transport to site (very heavy and rather large in size). Special arrangements would need to be made for transport, probably expensive special arrangement.
4. The pipework connecting the reactor vessel to the steam generator and the reactor coolant pump would also need to be big enough to take the entire primary coolant flow rate. One very large coolant pump would be more difficult to manufacture (and hence much more expensive) than 4 smaller pumps.

Splitting the heat load from the reactor vessel into 2, 3 or 4 separate steam generators does not cause any problems for us and is the sensible design choice to make.

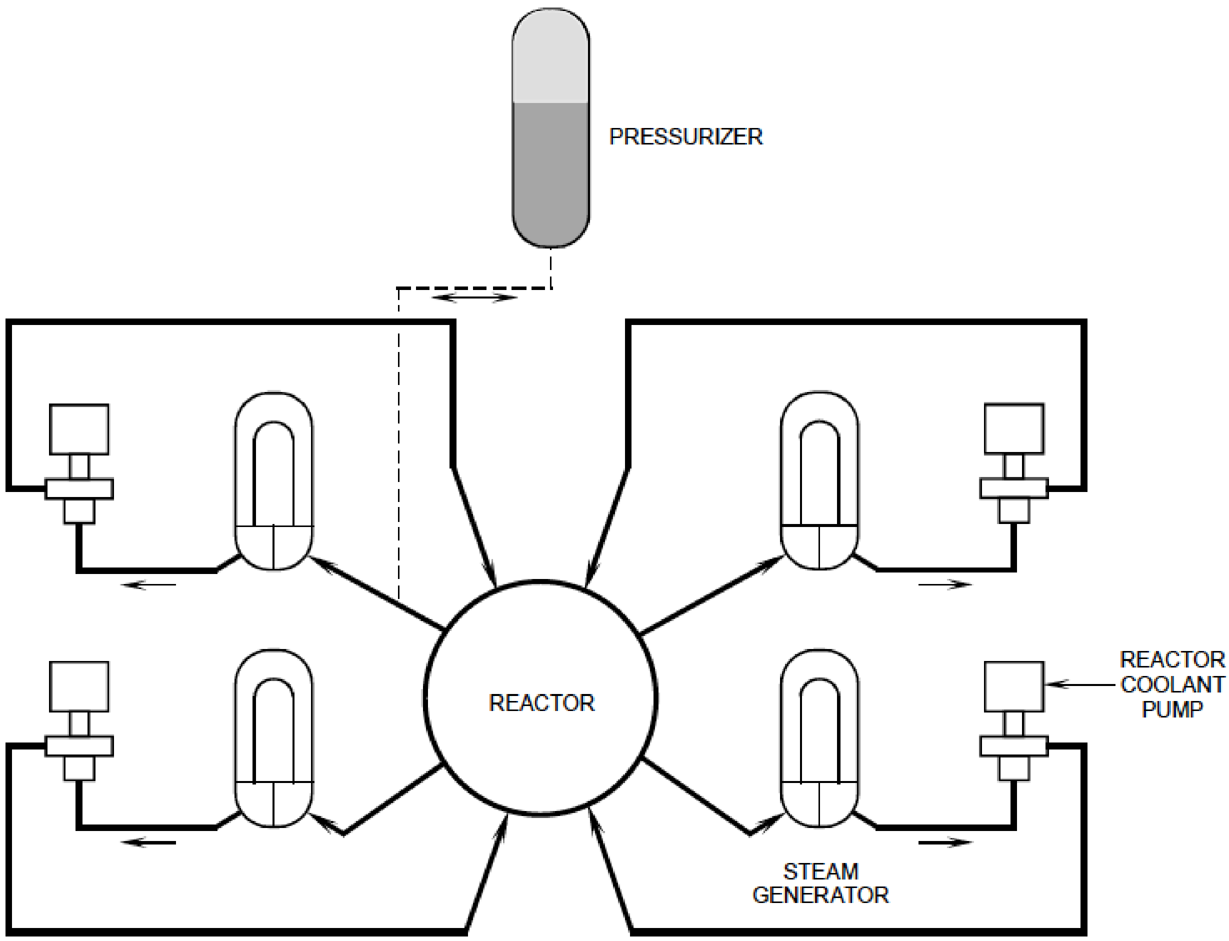


Figure 21: Primary circuit of a Pressurised Water Reactor with 4 steam generators

5.2 Secondary Circuit

Secondary circuit filled with deminerlised water dosed with oxygen scavenger and pH control

5.2.1 Steam Generators

Secondary (Steam) Side
The secondary side of the steam generator consists of the feed and steam nozzles, the tube bundle and supports, the tube bundle wrapper, primary and secondary moisture separators, appropriate instrumentation and blow down penetrations. The steam generator shell and its internals are constructed of carbon steel.

At 100% thermal power feedwater at a temperature of approximately 290 deg C enters the steam generator through the feedwater inlet nozzle. As the feedwater leaves the feed ring it is distributed to the annulus between the tube bundle wrapper and the steam generator shell where it mixes with the hot recirculation water from the moisture separation equipment. This annulus is called the downcomer and is where steam generator level is measured for indication, control and protection. The feed water is distributed through an upper feed ring (Figure 22) into the annulus.

The feedwater-recirculation flow mixture then flows between the bottom of the tube wrapper (shroud) and the tubesheet into the tube bundle region. In the tube bundle region, heat is transferred to the secondary coolant producing a steam-water mixture. This mixture flows upward to the primary or swirl-vane moisture separators (Figure 22). These separators consist of a number of stationary vanes which impart a swirling motion to the steam water mixture. The steam, being less dense than the water can change direction easily and passes through the swirl vanes. The water is slung to the outside and flows to the downcomer where it mixes with incoming feedwater. The water in the downcomer is maintained at a level that is equal to a height in the boiling section of the steam generator that is approximately at the bottom of the swirl vanes.

Although the swirl vanes remove most of the moisture from the steam, a second stage of moisture separation is necessary to meet design requirements. The steam passes through chevron separators and then leaves the generator through the outlet nozzle. These chevron separators force the steam to take a torturous path. Again the steam can change directions easily as it passes through while the more dense water cannot. The separated moisture is collected and drained to the downcomer. Steam exiting the steam generator has a minimum quality of 99.75% (less than 0.25% moisture).

The steam generator operates as a natural circulation boiler. The flow from the downcomer to the tube bundle is caused by the difference in density between the slightly subcooled liquid in the downcomer and the steam-water mixture in the tube bundle. At full power, the flow in the downcomer is three (3) to five (5) times that of the incoming feedwater. This is caused by the recirculation flow from the moisture separators and is necessary to ensure proper thermal-hydraulic performance of the steam generator. The higher flow velocities also help prevent the collection of impurities at the tube to tube sheet area of the steam generator.

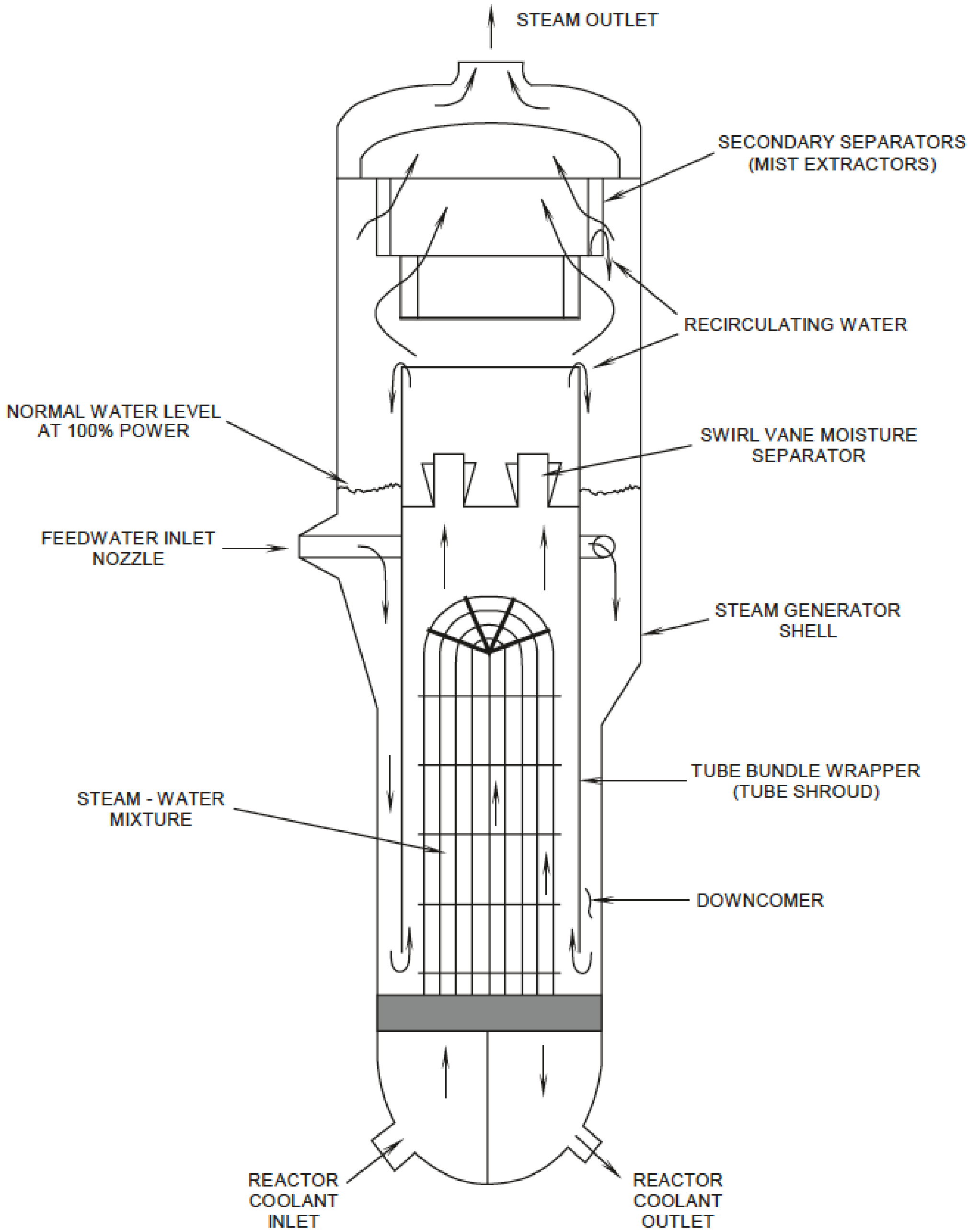


Figure 22: Steam Generator diagram indicating feedwater flowpath

5.2.2 Steam Turbine

The main turbine consists of one high pressure turbine and three low pressure turbines coupled to a single shaft. The four turbines that comprise the main turbine are coupled to the generator and exciter; they serve as the prime mover for these components. A cross section of the turbine is shown in image /24. Steam enters the main turbine at the high pressure turbine through the turbine throttle (stop) and governor (control) valves.

The thermal energy of the steam is converted to mechanical energy in the high pressure turbine, and the steam is exhausted to the moisture separator reheaters. In each MSR the steam is dried, reheated, and superheated prior to its entry into the low pressure turbines. The superheated steam is routed through the reheat stop and intercept valves as it travels from the MSRs to the low pressure turbines. Energy conversion occurs again in the low pressure turbines as the steam expands into the vacuum of the main condenser.

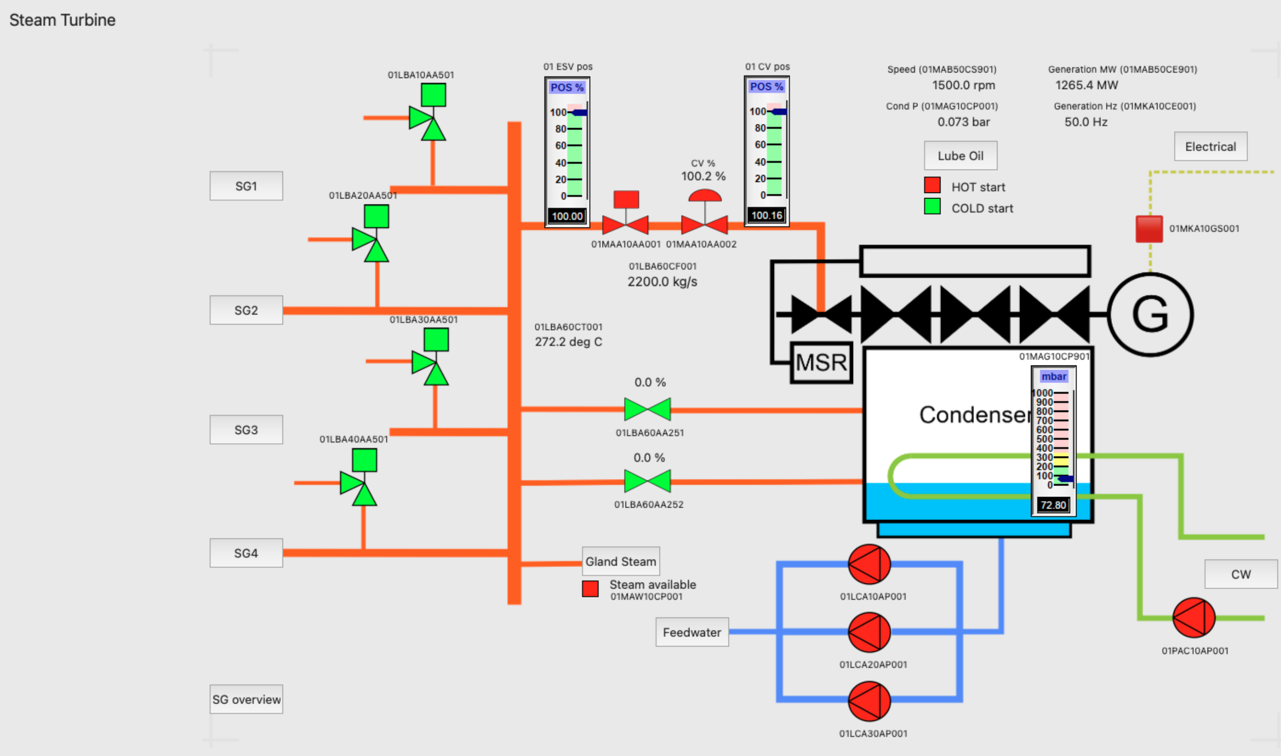


Figure 23: Steam Turbine page screenshot

High Pressure Turbine

The high pressure turbine is a double-flow turbine with a rateau (impulse) stage followed by several stages of reaction blading in each end of the turbine. Main steam enters the high pressure turbine through two steam chests. The steam chest outlets are connected to the high pressure casing through four inlet points; steam from the steam chest flows to each end of the high pressure turbine. Extraction steam exits the turbine via interstage outlets. The high pressure turbine exhaust outlets direct steam to the MSRs.

The high pressure turbine rotor is supported by two bearings, and one end is coupled to the low pressure turbines. An auxiliary shaft coupled to the opposite end of the high pressure turbine is connected to the turning gear motor.

Moisture Separator Reheater (MSR)

Steam from the high pressure turbine exhaust enters the moisture separator reheaters. In each MSR the steam is dried, reheated, and superheated prior to its entry into the low pressure turbines. The superheated steam is routed through the reheat stop and intercept valves as it travels from the MSRs to the low pressure turbines.

Low Pressure Turbines

Each of the three low pressure turbines is a dual-flow, reaction, condensing turbine. Steam from the moisture separator reheaters enters the low pressure turbines after passing through the reheat stop and intercept valves. In the low pressure turbines, steam is expanded through several reaction stages before it is exhausted to the condenser. Interstage extraction points provide steam for feedwater heating. Each low pressure turbine is supported by two journal bearings. Condenser overpressure protection is provided by rupture discs in the low pressure turbine casings.

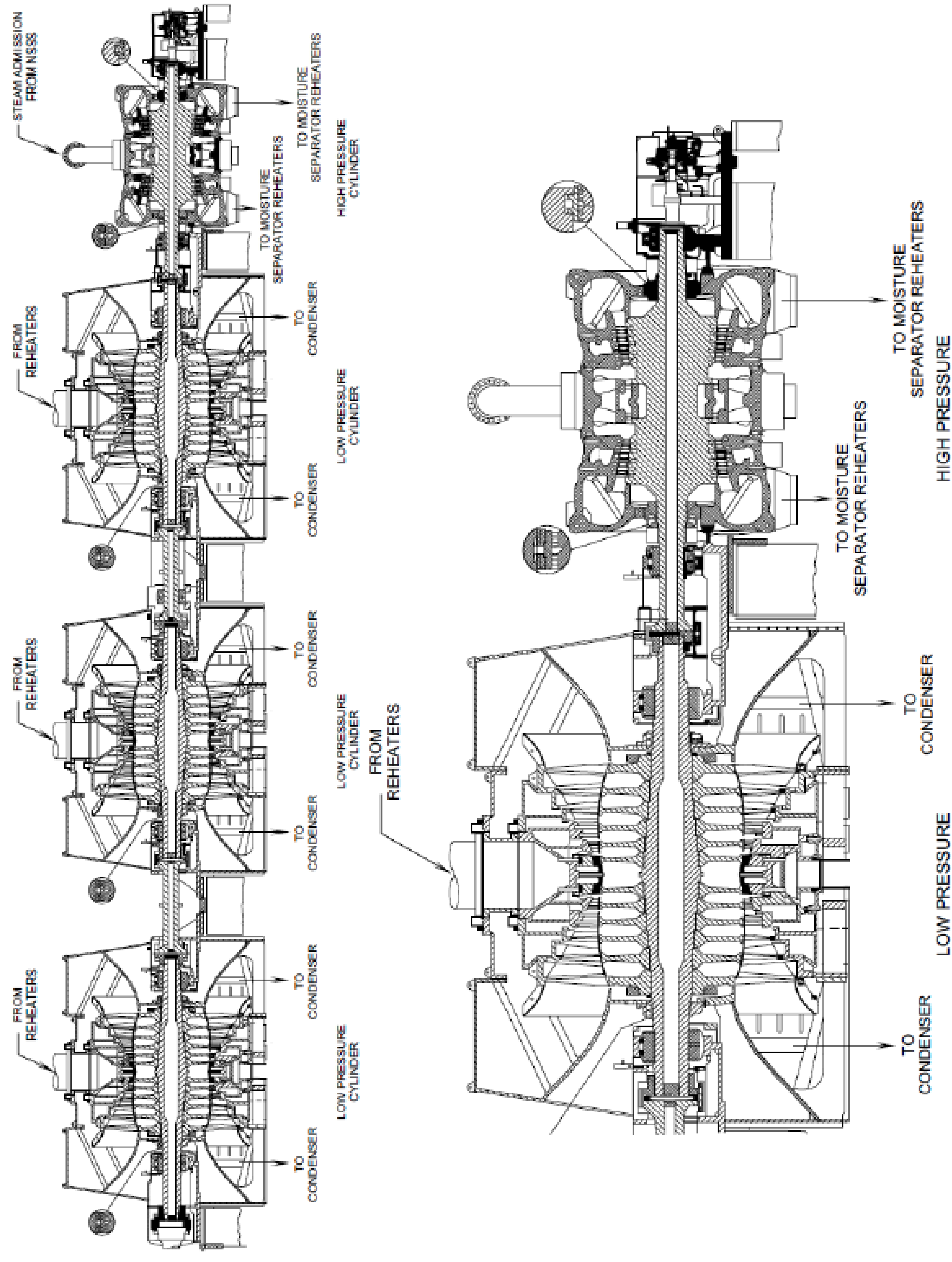


Figure 24: Steam Turbine

5.2.3 Steam PORV's

During plant startup when the reactor produces heat, steam is being produced in each steam generator. As the steam turbine is not yet in service and no steam is yet available for the the turbine gland steam system (so a vacuum cannot be established in the condenser) this steam will be dumped to atmosphere through each steam generator discharge line Power Operated Relief Valve (PORV) - (01LBA10AA501, 01LBA20AA501, 01LBA30AA501, 01LBA40AA501).

As steam generator outlet steam pressure increases, it will be eventually high enough in pressure to allow the turbine gland steam system to be placed in service (valve 01MAW10AA001 will open).

Condenser vacuum can now be established by "Pulling" vacuum with control 01MAJ10AH001. Once the condenser pressure has been reduced to an adequate level the bypass valves (01LBA60AA251 and 01LBA60AA252) are released for operation and will open at this stage.

Once steam generator steam flow has reached greater than 5% of total flow and with turbine bypass valves (01LBA60AA251 and 01LBA60AA252) open then steam generator PORV's (01LBA10AA501, 01LBA20AA501, 01LBA30AA501, 01LBA40AA501) valves will close.

If at any stage the condenser vacuum is lost and pressure within the condenser rises to a high level then firstly the steam turbine will trip, followed at a still higher pressure with a protection close of the turbine bypass valves (01LBA60AA251 and 01LBA60AA252). Witht he steam turbine shut down and the turbine bypass valves held close to prevent over-pressurisation of the condenser, the steam generator discharge line Power Operated Relief Valve (PORV) - (01LBA10AA501, 01LBA20AA501, 01LBA30AA501, 01LBA40AA501) will open.

5.2.4 Bypass valves

During plant startup when steam generator outlet steam pressure is high enough to allow the turbine gland steam system to be placed in service (valve 01MAW10AA001 will open).

Condenser vacuum can now be established by "Pulling" vacuum with control 01MAJ10AH001. Once the condenser pressure has been reduced to an adequate level the bypass valves (01LBA60AA251 and 01LBA60AA252) are released for operation and will open at this stage.

When all steam turbine start premissives are met, the operator can reset the STG trips using button 01MAA10AH001 and the turbine will run up to speed, synchronise to the electrical grid and slowly increase in load until all steam produced by the four steam generators is being used by the turbine.

As the steam turbine used more steam from the steam generators, the turbine bypass valves (01LBA60AA251 and 01LBA60AA252) will close.

At any time that steam generator output flow is higher than that required by the steam turbine, then the turbine load will increase. Conversely if the steam generator output flow is lower than that required by the steam turbine, then the turbine load will decrease. If however the steam generator output flow increases too quickly over the demand of the steam turbine, the turbine bypass valves (01LBA60AA251 and 01LBA60AA252) will open momentarily to dump the excess steam directly to the condenser.

When the steam turbine is stopped (button 01MAA10AH002), the turbine load will reduce causing the bypass valves (01LBA60AA251 and 01LBA60AA252) will open. Turbine will de-synchronise from the electrical grid and run down to turning gear speed. Turbine bypass valves will remain open to relieve steam generator output flow directly to the condenser.

5.2.5 Turbine Sequence

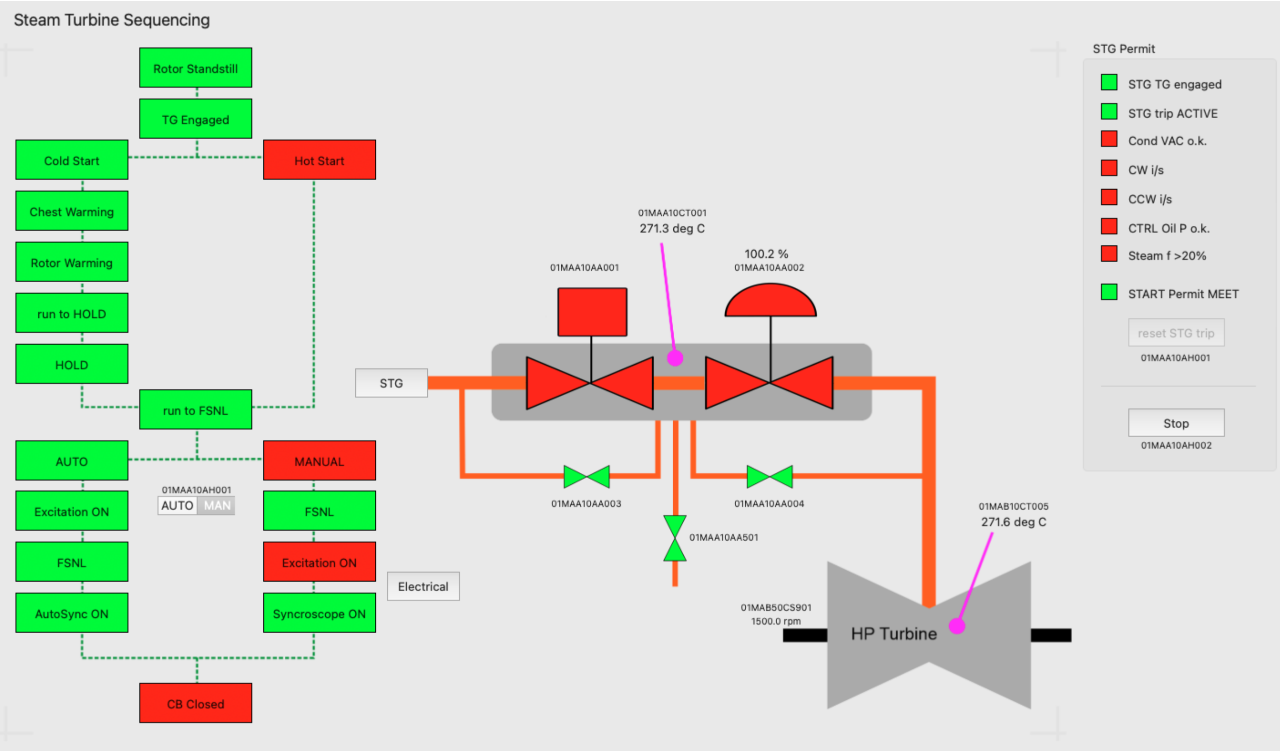
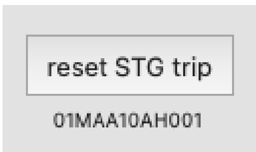


Figure 25: Turbine Sequencepage screenshot

Here is where the steam turbine can be started and stopped, but before starting all turbine permissive must be met. They are;

- STG TG engaged (Steam turbine turning gear engaged).
- STG trip ACTIVE (Steam turbine must have a trip active to enable restart).
- Cond VAC o.k. (Condenser vacuum is sufficient to enable turbine operation).
- CW i/s (Cooling water pump is running).
- CCW i/s (Closed cooling water system is running).
- Steam f >20% (Main steam flow is greater than 20%).

Once these are all satidfied then the operator will be allowed to pressure the "reset STG trip" button.



With no turbine trip signal present, the steam turbine will commence startup.

If starting the turbine from a cold condition (i.e. the turbine has been shut down for a long time and the turbine rotor temperature is near ambient conditions) then the following turbine warm up steps will be done.

- Steam Chest warming (slowly warming the stop and control valve bodies to prevent thermal stress). Chest warming will continue until valve body temperature is approx 350 deg C.
- Turbine Rotor warming (slow warm of turbine rotor and casing). This will also continue until HP rotor temperature is approx. 250 deg C.
- Turbine speed will hold at 900 rpm to ensure even heating of turbine rotor/casing, before increasing to synchronise speed (1500 rpm).

However, if the turbine is still in a Hot condition (recently shutdown) these steps will be bypassed in the sequence and the turbine will run up to synchronise speed (1500 rpm as it is a 4 pole generator operating on a 50Hz grid).

Depending if "AUTO" or "MAN" has been selected before the startup commenced, the following will happen;

AUTO If Automatic selected the runup will continue to 1500 rpm and the generator will auto synchronise to the grid and cclose generator circuit breaker (01MKA10GS001)

MAN If Manual selected the runup will complete just below 1500 rpm and the operator must then go to the Electrical/Generator Synchronising page and;

1. SELECT Excitation ON
2. ADJUST transformer Tap position and Increase/Decrease excitation current to match generator voltage to grid voltage.
3. ADJUST turbine speed setpoint to match generator frequency to grid frequency.
4. MATCH phase angle using synchroscope.
5. CLOSE Generator Circuit Breaker.

Turbine runup is now complete and turbine will now operate in "Turbine Follow Mode". This means that adjusting the reactor load will have the affect of adjusting the turbine load (The turbine control valve opening will follow the reactor output).

To Shutdown the turbine, the operator must open pressure the "STOP" button.

Turbine will decrease load (Turbine bypass valves will open to dump excess steam to the condenser) and when slightly negative power output is detected, the turbine will trip (Generator CB will open). Turbine speed will run down until turning gear is engaged.

5.2.6 Turbine Lube Oil and Control Oil

The steam turbine requires lubricating oil for the turbine rotor bearing before the turning gear can be engaged.

However before starting the lube oil system, the viscosity of the oil must be lowered to ensure it is in the correct range for proper lubrication of the bearing. This is achieved by heating the oil using an electric heating element (01MAV10AH001) placed within the lubricating oil tank.

Once the oil has reached the correct temperature and other permissive's have been met (in this case only lube oil temperature and Closed Cooling water running) the lubricating oil system can be started. This turbine is fitted with 2 lubricating oil pumps. The first is an electrically powered pump (01MAV10AP001) that is used for when the turbine is on turning gear and when the turbine is running up to speed and running down after a shutdown or trip. The second is a shaft driven lubricating oil pump (01MAV20AP001) that become effective when the turbine shaft is rotating at greater than 800 rpm. Once the shaft driven pump is operating the electric driven pump will shut down.

If the turbine rotor is at standstill and lubricating oil pump discharge pressure is adequate then the turbine turning gear (01MAK10AE001) can be started. This is used to slowly rotate the turbine rotor (30 rpm) to ensure the shaft is straight before startup (long shafts tend to sag over time from there own weight if left at standstill) and also to ensure even cooling after turbine shutdown.

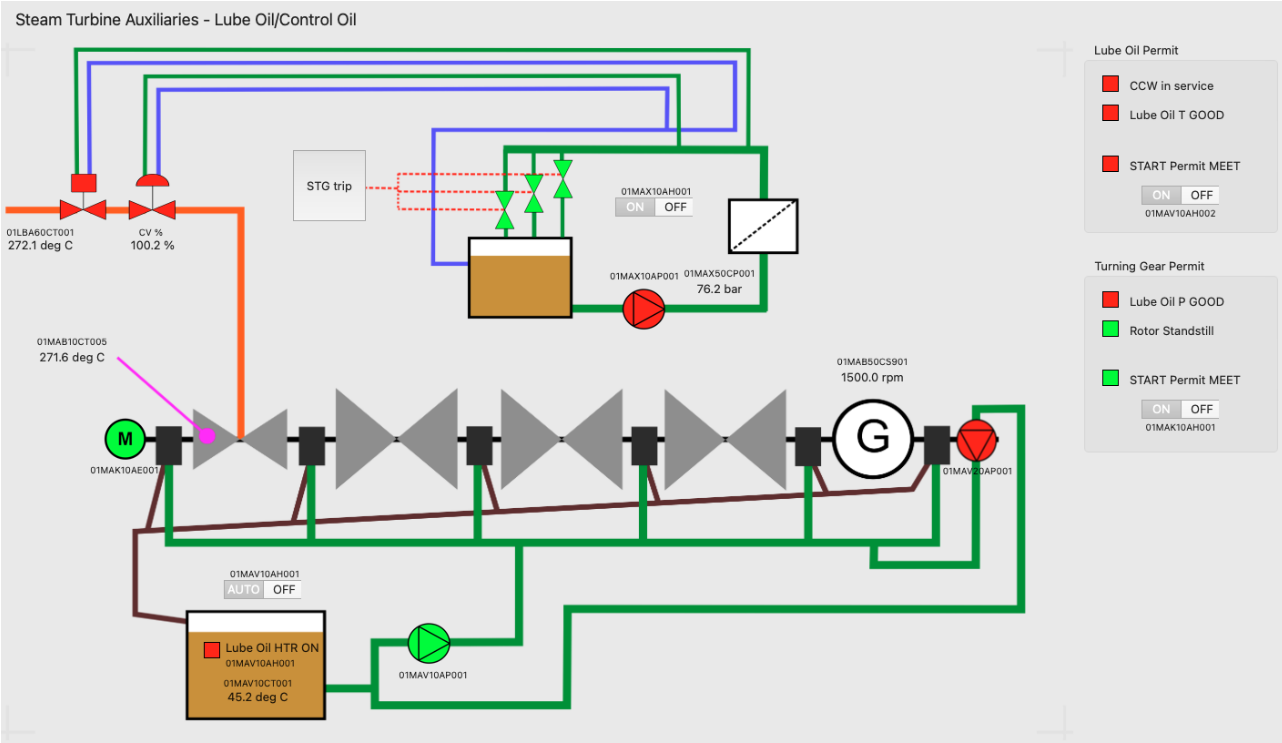


Figure 26: Turbine Lube Oil and Control Oil page screenshot

Additionally this plant has a Control Oil system (tank, pump filters, distribution pipework and dump valves) that provides hydraulic oil to the turbine stop and control valves.

The Control oil pump (01MAX10AP001) supplies oil pressure to open and hold open the turbine stop valve and to control the position of the turbine control valve. If pressure is lost, by either the control oil pump stopping or any of the three dump valves opening then the stop and control valve will close cutting off steam to the turbine. The three dump valves are connected to the turbine trip button, so pressing the Turbine Trip will cause these valves to open, dump the Control Oil pressure back to the oil tank, stop and control valves will close and turbine will trip.

5.2.7 Turbine Gland Steam and Vacuum

To increase the cycle efficiency (utilise the heat from the reactor more completely) we run with a vacuum in the condensers (3 Low Pressure turbines each had a condenser slung underneath). This vacuum is established using 3 Air Ejector pumps (01MAJ10AN001/002/003) which suck out the air and exhaust it to atmosphere.

The condensers and Low Pressure turbine outer casings thus need to be air tight, and they mostly are, however where the turbine shaft penetrates the casing is a source of air ingress that we must seal.

This sealing of the shaft is done with a combination of labyrinth glands and seal steam supply. This is also provided on the High Pressure turbine to limit the escape of high pressure steam from this casing.

Sealing steam is provided from the common steam generator outlet heater via isolation valve (01MAW20AA001) and pressure control valve (01MAW20AA151) and is available once this steam pressure is greater than approx.20 bar. To prevent visible signs of this seal steam escaping to atmosphere from each bearing, a exhauster fan (01MAW10AN001) is fitted to provide a slight negative pressure at each seal and venting this small amount of steam to atmosphere.

Gland steam must be established first before we can "pull" a vacuum within the condenser shells and conversely condenser vacuum must be "broken" before shutting down the gland steam system.

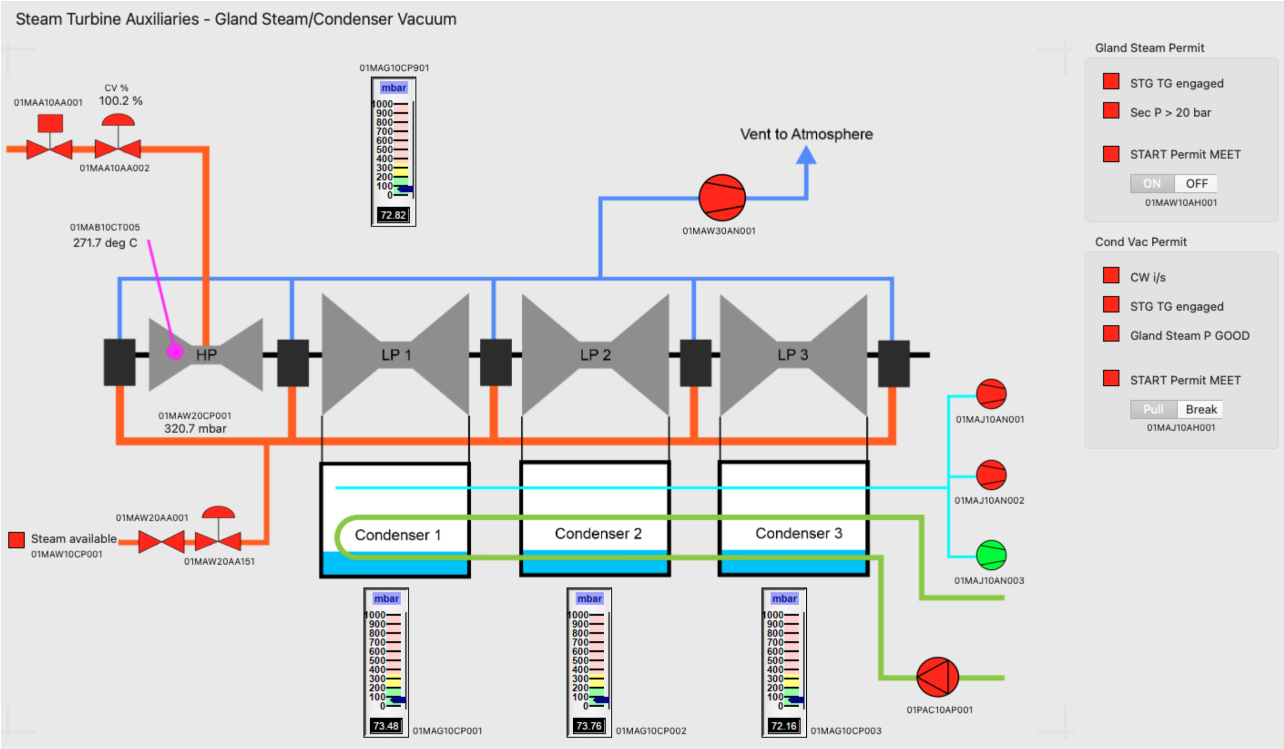


Figure 27: Turbine Gland Steam and Vacuum page screenshot

5.2.8 Turbine Bled Steam

Also to increase the cycle efficiency it is advantageous to increase the temperature of the condensate and feedwater being lead back to the reactor up to near the reactor cold leg temperature. This reduces the load on the reactor and allows a higher primary water flow and thus a higher steam flow from the steam generators.

To increase the condensate and feedwater temperatures we have installed a number of feedwater heaters (4 Low Pressure heaters, 1 Deaerator, 4 High Pressure heaters). Once the turbine has started and reached a load of approx. 285 MW bled steam valves will open in sequence to bled a small amount of steam from various locations on the HP and LP turbines. This steam enters each heater and warms the condensate and feedwater water inside.

Additionally bled steam is available to drive Feedwater Pumps 2, 3 and 4. These are turbine driven pumps, whilst Feedwater pump 1 is electrically driven. FWP 1 is required for start up and shutdown when bled steam is not available, however at higher loads the turbine driven pumps are required. These are also more efficient in operation than the electric pump.

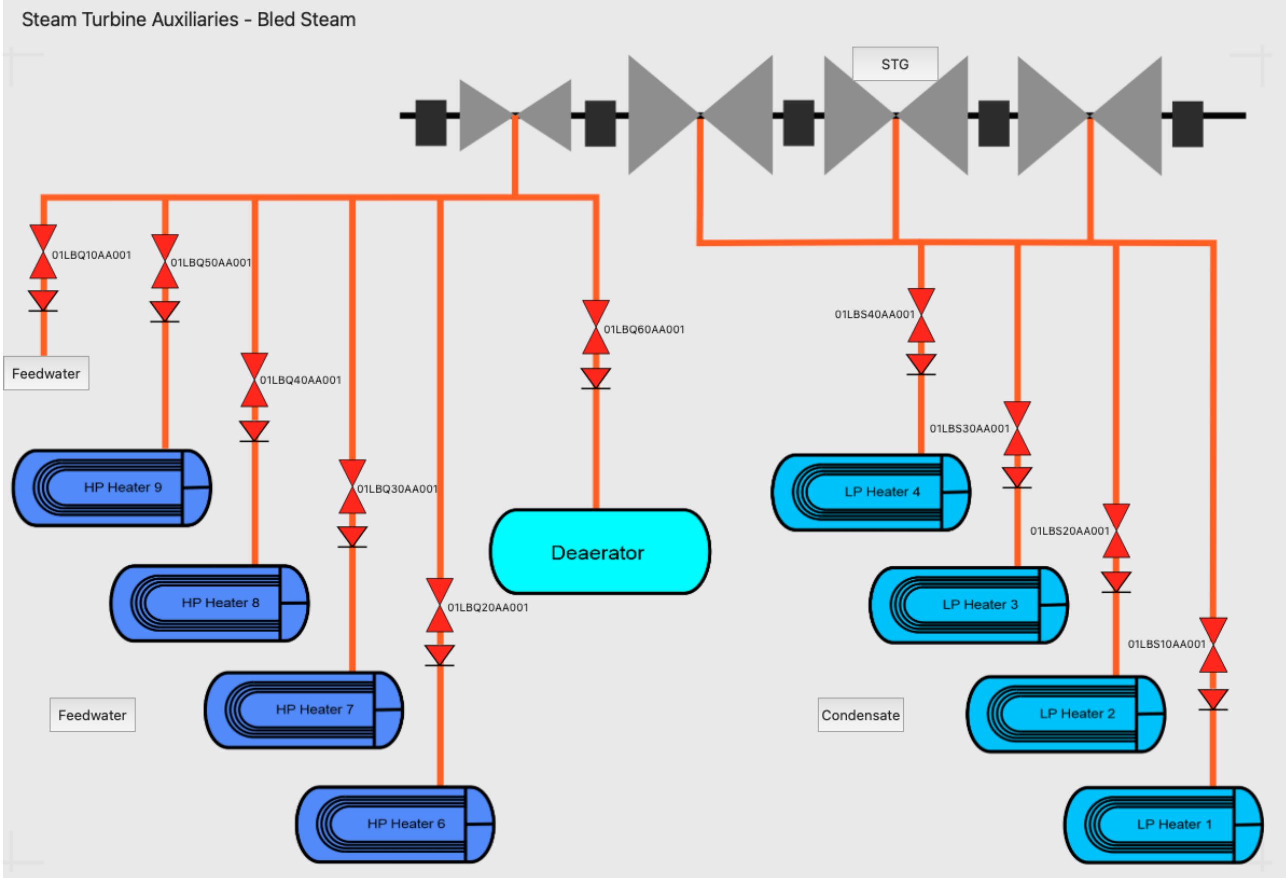


Figure 28: Turbine Bled Steam page screenshot

5.2.9 Condensate Extraction Pumps

The condensate system removes condensed water from the hotwell at the bottom of each condenser and using 3 Condensate Extraction Pumps (CEP's) feeds it through each of the 4 Low Pressure heaters and up to the Deaerator.

At each LP heater the temperature of the condensate water is increase, once the bled steam system is in service. and at full load this should be at about 140 deg C on entry to the Deaerator vessel.

When starting this system the condensate water first flows through all the pipework and each LP heater but is then diverted through a Mixed Bed Polisher vessel via valve 01LCA50AA001 and back to the condenser. This is to clean up the water quality before continuing to feed water to the Deaerator and is know as "Condensate System Clean-Up".

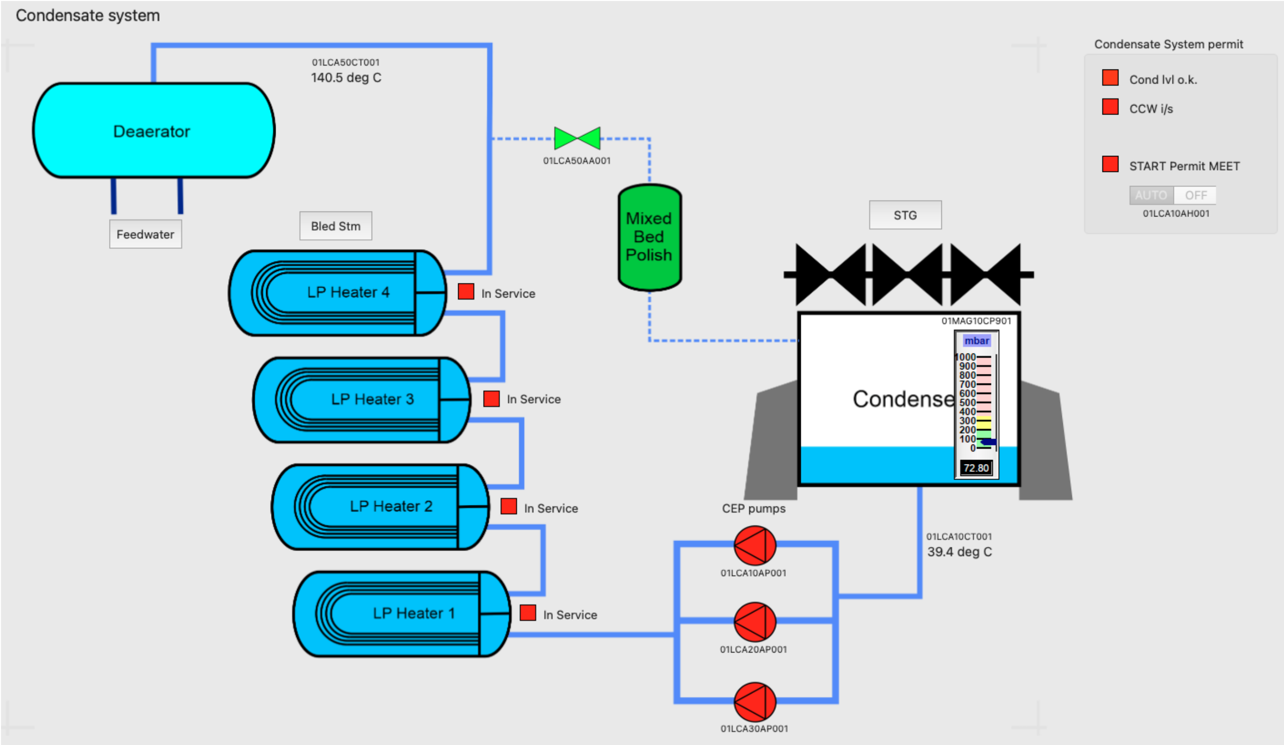


Figure 29: Condensate page screenshot

On this simulator, the Condensate system has been simplified considerable. On an actual plant this system would also include;

- Condenser level control valve after the CEP pumps.
- Chemical Dosing injection system (pH control and oxygen scavenger).
- Chemical Sampling system to measure water quality.
- Each LP heater would have inlet, outlet and bypass valves, level monitoring equipment, plus cascade drains from each higher pressure heater to the one lower.
- There may be another Mixed Bed polisher vessel after the CEP pumps that remains in service at all times.
- Each Mixed Bed polisher vessel needs equipment to backwash resins and monitor differential pressure.

Once this system is started the number of running Condensate Extraction pumps will vary depending on load and they will start up and shutdown automatically.

5.2.10 Deaerator

The Deaerator vessel has 3 functions, as follows;

1. Act as a contact feedwater heater once bled steam is available.
2. Removal of oxygen (de-aeration) as with the pressure and temperature inside this vessel being near the boiling point is ideal for the release of any entrained oxygen.
3. Act as a storage vessel and provide a positive head for the feedwater pumps that are situated directly below this vessel.

5.2.11 Feedwater Pumps

The feedwater system consists of 4 feedwater pumps (1 electric 01LAC10AP001 and 3 steam driven 01LAC20/30/40AP001), 4 High Pressure feedwater heaters and a mixed bed polisher to allow feedwater system cleanup when starting this plant.

Before starting the Feedwater system the Condensate system must have completed its startup and each of the four Steam Generators must be ready for service (SG level within control range).

If all permissives are met then Feedwater pump 1 (electrically driven) can be started. If this is the first start after a shutdown it will go through a feedwater system cleanup routine and pass the water through a Mixed Bed Polisher vessel via valve 01LAC60AA001 and back to the Deaerator vessel. Once the water is clean enough this polisher will be isolated and feedwater will then flow to each of the Steam Generators.

Once the Steam Turbine has been started and bled steam is available it is possible to start Feedwater pumps 2, 3 and 4. It assist the operator to know when a feedwater pump needs to be started or stopped a FWP Capacity gauge is provided. This shows the current required flow (needle pointer) and the current running pump capacity (green background colour on gauge). If the pointer is nearing the top of the green band then it is time to start another feedwater pump. Conversely if the needle nears the bottom of the green band then stop a feedwater pump.

The Electrically driven pump (FWP 1) has a minimum flow rate of 0% and a maximum of 40%.

Each of the turbine driven pumps (FWP 2, 3, 4) has a minimum flow rate of 15% and a maximum of approx. 35%.

On this simulator, the Feedwater system has also been simplified considerable. On an actual plant this system would also include;

- Each feedwater pump would be equipped with vibration monitoring equipment.
- FWP 2, 3 and 4 being turbine driven would require much additional equipment. As this is a small steam turbine (1 for each of these pumps), it would also require a condenser, gland steam system, lube oil, control oil, vibration monitoring, etc, etc
- Chemical Sampling system to measure water quality.
- Each HP heater would have inlet, outlet and bypass valves, level monitoring equipment,plus cascade drains from each higher pressure heater to the one lower.
- Mixed Bed polisher vessel would have equipment to backwash resins and monitor differential pressure.

Once this system is started the number of running Feedwater pumps must be controlled by the operator in charge. Failure to do so will result in a Reactor SCRAM due to low/high Steam Generator level.

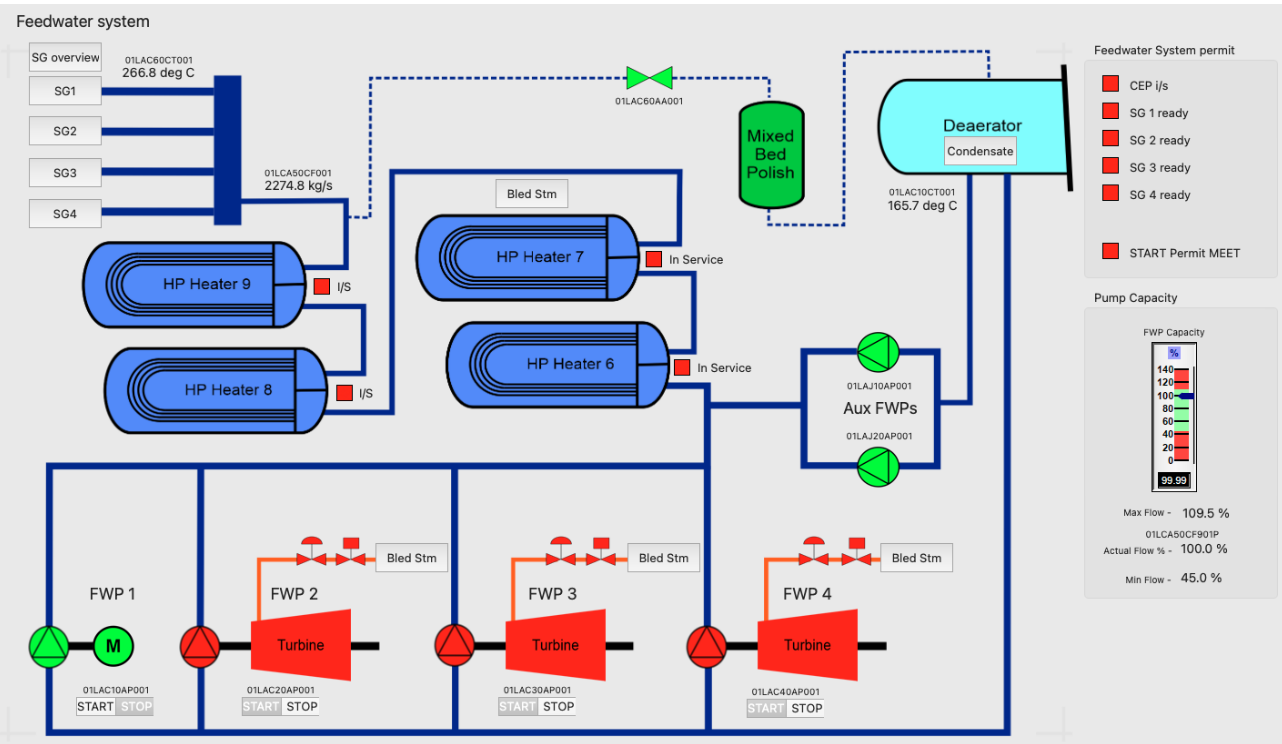


Figure 30: Feedwater page screenshot

5.2.12 Generator and Synchronising

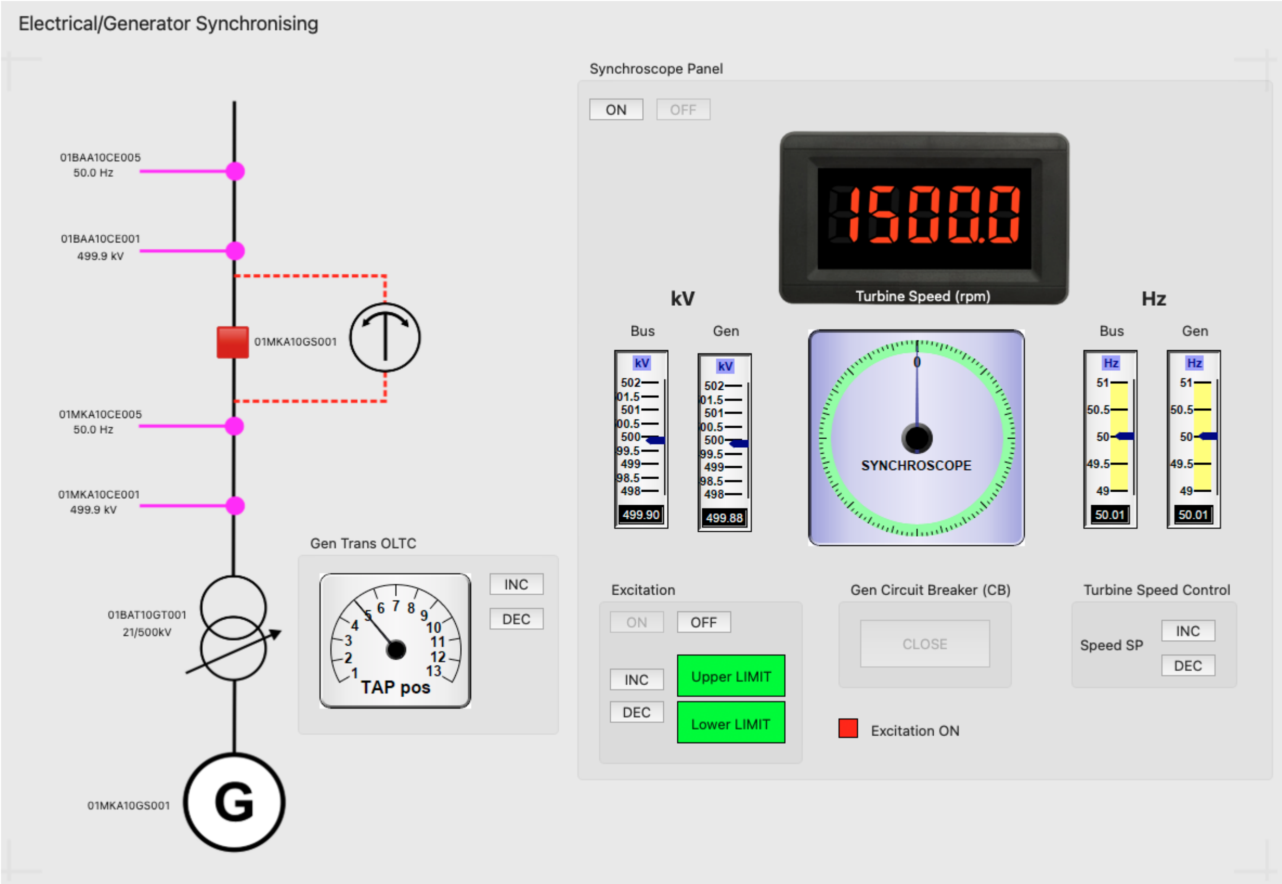


Figure 31: Electrical/Generator Synchronising page screenshot

If a Manual startup of the Steam Turbine has been selected on the Turbine Sequence page then once the turbine runup sequence has raised the turbine speed to near 1500 rpm, the operator must use this screen to manually synchronise the generator to the electrical grid.

To synchronise any generator, 3 values must match.

1. Match the Voltage (both generator and grid voltage must be as near as possible the same. Use transformer tap changer and excitation current increase/decrease).

2. Match Frequency (generator frequency is controlled by turbine speed. Adjust turbine speed to match gen frequency to grid frequency).

3. Match Phase Angle (Generator and Grid phase angle is indicated on the synchroscope. If the needle is pointing straight up at the 12 o'clock position then the phase angles match).

If these 3 values match then the operator can go ahead and CLOSE the Generator Circuit Breaker.

5.3 Tertiary Circuit

The tertiary circuit consists of plant cooling systems, as follows;

5.3.1 Cooling water, SW and CCW

When the steam has completed its work in each of the 3 Low Pressure Turbines it is directed to the Condensers (3 of these also, but we represent it as just one on this page). This steam must have it latent heat removed so it can convert back to water and allow us to pump it back to each Steam Generator using the Condensate and Feedwater systems. To remove this latent heat we use a heat exchanger with cooling water from the local river. This water is supplied by the Main Cooling Water Pump (01PAC10AP001). This pump can be very large (and it is usual to have 2 or 3 smaller pumps to work together) as the flow rate required is very high.

This Main Cooling water passes through the condenser tubes, cooling the turbine exhaust steam and is dumped back into the local river (downstream). We monitor the inlet (01PAC10CT001) and outlet (01PAC60CT001) temperatures to ensure we do not exceed our environmental permit limits.

Additionally we take a smaller amount of cooling water from the main cooling pump discharge before it enters the condenser and pass it through a Service water pump (01PJA10AP001) and heat exchanger which cools the Closed Cooling water system and then on to further heat exchangers for various plant equipment cooling (lube oil cooler, HVAC cooling, etc).

The Closed cooling system does not use the river water (which has sediment, etc), but is filled with demineralised water and dosed with chemicals to maintain pH and remove oxygen. It circulates using pump (01KAA10AP001) to cool various plant equipment (Generator coolers, CVCS coolers, etc) that require good water quality and is itself cooled byt he heat exchanger on the Service water system.

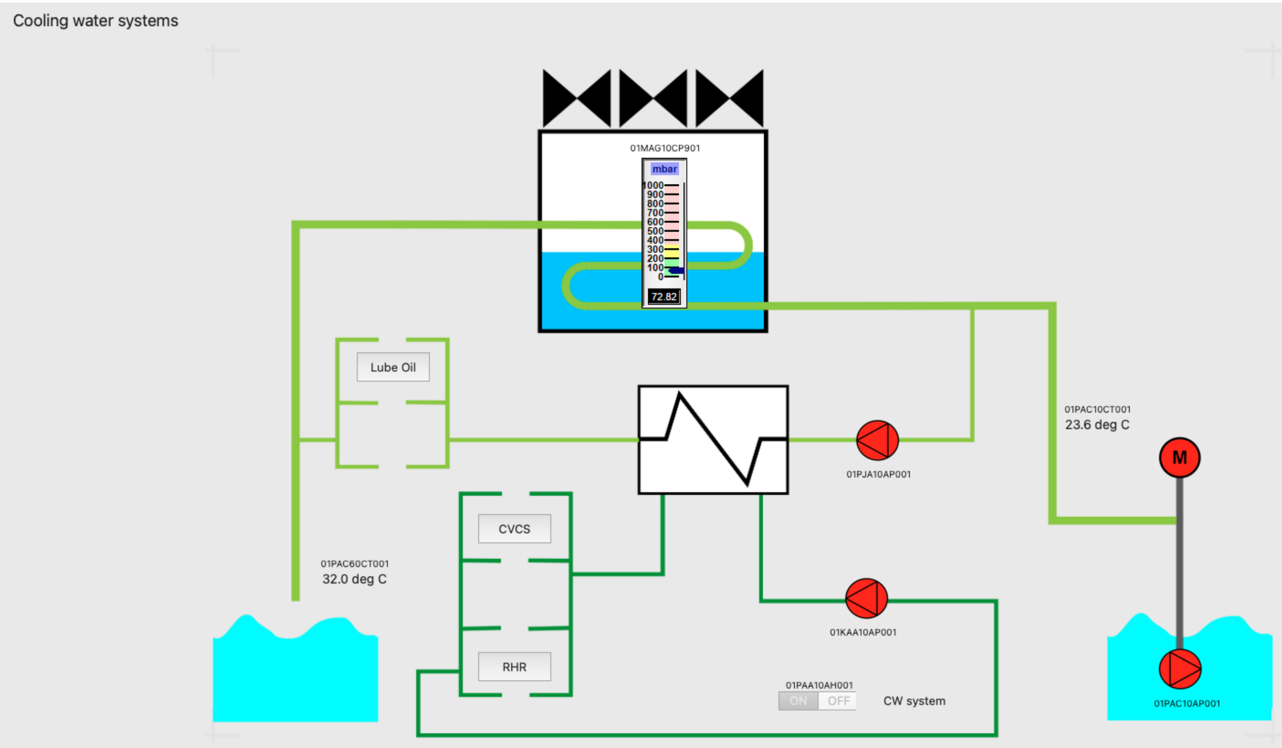


Figure 32: Main Cooling water, Service water and Closed Cooling water systems

5.4 Auxiliary Plant

Although this simulation covers many areas of the main reactor and steam turbine there are still a vast number of system not fully or even partially covered. Some of these systems are listed below, just so you know that a nuclear power plant is a very complicated group of systems;

- Water treatment plant
- Waste water treatment plant

- Dosing system for primary, secondary and tertiary systems.
- Chemical analysis system for primary, secondary and tertiary systems.
- Electrical power distribution within the plant.
- Emergency electrical generators.
- Emergency battery systems.
- Compressed air and Instrument air systems. Fire detection/protection systems.
- Reactor refuelling equipment.
- Spent fuel storage.
- Maintenance workshop
- Office space utilities (HVAC, water, sewage, power, security access, computer networks, etc)

5.5 Instrumentation

The purposes of the nuclear instrumentation system are to:

1. Provide indication of reactor power from shutdown to full power conditions,
2. Provide inputs to the reactor protection system during startup and power operation,
3. Provide reactor power information to the automatic rod control system, and
4. Provide axial and radial power distribution information during power operations.

The nuclear instrumentation system monitors the power level of the reactor by detecting neutron leakage from the reactor core. Leakage neutron flux from the core is monitored for two primary reasons. First, core neutron leakage is directly proportional to the core neutron flux (power level), and second, it is much easier to design and maintain neutron detectors which do not need to operate within the hostile environment of the reactor core.

Three overlapping ranges of instrumentation monitor the neutron flux level generated in the core from a few counts per second up to approximately 10^{15} neutrons/cm^2/sec (200 percent of full power). The three different ranges of indication are source, intermediate, and power. Monitoring and protective functions are provided by two independent source range channels, two independent intermediate range channels, and four independent power range channels. The power range instruments also provide an input into the automatic rod control system.

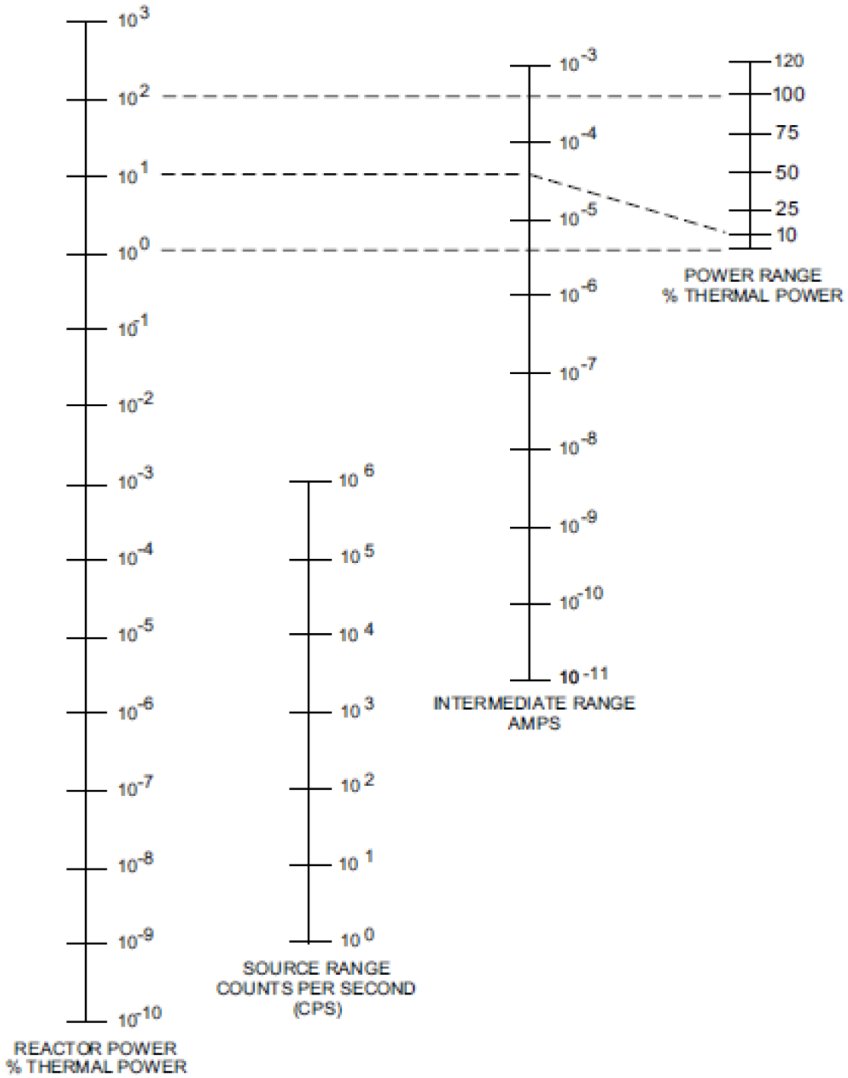


Figure 33: Neutron detectors range of operations

In addition, the source and intermediate range startup rates are provided to the reactor operator. This information is used by the reactor operator to determine the approach to criticality and to monitor how rapidly reactor power is changing.

The source, intermediate and power range detectors are placed in instrument wells located within the concrete shield surrounding the reactor vessel. The instrument well is movable and is positioned by a push-bar located outside the concrete shield wall. If an individual detector requires maintenance or replacement, the instrument well is pulled away from the reactor vessel to a location under an access pipe which is sealed by a water tight cap. After maintenance is complete, the instrument well is pushed back to a position adjacent to the reactor vessel.

5.5.1 Flux meter - Source range

The source range instrumentation consists of two independent channels, designated as source range channels N-31 and N-32. Both channels are physically and functionally identical. The source range detectors are located 180 degrees apart outside the bottom half of the core. This location provides the maximum sensitivity to low power neutron level increases. The source range circuits monitor and indicate the neutron flux level of the reactor core and the rate by which the neutron flux changes during a reactor shutdown and the initial phase of start-up. The rate of change of the neutron population is indicated as startup rate (SUR). The SUR is the number of decades (powers of ten) that the neutron flux (reactor power) is changing per minute and is indicated as decades per minute (DPM).

The meter face is calibrated to indicate counts/sec and represents the number of neutron pulses generated per second. This instrument can indicate up to a maximum neutron count rate of 10^6 cps. The count rate signal is also applied to bistable relay assemblies which in turn generate signals for remote protection equipment.

Figure 34: Source Range meter

5.5.2 Flux meter - Intermediate range

The intermediate range instruments consist of two independent channels, designated as intermediate range channels N-35 and N-36. Both channels are physically and functionally identical. The intermediate range detectors are located 180 degrees apart outside the midpoint of the core. The detectors share the same instrument well as the source range detectors. The midpoint of the core location allows the detectors to monitor the neutron population changes from low power operations to full power. The intermediate range channels monitor the neutron flux of the core and provide signals to the rate circuits to compute its rate-of-change. The intermediate range channels, which cover a span of eight decades, come on scale when the source range channel indications reach approximately 10^3 counts/sec. The intermediate instruments monitor neutron flux from this level through full power operation.

A logarithmic current measuring circuit is used to monitor reactor power over a range of eight decades (10^{-11} to 10^{-3} amperes). Indications of intermediate range neutron flux level and SUR are provided at the nuclear instrumentation cabinets and at the reactor control panel.

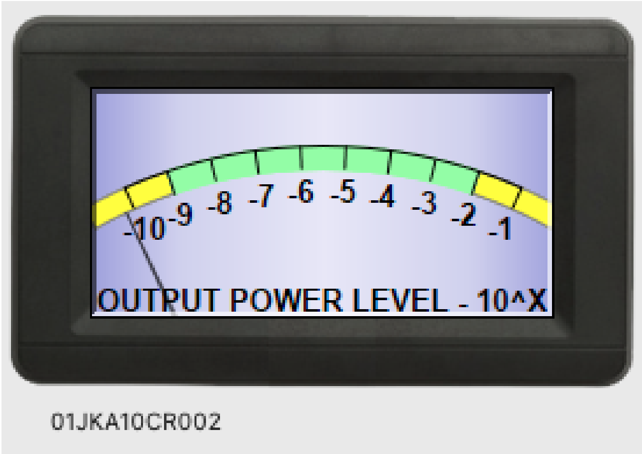


Figure 35: Intermediate Range meter

5.5.3 Flux meter - Power range

The power range circuits consist of four independent channels, designated as power range channels N-41 through N-44. All four channels are physically and functionally identical. Each power range channel employs an upper and a lower uncompensated ion chamber detector which provide current signals to the power range circuits. The power range detectors are located 90 degrees apart. Each location consists of an upper detector and a lower detector, mounted inside the same instrument well. The outputs of both detectors (upper and lower) are combined to produce a channel total power signal. The eight detector outputs (four upper detectors and four lower detectors) are compared to each other to provide power distribution information to the reactor operator.

Within each power range channel, the upper detector and lower detector current signals are monitored, summed and amplified, at the summing and level amplifier, to develop a voltage which is directly proportional to reactor power. The summed signal is monitored in percent full power, ranging from zero to 120 percent. The output of each power range channel provides reactor trip signals, alarms and input for control functions.

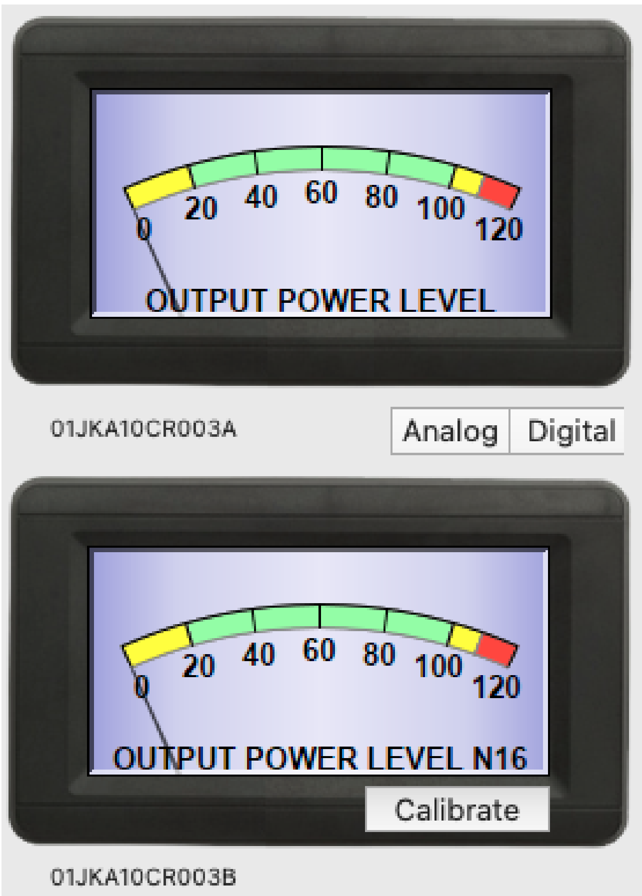


Figure 36: Power Range meter (analog)

5.5.4 Flux meter - Power range N16

Figure 37: Power Range meter (digital)

5.5.5 Flux meter - Calibration

Whilst the Source and Intermediate flux meters are very accurate over their operating range, the same cannot be said for the Power range and Power range N16 meters. The method of measurement for both of these instruments leads to inaccuracies at the lower end of the scale and the even at middle and higher reading a tendency to drift over time.

As some of the reactor protection measures are provided with information from these instruments a "Calibrate" button is provided that will compare the current instrument readings with a value calculated form a primary and secondary circuit heat balance (calorific) and reset the instrument to match.

This "Calibrate" button should be used at any time that doubt exists about the instrument output and also at times prescribed in the operating procedures.

5.5.6 SUR - Start Up Rate

After reactor criticality has been achieved, up until a reactor power level of 5% the operator will use the Start Up Rate gauge (01JSA10CR001).

This gauge is scaled from -1 to +4 decades per minute (DPM) with a Start Up Rate HIGH alarm at 2 and a reactor SCRAM if the value reaches 3. The operator should maintain this value less than 2 when loading the reactor.

Above a reactor power output of 5% this gauge will be switched out automatically.

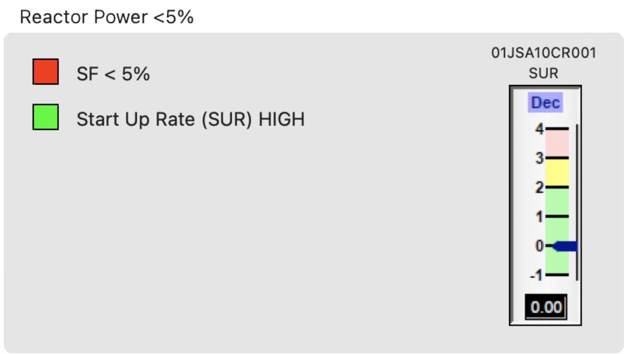


Figure 38: SUR (Start Up Rate) gauge and alarm indication

5.5.7 LIR - Load Increase Rate

Once a reactor load of >5% has been achieved the operator will use the Load Increase Rate gauge (01JSA10CR002).

This gauge is scaled from -2 to +6 with a Load Increase Rate HIGH alarm at 3.2 and a reactor SCRAM if the value reaches 5.2. The operator should maintain this value less than 3.2 when load the reactor.

This instrument is active from a reactor load of 5% upto full load.

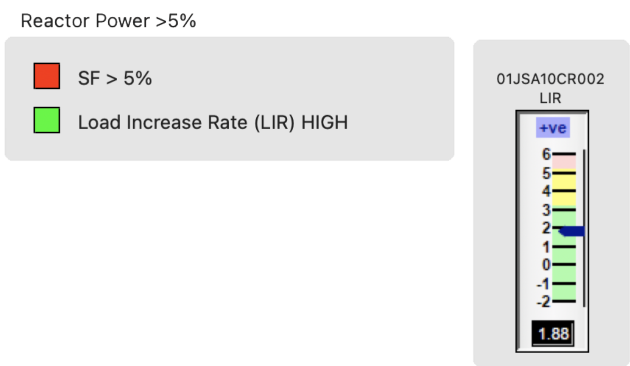


Figure 39: LIR (Load Increase Rate)

5.5.8 Axial Displacement

In addition to the Load Increase Rate HIGH alarm once reactor load is >5%, when this load exceeds >10% the Axial Displacement gauge (01JSA10CR003) and associated alarms/trips will become active.

This gauge measures the power distribution within the reactor core axially from top to bottom. Ideally we would like the nuclear chain reactions to occur evenly within the core to minimise hot spots, however some plant feature may prevent this. One such item is the control rods, as they feed into the core from the top it can cause the chain reaction to move near the bottom of the core.

Any deeply inserted rods will distort the core power distribution forcing the lower half of the reactor core to contribute more of the reactor load and the upper half less which can lead to a fuel rod experiencing higher than design temperatures in the lower core. To protect against this Axial Displacement gauge (01JSA10CR003) monitors this power distribution and will initiate an alarm or even Reactor SCRAM if over design limits.

This gauge is scaled from 0 to 120% and is provided with 2 indicating pointers. The GREEN pointer shows the calculated alarm value for axial displacement and will generate an alarm if it exceeds 100%.

The RED pointer shows the calculated trip value and will generate an alarm if it exceeds 100% and start a 30 second timer. If at the end of 30 seconds the pointer is still greater than 100% a reactor SCRAM will be initiated.

This instrument is active from a reactor load of 10% upto full load.

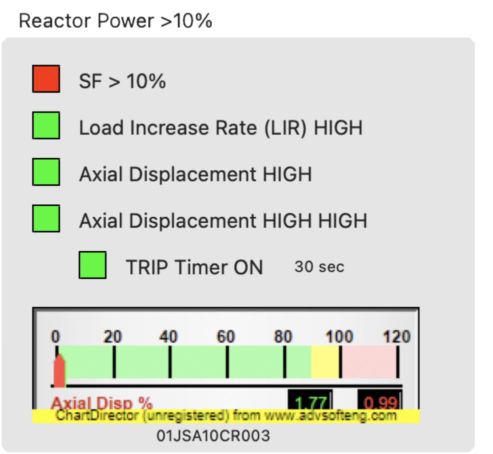


Figure 40: Axial Displacement

5.5.9 Criticality Estimator

This instrument is provided to enable the operator to estimate the approximate boron concentration required in the primary circuit to achieve reactor criticality given some input variables.

Input variables are;

- Fuel age in days. Time since last reactor refuelling.
- Time in hours since last shutdown. Xenon concentrations in the reactor can affect reactivity and time since shutdown can be used to predict the remaining Xenon.
- Expected position of each of the reactor control rods at reactor criticality.

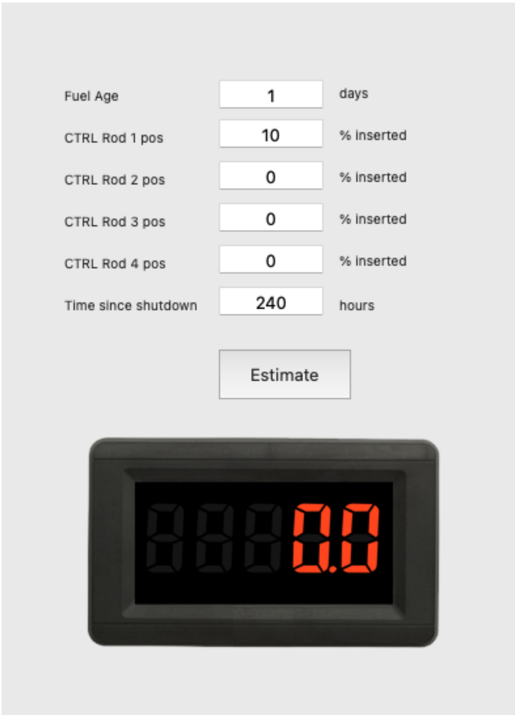


Figure 41: Estimation of Criticality calculator

To reduce distortion of the core power distribution it is desirable to operate the reactor will control rods nearly fully withdrawn. Therefore it is preferred to achieve reactor criticality with 3 control rods fully withdrawn and the remaining control rod between 10 - 20% inserted.

Once criticality is achieved load increases of the reactor can be accomplished by diluting the boron concentration in the primary circuit.

6 Simulator layout

6.1 Screen components

When the application is first started you are presented with two windows, as follows;

Simulator This is the main window used to operate the reactor, turbine and auxiliary plant. The trainee will use this screen.

Trainer Window This screen should be used by the instructor/Trainer from which he can select the simulator scenario, start/stop the simulator and input faults as required.

6.1.1 Simulator Window

The image below shows the full simulator window with the Reactor Control rod page currently displayed.

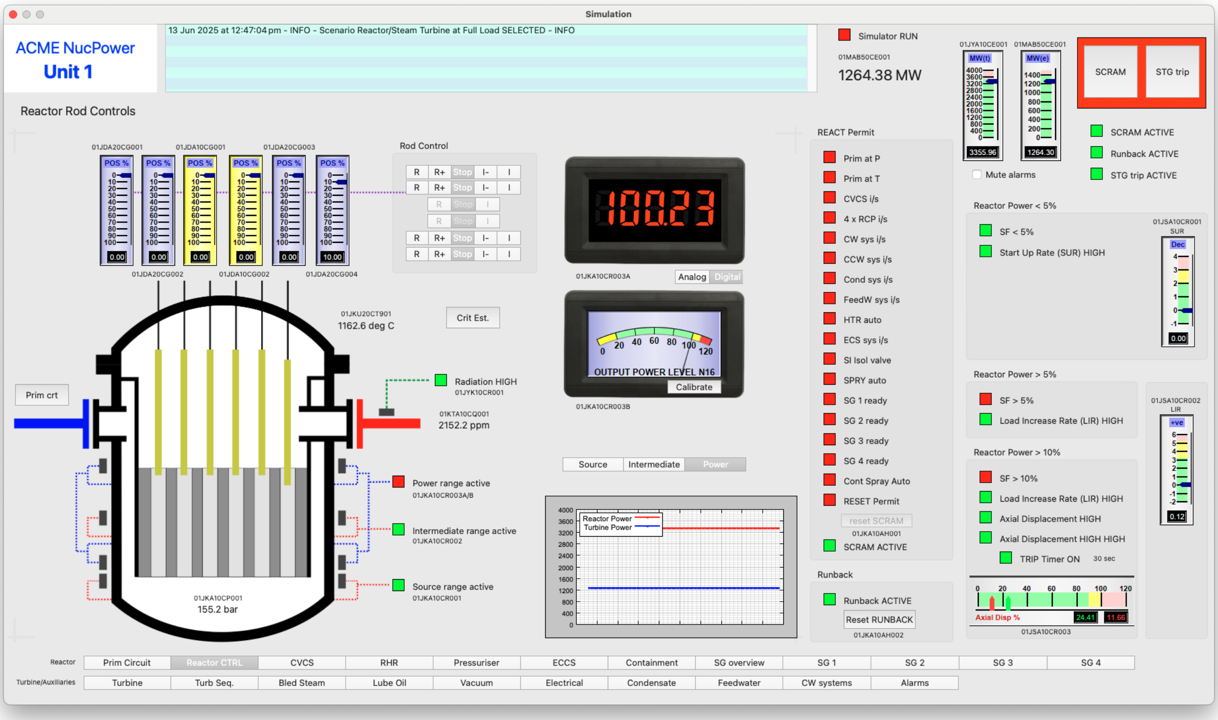


Figure 42: Simulation window

The main area of the window can be changed by selecting from the two button bars at the foot of the page (see figure 43). The top button bar can display pages related to the Reactor, whilst the bottom bar deals with the Steam Turbine and Auxiliary equipment.

Screenshots of all the different pages that can be displayed can be found in Appendix B.

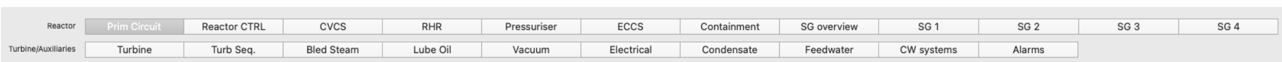


Figure 43: Select which display page you would like to view

Along the top of the Simulator window there is some information that always remains visible, no matter which page is selected by the bottom button bars.

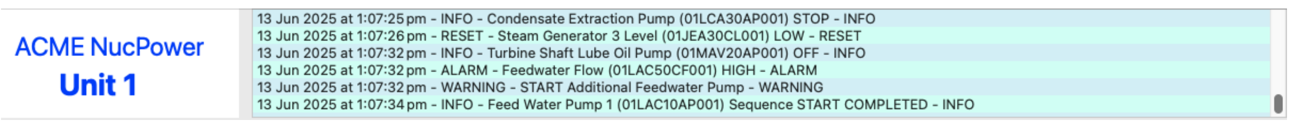


Figure 44: Plant identification and alarm/event information

Firstly we have the company and Unit number identification. This plant is proudly owned by ACME NucPower and is identified as Unit 1. Construction of Units 2 to 4 are pending!

To the right of this we have a small alarm and event display that will show the latest 6 alarms/events. The information displayed in this list can be broken down as follows;

INFO An item of plant equipment, such as a pump or valve has operated or changed condition.

WARNING Advice from the control system recommending some action by the operator. Usually occurs before the parameter alarm point is reached.

ALARM Some plant measurement has exceeded its normal parameters. It is advisable for the operator to correct this and return said parameter to normal range.

RESET Plant measurement that has previously been in the ALARM range has now returned to normal operating range.

TRIP An item of plant equipment has been stopped to either protect itself or to protect other plant items or personnel.

To the right of this is a small display area that provides information of plant output and current condition of Reactor and Steam Turbine. The information provided is as follows;

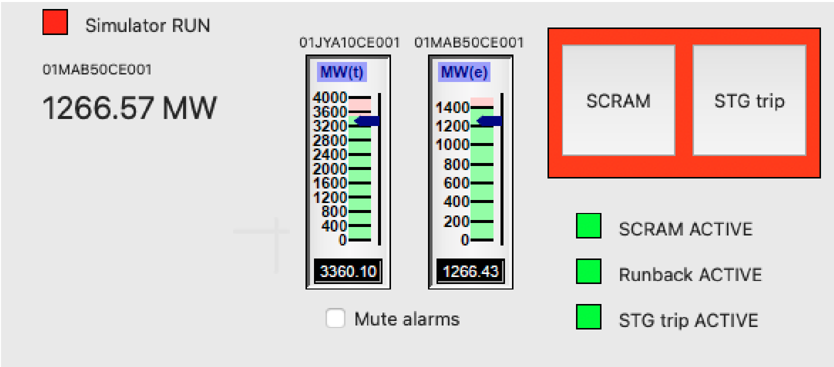


Figure 45: Power output and essential information

Simulator RUN/STOP indication This provides a display indicating if the simulator is currently in operation or paused/stopped. As with other indications of plant equipment it show RED for run and GREEN for stop.

Generator Load Below the simulator Run/Stop indication is an analogue display of generator output electrical power (currently displaying 1266.57 Megawatts). This is the electrical power we are exporting to the national electrical grid and what we get paid for. Note like all other indications of plant parameters this output has a KKS code to identify it. In this case the KKS identification tag is 01MAB50CE001.

Reactor output gauge A vertical linear gauge showing reactor thermal output in megawatts. Note that the reactor thermal output is much higher than the turbine electrical output due to inefficiencies in the reactor cycle. This gauge also has a KKS identification code, which is 01JYA10CE001.

Turbine output gauge When the steam turbine has been started and the generator connected to the national electrical grid this vertical linear gauge will show generator output power.

SCRAM Active Reactor TRIP signal is active. Control and protection rods are inserted into the reactor core and cannot be withdrawn until reactor SCRAM is reset.

Runback Active Reactor Runback is active, which indicated some plant parameter has been exceeded that requires a reduction in reactor steam output. For instance if the steam turbine trips then the reactor will runback to approximately 40% load to reduce the steam being dumped to the condenser by the turbine bypass valves. Whilst a runback signal is active the control and protection rods are prevented from being withdrawn further.

STG Trip Active A Steam Turbine trip is active, which means the turbine is shut down. Resetting this trip will start the turbine.

Additionally we provide here 2 emergency shutdown buttons, so that they are always within easy reach of the operator when needed. They are;

SCRAM Pressing this button will remove power from the magnets holding the reactor control and protection rods at their current position and they will then drop into the reactor core and shut down the chain reaction. Reactor power output will drop quickly when this occurs, however residual heat in the core, primary circuit and secondary circuit will mean steam production continues for some time. A reactor SCRAM will also cause a Steam Turbine trip.

STG Trip This button will cause a trip/emergency shutdown of the Steam Turbine. Generator circuit breaker will open, turbine power output will reduce to zero and turbine speed will rundown to turning gear speed. Depending on the reactor load at the time of steam turbine trip, this may also result in a reactor runback.

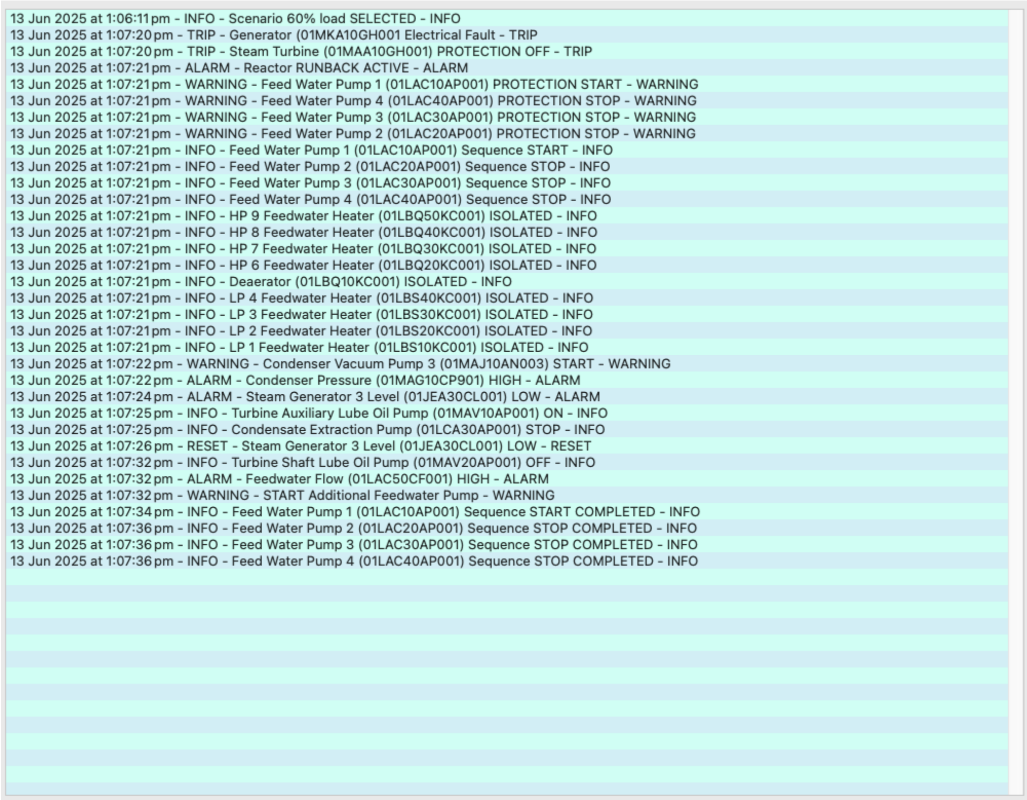

13 Jun 2025 at 1:06:11 pm - INFO - Scenario 60% load SELECTED - INFO
13 Jun 2025 at 1:07:20 pm - TRIP - Generator (01MKA10GH001 Electrical Fault - TRIP
13 Jun 2025 at 1:07:20 pm - TRIP - Steam Turbine (01MAA10GH001) PROTECTION OFF - TRIP
13 Jun 2025 at 1:07:21 pm - ALARM - Reactor RUNBACK ACTIVE - ALARM
13 Jun 2025 at 1:07:21 pm - WARNING - Feed Water Pump 1 (01LAC10AP001) PROTECTION START - WARNING
13 Jun 2025 at 1:07:21 pm - WARNING - Feed Water Pump 4 (01LAC40AP001) PROTECTION STOP - WARNING
13 Jun 2025 at 1:07:21 pm - WARNING - Feed Water Pump 3 (01LAC30AP001) PROTECTION STOP - WARNING
13 Jun 2025 at 1:07:21 pm - WARNING - Feed Water Pump 2 (01LAC20AP001) PROTECTION STOP - WARNING
13 Jun 2025 at 1:07:21 pm - INFO - Feed Water Pump 1 (01LAC10AP001) Sequence START - INFO
13 Jun 2025 at 1:07:21 pm - INFO - Feed Water Pump 2 (01LAC20AP001) Sequence STOP - INFO
13 Jun 2025 at 1:07:21 pm - INFO - Feed Water Pump 3 (01LAC30AP001) Sequence STOP - INFO
13 Jun 2025 at 1:07:21 pm - INFO - Feed Water Pump 4 (01LAC40AP001) Sequence STOP - INFO
13 Jun 2025 at 1:07:21 pm - INFO - HP 9 Feedwater Heater (01LBQ50KC001) ISOLATED - INFO
13 Jun 2025 at 1:07:21 pm - INFO - HP 8 Feedwater Heater (01LBQ40KC001) ISOLATED - INFO
13 Jun 2025 at 1:07:21 pm - INFO - HP 7 Feedwater Heater (01LBQ30KC001) ISOLATED - INFO
13 Jun 2025 at 1:07:21 pm - INFO - HP 6 Feedwater Heater (01LBQ20KC001) ISOLATED - INFO
13 Jun 2025 at 1:07:21 pm - INFO - Deaerator (01LBQ10KC001) ISOLATED - INFO
13 Jun 2025 at 1:07:21 pm - INFO - LP 4 Feedwater Heater (01LBS40KC001) ISOLATED - INFO
13 Jun 2025 at 1:07:21 pm - INFO - LP 3 Feedwater Heater (01LBS30KC001) ISOLATED - INFO
13 Jun 2025 at 1:07:21 pm - INFO - LP 2 Feedwater Heater (01LBS20KC001) ISOLATED - INFO
13 Jun 2025 at 1:07:21 pm - INFO - LP 1 Feedwater Heater (01LBS10KC001) ISOLATED - INFO
13 Jun 2025 at 1:07:22 pm - WARNING - Condenser Vacuum Pump 3 (01MAJ10AN003) START - WARNING
13 Jun 2025 at 1:07:22 pm - ALARM - Condenser Pressure (01MAG10CP901) HIGH - ALARM
13 Jun 2025 at 1:07:24 pm - ALARM - Steam Generator 3 Level (01JEA30CL001) LOW - ALARM
13 Jun 2025 at 1:07:25 pm - INFO - Turbine Auxiliary Lube Oil Pump (01MAV10AP001) ON - INFO
13 Jun 2025 at 1:07:25 pm - INFO - Condensate Extraction Pump (01LCA30AP001) STOP - INFO
13 Jun 2025 at 1:07:26 pm - RESET - Steam Generator 3 Level (01JEA30CL001) LOW - RESET
13 Jun 2025 at 1:07:32 pm - INFO - Turbine Shaft Lube Oil Pump (01MAV20AP001) OFF - INFO
13 Jun 2025 at 1:07:32 pm - ALARM - Feedwater Flow (01LAC50CF001) HIGH - ALARM
13 Jun 2025 at 1:07:32 pm - WARNING - START Additional Feedwater Pump - WARNING
13 Jun 2025 at 1:07:34 pm - INFO - Feed Water Pump 1 (01LAC10AP001) Sequence START COMPLETED - INFO
13 Jun 2025 at 1:07:36 pm - INFO - Feed Water Pump 2 (01LAC20AP001) Sequence STOP COMPLETED - INFO
13 Jun 2025 at 1:07:36 pm - INFO - Feed Water Pump 3 (01LAC30AP001) Sequence STOP COMPLETED - INFO
13 Jun 2025 at 1:07:36 pm - INFO - Feed Water Pump 4 (01LAC40AP001) Sequence STOP COMPLETED - INFO

Figure 46: A full page view of alarms and event is also available

6.1.2 Trainer Window

The image below shows the Trainer Window as displayed when the application is first started. It consists of the following important parts;

Sim RUN This checkbox can be used by the trainer to select the simulator to RUN or STOP/PAUSE. Select run to allow operation from the Simulator window or deselect to pause the simulator window and allow discussion between the trainer and trainee.

Scenarios This tab allows a number of differing pre-sets to be selected to offer different condition to the trainee. Firstly we can select the plant in a cold shutdown (Mode 5) condition with fuel of various ages, such as newly refuelled, 3 month, 6 month, 12 month and 18 month old. As the nuclear fuel ages its reactivity fails and this will change how we operate the plant in respect to boron dosing amounts and rates, etc.

Secondly within the newly refuelled choice we can also select the current reactor and turbine load we would like to start the simulation on. Everything from reactor at 5% load with steam turbine shutdown, up to 100% load conditions.

Faults This tab allows the trainer to cause faults to occur on the simulator window that we then require the trainee to react to. Each fault and its effects is covered in more detail in section 8.

Accelerate Reactor Ramp Up During reactor startup when criticality is achieved, the build up of the chain reaction is very slow. The number of fissions is small, and although the Start Up Rate (instrument 01JSA10CR001) may be indicating a rate of up to 2 decades it will still take a long time for the reactor power output to increase to even 1% power. If this checkbox is unselected it will give a more realistic reactor power increase rate. If however it is selected then the reactor power will increase much more quickly once criticality is achieved which allows the training lesson to flow better.

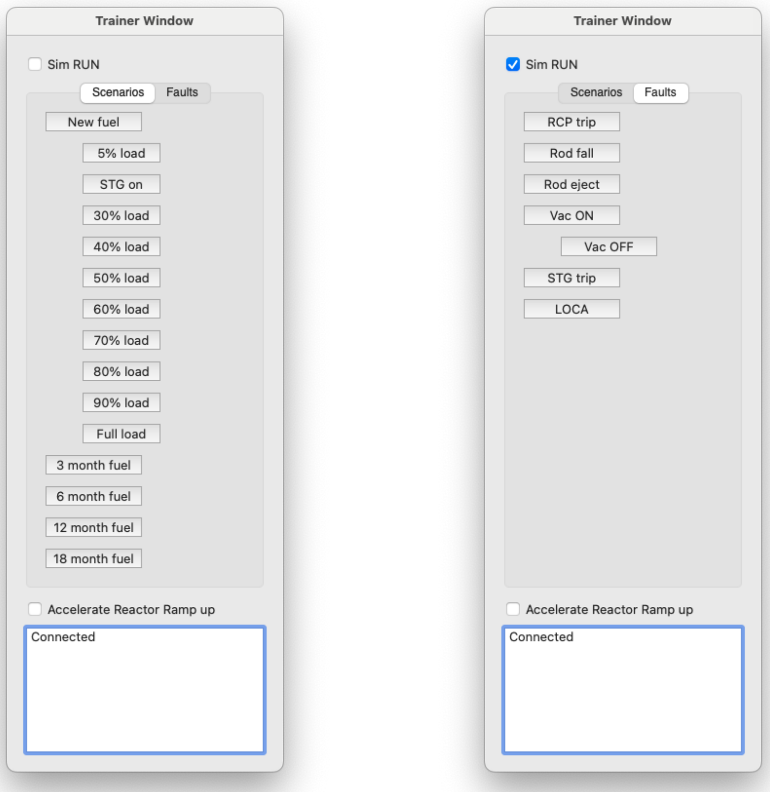


Figure 47: Trainer window showing scenarios on the left and faults on the right

6.2 Getting started

As we discuss above, when the application is first started you are presented with two windows, the Simulator window and the Trainer Window.

As the trainer, you should firstly select the scenario that you will be using from the Trainer Window scenario tab. For this example we will select the button labelled as "30% load". This will load the parameters into the Simulator window with setting of a newly refuelled reactor with Steam Turbine in service and reactor/Turbine load of 30%.

When the training session is ready to start select the "Sim RUN" checkbox at the top of the Trainer Window and the simulation will be running.

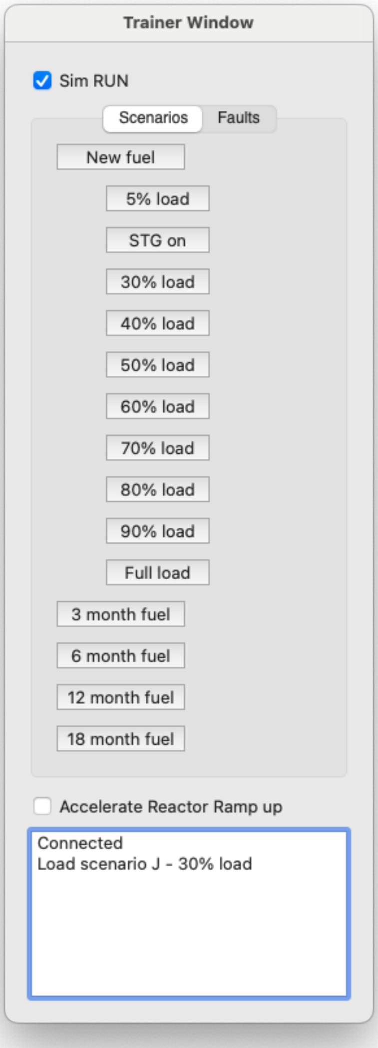


Figure 48: 30% load with newly refuelled reactor scenario selected.

The Trainee can now use the Simulator Window and will find the plant already running at 30% load. Please refer to section 7 to learn how to operate the power plant.

7 Operating the Plant

7.1 Reactor modes

Mode	Condition	Reactivity	Power lvl	Temperature
Mode 5	**Cold shutdown**	**K<0.99**	**0%**	**Tavg<95C**
Mode 4	**Hot shutdown**	**K<0.99**	**0%**	**Tavg>95C and Tavg<176C**
Mode 3	**Hot standby**	**K<0.99**	**0%**	**Tavg>176C**
Mode 2	**Startup**	**K>=0.99**	**<5%**	
Mode 1	**Power operations**	**K>=0.99**	**>5%**	

7.2 Boiling point of Water

I would expect that everyone knows that water boils at 100 deg C at sea level on planet Earth. However if the atmospheric pressure changes, maybe due to climbing a mountain then the boiler point will also change. e.g. atmospheric pressure at the summit of Mt Everest is approximately 253 mbar as compared to sea level average of 1013.2 mbar. At this pressure the boiling point of water is 65 deg C - which is not good if you would like a nice cup of tea.

Conversely if the pressure in a system should increase, then the boiling point of water will also increase. At the reactor normal operating pressure of 155 bar the boiling point is at 344.8 deg C. As the water in the primary circuit as it leaves the reactor core at full load is only at a temperature of 322.1 deg C we can see that it is below the boiling point so will contain no steam and hence no bubbles. This is why this type of reactor is referred to as a PWR (Pressurised Water Reactor) as the high pressure (155 bar) ensures the primary coolant remains in the liquid phase.

An alternative reactor design is the BWR (Boiling Water Reactor) which does allow steam to be generated within the reactor core and therefore does away with the need for steam generators. This reactor type however does have the disadvantage of the steam going to the turbine being radioactive.

7.3 Basic overview of Start Up

If the simulation is started from a Cold Shutdown (Mode 5) condition, the startup should follow the main outline as follows;

- Prepare the auxiliary plant.
  - Cooling water system in service.
- Drain Pressuriser and Steam Generator levels to NWL (Normal Working Levels).
- Prepare the Steam Turbine.
  - Warm up the lubricating oil
  - Start Lube oil and Jacking oil systems
  - Start turbine turning gear. Turbine should be on turning gear for at least 12 hours before turbine run up.
- Prepare the Containment and Emergency Core Cooling systems.
- Ensure adequate shutdown margin of Boron levels within the primary circuit.
- Use Pressuriser heaters to warm up the primary coolant to operating pressure and temperature.
- Prepare condensate and feedwater systems for service.
- Make estimate of criticality and does boron accordingly.
- Ensure all permissives are met to reset reactor SCRAM.

- Reset reactor SCRAM.
- Withdraw protection and control rods to reach criticality.
- Dilute primary circuit boron concentrations to reach 2% load. Monitor Start Up Rate to ensure safe and controlled reactor load increase.
- Start turbine gland steam and pull condenser vacuum.
- Dilute primary circuit boron concentrations to reach 5% load. Monitor Start Up Rate to ensure safe and controlled reactor load increase.
- Dilute primary circuit boron concentrations to reach 20% load. Monitor Load Increase Rate to ensure safe and controlled reactor load increase.
- Start Steam Turbine.
- Synchronise generator to national grid.
- Dilute primary circuit boron concentrations to reach 100% load, whilst placing additional feedwater pumps in service as required.

This is just a brief overview and in a real life situation this would involve closely following a plant startup procedure and the completion of many plant setup check lists before each step is attempted. A more complete startup procedure is provided in the next section for use on this simulator, but even this is but a abbreviated document to what would be used on a real plant.

7.4 Start Up procedure

The following is an operations procedure to take the plant from a Cold Shutdown condition (mode 5) and pass through all the steps required to commence Power Operation (Mode 1) and then achieve plant full load.

The reactor has just completed a refuelling where approximately 33% of the spent fuel rod have been removed for reprocessing and replace with new, therefore most of the the plant equipment is shutdown and will need to be re-started in the correct order to ensure safe operation.

- Reactor SCRAM active and at Mode 5 condition (Cold Shutdown).
- Pressuriser wet stored (water level raised to near top of vessel to prevent corrosion).
- Reactor primary circuit filled with borated water - current concentration is 2450 ppm.
- Refuelling Water Storage Tank (RWST) filled with borated water
- Containment vessel HVAC (Heating, Ventilation and Air Conditioning) system (0KLA10AN001) is running.
- Condensate system filled with demin water and Condenser Hotwell (01MAG10BB001) is at normal working level.
- Feedwater system filled with demin water and Deaerator vessel (01LAA10BB001) is at normal working level.
- All Steam Generators are wet stored.
- Cold Leg accumulator are filled with highly borated water and isolated.
- Electrical system are on line and Emergency Diesel Generators (EDG's) selected to Auto start.

The step by step procedure below should now be followed to start the reactor in a safe manner.

1. START Cooling Water system controller (01PAA10AH001). This will start the following pumps in sequence so as to place the Main Cooling Water, Service Water and Closed Cooling Water systems in service;
   - 01PAC10AP001 - Main Cooling Water pump
   - 01PJA10AP001 - Service Water pump
   - 01KAA10AP001 - Closed Cooling Water pump
2. OPEN valve 01LAC60AA501 to drain Steam Generator 1 (01JEA10BB001) down to Normal Working Level (NWL). Steam Generators have been wet stored so the level must be reduced before Feedwater pump start permissive is obtained. Once level is at 50% (NWL) then valve 01LAV60AA501 will automatically CLOSE. The level of SG1 can be monitored on level gauge 01JEA10CL001.
3. OPEN valve 01LAC70AA501 to drain Steam Generator 2 (01JEA20BB001) down to NWL.
4. OPEN valve 01LAC80AA501 to drain Steam Generator 3 (01JEA30BB001) down to NWL.
5. OPEN valve 01LAC90AA501 to drain Steam Generator 4 (01JEA40BB001) down to NWL.
6. START Chemical and Volume Control system (CVCS) Charging pump (either 01KBD10AP001 or 01KBD20AP001).
7. SELECT CVCS mode to DRAIN. This will reduce the Pressuriser level from its wet stored condition to NWL. Once Pressuriser NWL is achieved then draining will stop.
8. SELECT CEP/FWP system controller (01LCA/LAC10AH001) to AUTO. This will start the sequence for placing these system in service as follows;
   - START Condensate Extraction Pump 1 (01LCA10AP001).
   - Clean up the condensate system by recirculating the condensate water back to the condenser (and through a mixed bed vessel) by OPENING valve 01LCA50AA001.
   - Once Condensate system clean-up completed CLOSE valve 01LCA50AA001.
   - START Auxiliary Feedwater Pump 1 (01LAJ10AP001).

- Clean up the Feedwater system by recirculating the feedwater back to Deaerator storage tank (01LAA10BB001) by OPENING valve 01LAC60AA001.
- Once Feedwater system clean-up completed CLOSE valve 01LCA60AA001.
- Place all remaining Condensate Extraction pumps, Auxiliary Feedwater pumps and Main Feedwater pumps on AUTO, so they will START and STOP as required by reactor load.

9. PREPARE Steam Turbine systems.
   - SELECT Lube Oil Heater (01MAV10AH001) to AUTO. This will increase lube oil temperature up to approx. 45 deg C and then control it to maintain this value.
   - START Auxiliary Lube Oil Pump (01MAV10AP001) when lube oil tank temperature (01MAV10CT001) is > 40 deg C
   - START Turbine turning gear (01MAK10AH001). Turbine rotor will start to rotate and increase upto approx. 30 rpm.
10. Take first ESTIMATE of CRITICALITY.
11. SELECT ECCS (Emergency Core Cooling System) system (01JNB00AH001) to AUTO. This will align pump suction valves to accept feed from RWST tank (valve 01JNK10AA001 OPEN) and isolate suction from reactor containment sump (valve 01KPF10AA001 CLOSED). All Emergency Cooling water pumps (HP and LP) will now automatically start when required.
12. SELECT Containment Spray system (01JMN10AH001) to AUTO.
13. START Residual Heat Removal pump (01JNA10AP001).
14. SELECT Pressuriser Spray valve (01JEF10AH001) controller to AUTO. After a short interval spray water block valve (01JEF10AA001) will open fully and spray water control valve (01JEF10AA151) will open to minimum opening of 5%.
15. SELECT Pressuriser Heater controller (01JEF10AH002) to AUTO. This will cause Pressuriser heaters to go to 100% power and start warming primary circuit coolant from ambient conditions up to operating Pressure and Temperatures.
16. MONITOR primary circuit Pressure and Temperature as these increase. Note - as primary circuit temperature rises the water within this circuit will expand and Pressuriser level will increase.
17. START Reactor Coolant Pump (RCP) 1 (01JEB10AP001) after Reactor pressure (01JKA10CP001) is > 20 bar.
18. STOP Residual Heat Removal pump (01JNA10AP001) as it is no longer required for circulating primary circuit coolant.
19. START RCP 4 (01JEB40AP001) after Reactor pressure (01JKA10CP001) is > 30 bar.
20. START RCP 2 (01JEB20AP001) after Reactor pressure (01JKA10CP001) is > 40 bar.
21. START RCP 3 (01JEB30AP001) after Reactor pressure (01JKA10CP001) is > 50 bar.
22. When reactor primary circuit pressure (01JKA10CP001) is > 142 bar OPEN Safety Injection Isolation valve (01JNG60/70/80/90AA001).
23. REACTOR is now ready to reset SCRAM.
24. Take second ESTIMATE of CRITICALITY.
25. If indicated boron concentration from Criticality Estimate is different than current primary circuit boron concentration (01KTA10CQ001), adjust primary circuit boron concentration by either diluting or borating using CVCS Control panel.
26. WAIT until boron concentration in primary circuit (01KTA10CQ001) has reached required value before proceeding.
27. SELECT Source Range flux meter (01JKA10CR001).
28. RESET SCRAM (01JKA10AH001). This will allow Reactor Protection Rods to be withdrawn.

29. SELECT retract (R) for Reactor Protection Rod 01JDA10CG001.
30. MONITOR Source range flux meter for increasing activity and Neutron trend for any sudden increases. If this trend increases suddenly then stop rod withdrawal and reassess Criticality Estimate.
31. MONITOR Start Up Rate (SUR) gauge (01JSA10CR001) to ensure increase in reactivity rate stays within design limits (SUR High alarm at 2 decades, whilst Reactor SCRAM at 3 decades).
32. WAIT until Reactor Protection Rod 01JDA10CG001 is fully retracted (NOTE - rod position 100% equals fully inserted, whilst 0% equal fully retracted.
33. SELECT retract (R) for Reactor Protection Rod 01JDA10CG002.
34. Again MONITOR Source range flux meter for increasing activity and Neutron trend for any sudden increases.
35. WAIT until Reactor Protection Rod 01JDA10CG002 is fully retracted. Note - Once both Reactor Protection Rods (01JDA10CG001 and 01JDA10CG002) are fully retracted it will be possible to retract any of the 4 Control Rods.
36. CONTINUE to RETRACT Reactor Control Rods 01JDA20CG001, 01JDA20CG002, 01JDA20CG003, 01JDA20CG004. MONITOR Start Up Rate (SUR) gauge (01JSA10CR001) to ensure increase in reactivity rate stays within design limits.
37. MONITOR Source range flux meter (01JKA10CR001) for increasing activity and Neutron trend for any sudden increases. As trend Neutron detection line takes higher and higher vertical steps it may be necessary to change the vertical scale.
38. If Criticality Estimate is accurate then Source range flux meter will go off-scale and Neutron detection trend off scale vertically (i.e. the number of released Neutrons has increased exponentially and the reactor is now Critical (i.e. the chain reaction is self sustaining).
39. SELECT Intermediate range flux meter (01JKA10CR002).
40. CONTINUE retracting Reactor control rods 01JDA20CG001, 01JDA20CG002, 01JDA20CG003, 01JDA20CG004 until desired rod configuration is achieved. Note - At higher reactor loads all Reactor Control Rods must be near to fully retracted. Any deeply inserted rods will distort the core power distribution forcing the lower half of the reactor core to contribute more of the reactor load and the upper half less which can lead to a fuel rod experiencing higher than design temperatures in the lower core. To protect against this Axial Displacement gauge (01JSA10CR003) monitors this power distribution and will initiate an alarm or even Reactor SCRAM if over design limits.
41. Once Reactor Control Rods are at required position it is necessary to dilute the primary circuit boron concentrations to further increase Reactor load.
42. DILUTE primary circuit boron concentrations whilst monitoring Start Up Rate (SUR) gauge (01JSA10CR001) if reactor power $< 5\%$ or Load Increase Rate (LIR) gauge (01JSA10CR002) if reactor power $> 5\%$. LIR will monitor rate and if necessary give High alarm at 3.2 and even Reactor SCRAM at 5.2.
43. START gland steam system (01MAW10AH001) when Reactor power $> 2\%$. This will initiate the following sequence;
    - Gland steam supply isolation valve (01MAW20AA001) will OPEN.
    - Gland steam exhauster fan (01MAW30AN151) will START.
    - Gland steam pressure control valve (01MAW10AA151) will SELECT to AUTO.
    - Gland Steam pressure (01MAW20CP001) will increase to approx. 320 mbar and be controlled at this pressure by the actions of gland steam pressure control valve (01MAW10AA151).
44. SELECT Pull Condenser Vacuum (01MAJ10AH001).
45. When Reactor power $> 5\%$ SELECT Power range flux meter (01JKA10CR003A/B).
46. DILUTE primary circuit boron concentrations until reactor load is $> 20\%$
47. MONITOR Load Increase Rate (LIR) gauge (01JSA10CR002) as Reactor power increases
48. CALIBRATE Power range flux meter (01JKA10CR003A/B) regularly.

49. START turbine Control Oil Pump (01MAX10AP001).

50. SELECT AUTO or MANUAL turbine runup (01MAA10AH001). AUTO mode will run turbine to synchronise speed, start excitation and auto-sync to 500kV grid. Manual mode will run turbine to FSNL (Full Speed No Load) and the operator will then need to START excitation and manually Synchronise the generator to grid.

51. RESET STG Trip (01MAA10AH001). Steam Turbine should now automatically do the following steps;

    Cold start Steam Turbine rotor temperature (01MAB10CT005) is < 150 deg C.

    - Steam Chest Warming valves (01MAA10AA003 and 01MAA10AA501) will OPEN and start warming valve body until approx. 250 deg C.
    - Turbine Rotor Warming valves (01MAA10AA003 and 01MAA10AA004) will OPEN and start warming turbine HP rotor until approx. 250 deg C.
    - Steam Turbine Emergency Stop Valve (01MAA10AA001) will OPEN to 100%.
    - Steam Turbine Steam Admission Control Valve (01MAA10AA002) will open sufficiently to accelerate steam turbine rotor speed upwards.
    - Steam Turbine speed will HOLD at 900 rpm to ensure complete rotor warming.
    - Steam turbine will again accelerate up to synchronise speed.

    Hot start Steam Turbine rotor temperature (01MAB10CT005) is > 150 deg C.

    - Steam Turbine Emergency Stop Valve (01MAA10AA001) will OPEN to 100%.
    - Steam Turbine Steam Admission Control Valve (01MAA10AA002) will open sufficiently to accelerate steam turbine rotor speed upwards to synchronise speed.

    AUTO runup The following steps will occur automatically;

    - Excitation ON.
    - Auto-Sync ON.
    - Generator Circuit Breaker (01MKA10GS001) will CLOSE.

    MANUAL runup Once Steam Turbine speed is at FSNL (Full Speed No Load), the following steps must be undertaken by the Operator;

    - SELECT Excitation ON.
    - SELECT Synchroscope ON
    - USE Generator Transformer OLTC (On Load Tap Changer) to make coarse adjustments to Generator Voltage.
    - USE Excitation INC and DEC buttons to make fine adjustments to Generator Voltage.
    - MATCH Generator output voltage to Bus voltage.
    - USE Turbine Speed Control INC and DEC buttons to adjust turbine speed and hence generator frequency.
    - MATCH Generator output frequency to Bus frequency.
    - WAIT until synchroscope needle is at the 12 o'clock position (indicating Bus and Generator Frequency are in phase) then;
    - CLOSE Generator Circuit Breaker (01MKA10GS001)

52. The Generator is now connected to the electrical grid and the electrical power output will show on gauge 01MAB50CE001.

53. Steam Turbine Steam Admission Control Valve (01MAA10AA002) will continue to OPEN to increase Steam Turbine Load. Simultaneously Turbine Bypass Valves (01LBA60AA251 and 01LBA60AA252) will CLOSE.

54. Steam Turbine load will increase to the point where all steam generated by the Reactor is utilised. To Further increase Steam Turbine load Reactor power must be increased.

55. DILUTE primary circuit boron concentrations until reactor load is = 100%

56. at 50% Reactor load CALIBRATE Power range flux (01JKA10CR003A/B).

57. at 90% Reactor load CALIBRATE Power range flux (01JKA10CR003A/B).

58. at 95% Reactor load CALIBRATE Power range flux (01JKA10CR003A/B).

59. at 100% Reactor load CALIBRATE Power range flux (01JKA10CR003A/B).

Full Load Achieved

7.5 Shut Down procedure

The following is an operations procedure to take the plant from a Power Operation (Mode 1) at or near Reactor 100% power down to Hot Standby (Mode 3).

- Reactor critical at Mode 1 (Power Operations).
- Steam Turbine is IN SERVICE.

The step by step procedure below should now be followed to start the reactor in a safe manner.

1. BORATE primary circuit boron concentrations until reactor load is = 50%
2. BORATE primary circuit boron concentrations until reactor load is = 30%
3. BORATE primary circuit boron concentrations until reactor load is = 22 to 25%
4. STOP Steam Turbine (01MAA10AH002).
   - Steam Turbine Steam Admission Control Valve (01MAA10AA002) will start to CLOSE to reduce Steam Turbine Load. Simultaneously Turbine Bypass Valves (01LBA60AA251 and 01LBA60AA252) will OPEN to ensure steam generated by Reactor has a flow path.
   - Once Steam Turbine Steam Admission Control Valve (01MAA10AA002) is CLOSED, Steam Turbine will TRIP.
   - Steam Turbine Emergency Stop Valve (01MAA10AA001) will CLOSE.
   - Generator Circuit Breaker (01MKA10GS001) will OPEN.
   - Generator Excitation OFF.
   - Steam Turbine speed will reduce to 30 rpm.
   - Steam Turbine Turning Gear will START and maintain turbine at 30 rpm.
5. INSERT Reactor control rods 01JDA20CG001, 01JDA20CG002, 01JDA20CG003, 01JDA20CG004 step by step (pulse) until Reactor power < 20%
6. PRESS Reactor SCRAM button.
7. CHECK all Protection and Control Rods are at 100% position (i.e. fully inserted).
8. MONITOR Bypass valves (01LBA60AA251/252) slowly closing to dump residual steam from Steam Generator.
9. MONITOR Steam Generator outlet PORV's (01LBA10/20/30/40AA501) OPEN.
10. WAIT until Bypass valves (01LBA60AA251/252) are FULLY CLOSED.
11. BREAK Condenser Vacuum (01MAJ10AH001).
12. WAIT until Condenser Pressure (01MAG10CP901) is > 900 mbar.
13. STOP Gland Steam System (01MAW10AH001). This will initiate the following sequence;
    - Gland steam pressure control valve (01MAW10AA151) will SELECT to MANUAL and CLOSE.
    - Gland Steam pressure (01MAW20CP001) will decrease to ZERO.
    - Gland steam supply isolation valve (01MAW20AA001) will CLOSE.
    - Gland steam exhauster fan (01MAW30AN151) will STOP.

Hot Standby Achieved

Reactor is now at Mode 3 condition - Hot Standby. If the plan is to restart the plant within the next 24 hours we can maintain the plant at this condition.

However if the plan is for a longer shutdown or even a maintenance outage or reactor refuelling we should continue with the Reactor cool down so as to reach Mode 5 condition - Cold Shutdown.

7.6 Reactor Cool Down procedure

This procedure provides a step by step instruction for ACME NucPower Unit 1 Reactor cool down from Mode 3 condition (Hot Standby) until Mode 5 condition (Cold Shutdown) has been achieved. It shall be used as a reference each time this plant is started and a record kept of plant start up progress and any issues, events or error for future improvements.

The reactor has 5 operating modes as described below;

Mode 5 Cold shutdown - reactor is sub-critical with 0% power output and primary coolant average temperature < 95 degC.

Mode 4 Hot shutdown - reactor is sub-critical with 0% power output and primary coolant average temperature is > 95 degC and < 176 degC.

Mode 3 Hot standby - reactor is sub-critical with 0% power output and primary coolant average temperature > 176 degC.

Mode 2 Startup - reactor is critical with power output < 5%

Mode 1 Power operations - reactor is critical with power output > 5%

1. SELECT Pressuriser heater controller (01JEF10AH002) to OFF.
2. Monitor primary circuit Pressure (01JKA10CP001) and Temperature (01JEC10/20/30/40CT001) as it slowly decreases.
3. STOP Reactor Coolant Pump (RCP) 3 (01JEB30AP001).
4. CLOSE SI isolation valves 01JNG60/70/80/90AA001 when primary circuit pressure (01JKA10CP001) is <140 but >125 bar.
5. STOP Reactor Coolant Pump (RCP) 4 (01JEB40AP001) when primary circuit pressure (01JKA10CP001) is < 100 bar.
6. STOP Reactor Coolant Pump (RCP) 2 (01JEB20AP001) when primary circuit pressure (01JKA10CP001) is < 60 bar.
7. START Residual Heat Removal pump (01JNA10AP001) when primary circuit pressure (01JKA10CP001) is < 30 bar.
8. STOP Reactor Coolant Pump (RCP) 1 (01JEB10AP001).
9. SELECT CVCS mode to FILL. This will increase the Pressuriser level to its Wet Storage level.
10. STOP Residual Heat Removal pump (01JNA10AP001) when primary circuit pressure (01JKA10CP001) is < 1 bar.
11. When Turbine Rotor temperature < 100 deg C.
    - STOP Turbine turning gear (01MAK10AH001). Turbine rotor speed will decrease to ZERO rpm.
    - STOP Auxiliary Lube Oil Pump (01MAV10AP001) when Turbine rotor is at standstill.
    - SELECT Lube Oil Heater (01MAV10AH001) to OFF.

Cold Shutdown Achieved

7.7 Diluting or Borating

To provide control of the reactor power output we use the Chemical and Volume Control System (CVCS) to change the amount of the element Boron within the primary circuit water.

Boron is a neutron absorber, so by changing its concentration we can control the reactor reactivity.

As stated earlier in this document we use the terms Diluting and Borating to indicate reducing or increasing the boron concentration.

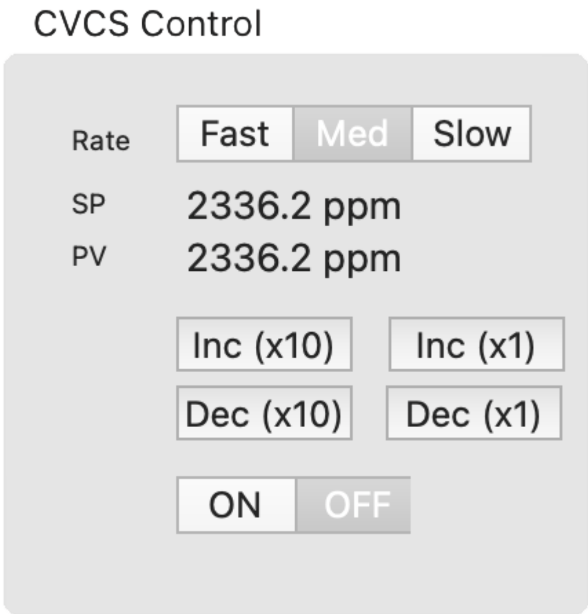


Figure 49: Operating panel for dilluting/borating primary circuit

Referencing the CVCS control panel shown above we can see the PV (Process Value) which is the actual boron concentration in the primary circuit at this moment.

Above this value is the SP (Set Point) which we can adjust using the "INC" and "DEC" buttons. For small steps we use the ×1 buttons for bigger steps the ×10 buttons.

We can also adjust the rate of change of boron concentration we require, by selecting Fast, Medium or Slow at the top of the control panel. Beware the fast rate can change reactor power rather quickly so be careful you do not exceed the LIR (Load Increase Rate) maximum.

Once we are happen with the new Set Point we can select the CVCS to ON and depending on the setpoint entered the system will start diluting or borating.

If we determine that the dosing rate is changing the boron concentrations too quickly we can always select CVCS to OFF.

7.8 Synchronising (manually)

Synchronising is the process of matching two a.c. supplies prior to closing a circuit breaker, paralleling the two supplies. The turbine/alternator conditions are termed "incoming/Generator" and the system conditions called "running/grid".

The parameters to be matched are, voltage, frequency (speed) and phase angle.

When the turbine/alternator is up to speed, the alternator field is excited and the voltage adjusted to match "system" voltage.

A synchroscope indicates the difference in speed and phase angle, between the incoming and running supplies. If the incoming speed is faster than the running speed, the pointer on the synchroscope will rotate in a clockwise (fast) direction. If the speed is lower than the running speed, it will rotate anticlockwise (slow). When the pointer is stationary the incoming and running speeds are identical. The two supplies are in phase when the pointer is at 12 o'clock. It is preferable, at the point of closing the circuit breaker, that the incoming speed is slightly faster than the running speed, i.e. indicated by a clockwise rotation on the synchroscope. The pointer should also be at the 12 o'clock position, when the circuit breaker is closed. The slightly faster speed ensures that there will, immediately be a small MW output from the alternator. Matching the phase angle causes less disturbance to the system. Figure 50 shows a synchroscope faceplate.

Figure 50: Synchroscope faceplate

7.8.1 Effects of Faulty Synchronising

If timing, or voltage adjustment is markedly in error when a generator is connected to the system there will be a sudden flow of overcurrent which may damage the generator. The severity of the overcurrent surge will depend on the phase or voltage error, and the impedance of the generator-to-system loop. This loop includes the transient reactance of the generator itself, the reactance of its transformer (if present) and the internal impedance of the busbars (which is usually low). A "bad shot" at synchronising is likely to have similar effects on a generator to a three phase fault on the output side of its transformer. If the generator is paralleled when there is phase opposition the voltage available to produce fault current could approach twice normal voltage and so correspondingly increase current.

As with overcurrent from any other cause, the undesirable effects are those due to conductor heating and electo-magnetic forces.

In most cases of bad synchronising the periods during which the initial heavy current flows is fairly short and so the value of I^2R is not high and does not produce unacceptable heating in the conductors.

There is a very brief period after the CB is closed when a high transient current may flow. It is the electromagnetic forces produced by these sudden high current particularly in the unsupported parts of the conductors comprising the end turns of the generator windings which are likely to cause mechanical shock and distortion. This may cause damage to insulation particularly near the position where the conductors emerge from the stator slots.

7.8.2 Synchronising Procedure

Turbine runup when selected to Manual on the Turbine Sequence page, should complete with the Steam Turbine rotating at approx. 1495 rpm. As this plant is equipped with a 4-pole generator and connects to a 50Hz grid the turbine speed required to synchronise is 1500 rpm. So we are almost there.

Once this point has been reached, follow the procedure below for synchronising the generator to the grid;

1. Go to Electrical/Generator Synchronising screen.
2. SELECT excitation ON.
3. ADJUST Generator Transformer OLTC (On Load Tap Changer) to match Bus and Generator voltages. Tap changer provides a coarse adjustment only, so it may not be possible to get an exact match.
4. USE Excitation INC (Increase) or DEC (Decrease) button to further match Bus and Generator voltage. These button provide a finer adjustment so you should be able to match the volatge very closely.
5. SELECT Synchroscope ON.
6. USE Turbine Speed SP (Set Point) INC and DEC buttons to match Bus and Generator frequency (Hz).
   - If the synchroscope needle is rotating anti-clockwise then the generator is running slower than the grid frequency. Need to increase turbine speed set point.
   - If the synchroscope needle is rotating clockwise then the generator is running faster than the grid frequency.
   - Our aim is to have the needle rotating slowly in the clockwise direction.
7. Once the synchroscope needle reaches the 12 o'clock position - CLOSE generator Circuit Breaker.
8. Turbine Generator is now synchronised to the electrical grid and further increases of steam flow will not increase the turbine speed, but instead will increase the power output of the generator.
9. Synchronising COMPLETED.

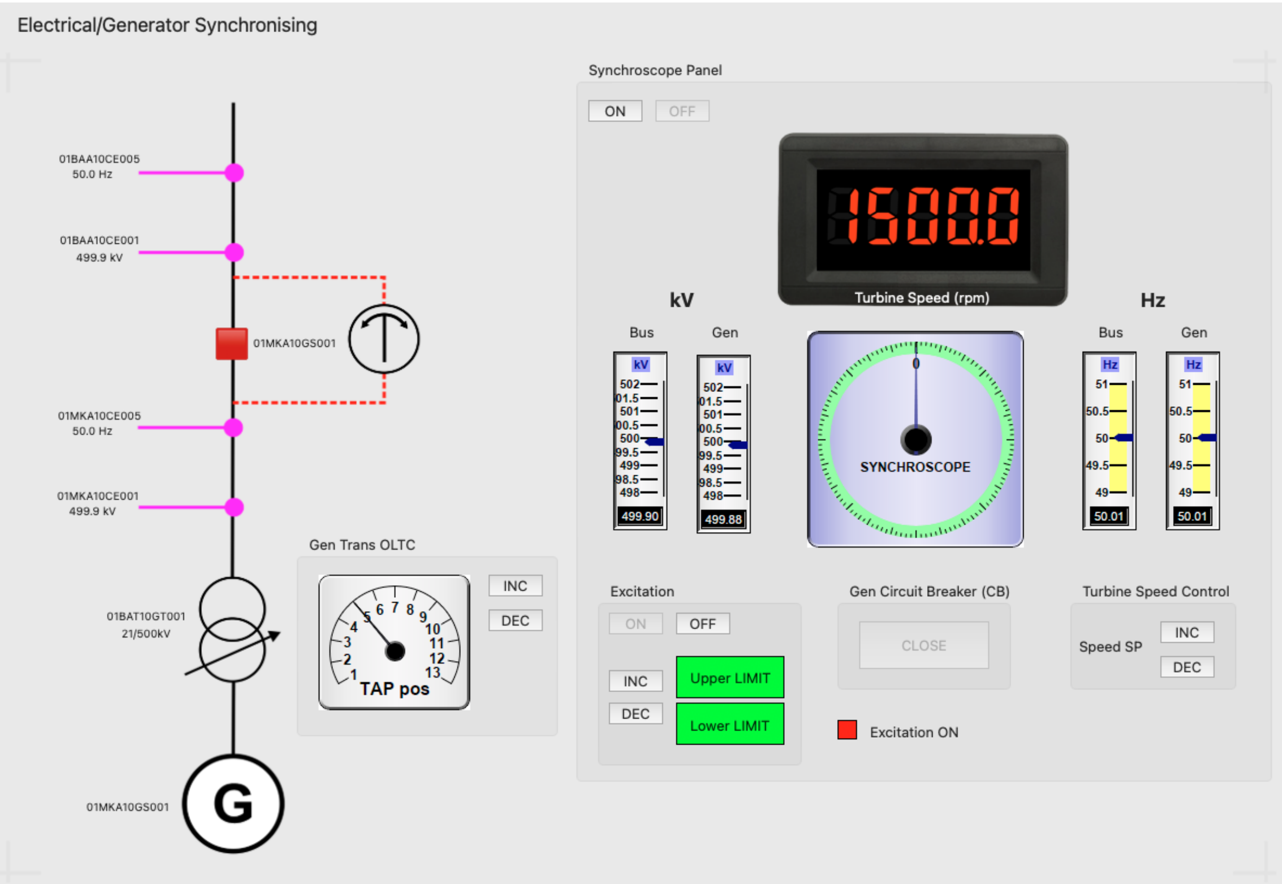


Figure 51: Electrical/Generator Synchronising page screenshot

7.8.3 Why does the turbine rotate at 1500 rpm

As stated above, our Generator has 4-poles (2 North and 2 South) and we will be connecting to a 50 Hz grid.

The formula relating frequency to speed is as follows;

$$\mathrm{f} = \frac{(\mathrm{N} \times \mathrm{P})}{120}$$

Where;

f (Frequency) - This is the number of cycles per second, measured in Hertz (Hz).

N (Turbine Speed RPM) - This is the rotational speed of the turbine in revolutions per minute.

P (Number of Poles) - This refers to the number of magnetic poles in the generator.

Rearranging for N;

$$\mathrm{N} = \frac{(\mathrm{f} \times 120)}{\mathrm{P}}$$

$$\mathrm{N} = \frac{50 \times 120}{4}$$

$$\mathrm{N} = 1500\mathrm{rpm}$$

7.8.4 Video Tutorial

A video demonstrating synchronising using this simulator can be found on my YouTube page, at; `https://www.youtube.com/@RichardSmith-zc9zi`. - Video "NucSIM 2025 part 5 STG start"

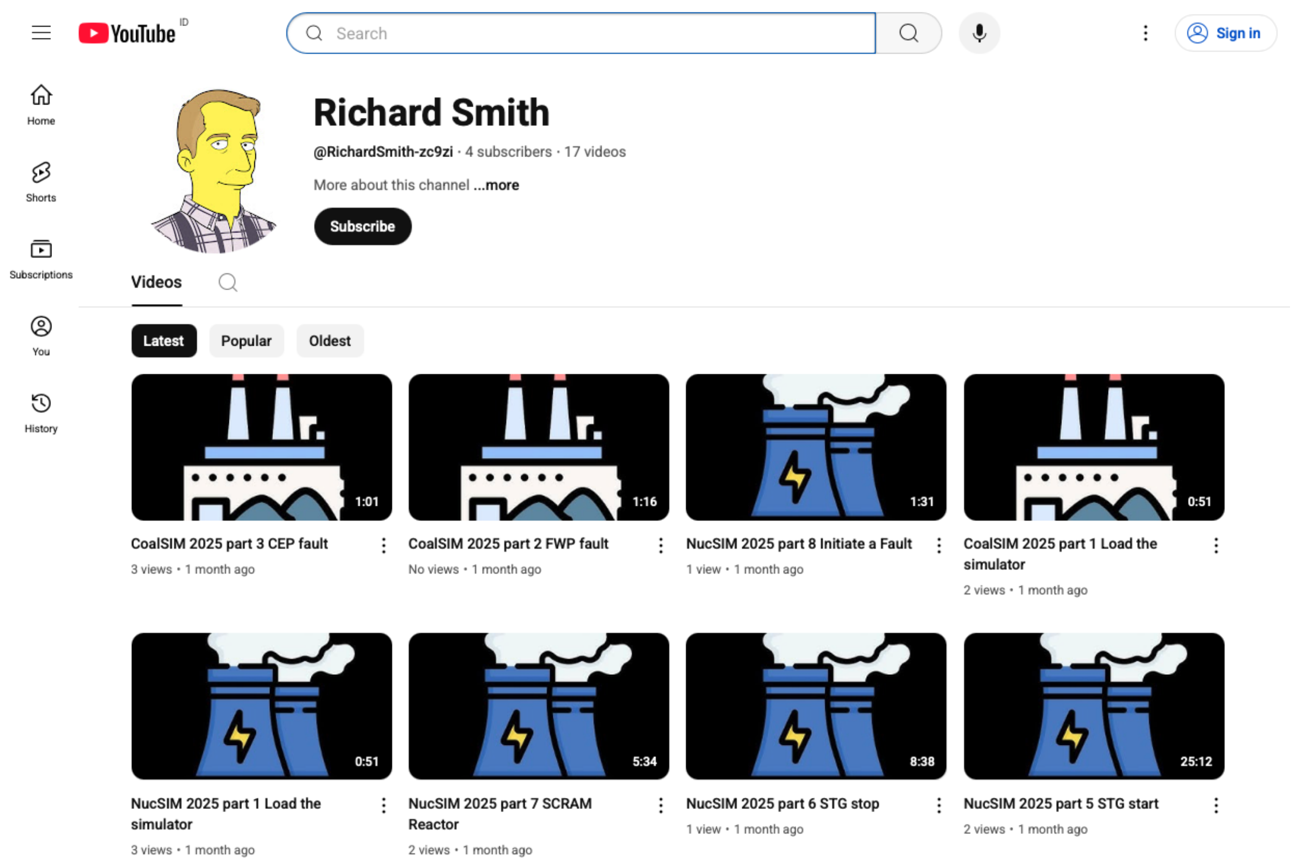


Figure 52: My YouTube page with some tutorials

8 Faults

Some of the possible faults that can occur at a nuclear power plant are listed below.

8.1 Electrical Blackout

If the electrical grid that the power plant is connected to suffers a blackout then all incoming electrical power to the plant will be lost. Some items such as the plant control system will continue to operate as they are provided with an uninterruptibility power supply with battery backup.

All system will fail into there failsafe position. The reactor will SCRAM, the steam turbine will trip. Some systems such as the turbine lube oil will be provided with an emergency DC lube oil pump (Direct current - from batteries) and these will keep oil flowing for a limited time as the turbine rotor runs down in speed.

As soon as power is lost a signal will be actuated to start the EDG (Emergency Diesel Generators). These will take 30 seconds or so to fire up, reach speed, synchronise and start delivering power. Once this power is available the AC pumps can ce restarted in sequence. At a nuclear power plant the EDG's can be rather large and provide power to many items of plant, however they are not large enough to start a RCP (Reactor Coolant Pump) so it is not possible to restart the reactor without an external power supply.

This fault scenario is rather complicated to implement in a simulation (possible, but difficult) and I have not attempted to include it in this simulator.

8.2 LB LOCA (Large break Loss Of Coolant Accident)

A Large Break Loss of Coolant Accident refers to the instance where either a cold leg or hot leg pipe from the reactor to the coolant pump and steam generator suffers a full diameter fracture (The pipe breaks clean off). This has never occurred at any nuclear plant but is worse case possible so must be planned for.[6]

This fault can be initiated from the Trainer Window (press button marked "LOCA") and hang on. The reactor will depressurise quickly resulting in a SCRAM, cold leg accumulator actuation, Safety Injection actuation and isolation of containment vessel and actuation of containment sprays to reduce pressure.

The operator can monitor the safety system shutting down the plant, but the result will be years of cleanup work and a badly damaged reactor that will never run again.

8.3 Small LOCA (Loss Of Coolant Accident)

A Small Loss of Coolant Accident is one in which a small pipe attached to the primary coolant pipework or a fitting on the pressuriser fractures resulting in a slower depressurisation of the reactor vessel. Depending on the size of the leak this can be a very slow depressurisation. Three Mile Island Unit 2 accident back in 1979 can be classified as a small LOCA.[7]

This fault is not specifically modelled in this simulator currently.

8.4 Reactor Coolant Pump trips

Four RCP (Reactor Coolant Pumps) must be in operation to enable the reactor to reach 100% load. The trip of a single RCP pump will result in a reactor runback to 75% load. Minimum number of RCP pumps running is 3. If less than 3 pumps running then a reactor SCRAM will occur.

This fault can be initiated from the Trainer Window (press button marked "RCP trip"). Press once for runback (if plant load greater than 75%) and press again for reactor SCRAM.

Note: If a reactor Runback occurs then control rods will be prevented from being retracted until the Runback is reset. In this case check the affected RCP is good to operate. Start the RCP and then press the "Reset RUNBACK" button on the Reactor Rod Control screen. Control rods can now be retracted to increase load.

[6] Although this could be considered a LOCA near miss - `https://www.nrc.gov/docs/ML0824/ML082490129.pdf`

[7] Nuclear Regulatory Commission report - `https://www.nrc.gov/docs/ML0825/ML082560250.pdf`

Figure 53: Reactor Runback active indication and RESET button

8.5 Control Rod ejected

It is possible for a control rod to be ejected from the reactor and this will cause a sudden increase in reactor power depending on the pre-ejection position of the rod.

This fault can be initiated from the Trainer Window (press button marked ”Rod eject”).

8.6 Control Rod fall

It is possible for a single control rod to fall into the reactor and thus will cause a sudden drop in reactor power.

This fault can be initiated from the Trainer Window (press button marked ”Rod fall”).

8.7 SLB (Steam Line Break)

The steam pipe from the Steam Generator outlet to the Steam Turbine inlet can also suffer a pipe fracture. This can occur both inside or outside the containment vessel as this pipe passes through the containment vessel wall (Steam generator inside containment vessel, but Steam Turbine outside).

A break of the main steam line would result in the affected Steam Generator level decreasing quickly (flash boiling) and a trip of the Steam Turbine and reactor SCRAM.

This fault is not specifically modelled in this simulator currently.

8.8 Steam Turbine trips

If a steam turbine trip occurs the turbine stop and control valve will shut and the generator circuit breaker will open. The steam previously flowing through the turbine will now be dumped to the condenser through the Turbine bypass valves. However these valves are only designed for 50% of full load steam flow, so if the reactor load is greater than 50% a reactor runback will occur. See trend below showing steam turbine power (Blue line) and reactor power output (Red line).

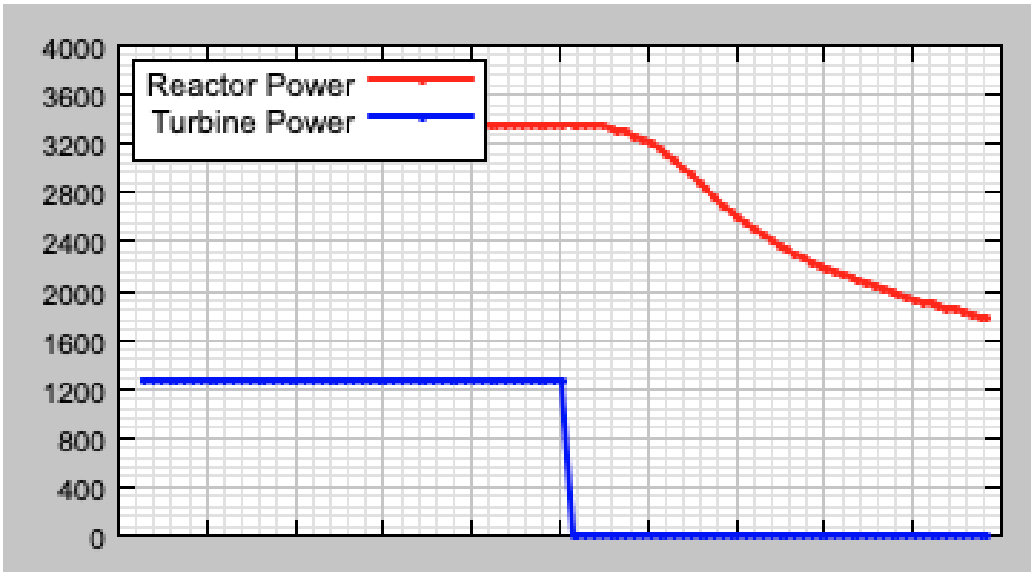


Figure 54: Trend showing Turbine trip and Reactor Runback

Reactor will runback and eventually stablise, however the operator should be mindful of feedwater pump capacity. Once the steam turbine trips, bled steam is lost to drive the steam driven feedwater pumps (FWPs 2, 3, 4) however the electrically driven pump (FWP 1) will automatically start. This pump is only rated for 40% of maximum reactor flow so further operator reduction of reactor power may be necessary.

This fault can be initiated from the Trainer Window (press button marked "STG trip").

A List of equipment

Reactor Primary Circuit screen;

01JEB10AP001 Reater Coolant Pump 1

01JEB20AP001 Reater Coolant Pump 2

01JEB30AP001 Reater Coolant Pump 3

01JEB40AP001 Reater Coolant Pump 4

01KAW10AA001 Seal water supply valve for RCP 1

01KAW20AA001 Seal water supply valve for RCP 2

01KAW30AA001 Seal water supply valve for RCP 3

01KAW40AA001 Seal water supply valve for RCP 4

01JEA10BB001 Steam Generator 1

01JEA20BB001 Steam Generator 2

01JEA30BB001 Steam Generator 3

01JEA40BB001 Steam Generator 4

01JAA00BB001 Reactor vessel

01JEF10BB001 Pressuriser vessel

01JEF10CL001 Pressuriser vessel level

01JEF10CP001 Pressuriser pressure

01JEF10CT001 Pressuriser temperature

01JEC10CT001 Hot leg 1 temperature

01JEC20CT001 Hot leg 2 temperature

01JEC30CT001 Hot leg 3 temperature

01JEC40CT001 Hot leg 4 temperature

01JEC60CT001 Cold leg 1 temperature

01JEC70CT001 Cold leg 2 temperature

01JEC80CT001 Cold leg 3 temperature

01JEC90CT001 Cold leg 4 temperature

01JEC60CF001 Circuit 1 flow

01JEC70CF001 Circuit 2 flow

01JEC80CF001 Circuit 3 flow

01JEC90CF001 Circuit 4 flow

01KTA10CQ001 Boron concentration

01JKA10CP001 Reactor pressure

Reactor screen;

01JDA10CG001 Protection Rod 1 position

01JDA10CG001 Protection Rod 2 position

01JDA20CG001 Control Rod 1 position

01JDA20CG002 Control Rod 2 position

01JDA20CG003 Control Rod 3 position

01JDA20CG004 Control Rod 4 position

01KTA10CQ001 Boron concentration

01JKA10CP001 Reactor pressure

01JKU20CT901 Fuel element Temperature

01JKA10CR001 flux meter 1

01JKA10CR002 flux meter 2

01JKA10CR003A flux meter 3

01JKA10CR003B flux meter 3 N16

01JSA10CR001 SUR gauge

01JSA10CR002 LIR gauge

01JSA10CR003 Axial Displacement gauge

01JYK10CR001 Radiation in Coolant

01JKA10AH001 Reset SCRAM button

01JKA10AH002 Reset Reactor RUNBACK button

Chemical and Volume Control System (CVCS) screen;

01KAW10AA001 Seal water supply valve for RCP 1

01KAW20AA001 Seal water supply valve for RCP 2

01KAW30AA001 Seal water supply valve for RCP 3

01KAW40AA001 Seal water supply valve for RCP 4

01KBA10AA261 dump control valve

01KBC10AA251 feed in control valve

01KTA10CQ001 Boron concentration

01KBD10AP001 Charging pump 1

01KBD20AP001 Charging pump 2

01KBC40AP010 Pure water transfer pump

01KBC40AP020 Boric Acid transfer pump

01KBC10BB001 volume control tank

Residual Heat Removal (RHR) screen;

01JAA00BB001 Reactor vessel

01JKA10CP001 Reactor pressure

01JNA10AC001 RHR Heat Exchanger

01JNA10AP001 RHR pump

01JNA10AA001 RHR pump suction valve

01JNA10AA006 RHR pump discharge valve

Pressuriser screen;

01JEF10CL001 Pressuriser vessel level

01JEF10CP001 Pressuriser pressure

01JEF10CT001 Pressuriser temperature

01JEF10AA501 Pressuriser PORV 1

01JEF10AA502 Pressuriser PORV 2

01JEG00BB001 Pressuriser Relief Tank

01JEG10AA501 Pressuriser Relief Tank Safety Valve 1

01JEG10AA502 Pressuriser Relief Tank Safety Valve 2

01JEF10AA001 Spray water isolation valve

01JEF10AA151 Spray water Control valve

01JEF10AH001 Spray Water Controller

01JEF10AH002 Heater Power Controller

Emergency Core Cooling System (ECCS) screen;

01UJA10BB001 Reactor containment sump

01UJA10CL001 Reactor containment sump level

01JNK10BB001 Refuelling Water Storage Tank

01JNK10CL001 Refuelling Water Storage Tank level

01JNB10AP001 Emergency Cooling LP Pump 1

01JNB10AP002 Emergency Cooling LP Pump 2

01JNB30AP001 Emergency Cooling HP Pump 1

01JNB30AP002 Emergency Cooling HP Pump 2

01JNB30AP003 Emergency Cooling HP Pump 3

01JNB30AP004 Emergency Cooling HP Pump 4

01KPF10AA001 Containment Sump Isolation valve to Emergency Core Cooling Pumps

01JNK10AA001 Refuelling Water Storage Tank Isolation valve to Emergency Core Cooling Pumps

01JKA10CP001 Reactor pressure

01JAA00BB001 Reactor Vessel

01JNG60AA001 Cold Leg Accumulator 1 Isolation Valve

01JNG70AA001 Cold Leg Accumulator 2 Isolation Valve

01JNG80AA001 Cold Leg Accumulator 3 Isolation Valve

01JNG90AA001 Cold Leg Accumulator 4 Isolation Valve

01JNG60AA002 Cold Leg Accumulator 1 NRV

01JNG70AA002 Cold Leg Accumulator 2 NRV

01JNG80AA002 Cold Leg Accumulator 3 NRV

01JNG90AA002 Cold Leg Accumulator 4 NRV

01JMN10AP001 Containment Spray Pump 1

01JMN20AP001 Containment Spray Pump 2

Containment screen;

01JMN10AP001 Containment Spray Pump 1

01JMN20AP001 Containment Spray Pump 2

01KPF10AA001 Containment Sump Isolation valve to Emergency Cooling Water Pumps

01JNK10AA001 Refuelling Water Storage Tank Isolation valve to Emergency Cooling Water Pumps

01UJA10BB001 Reactor containment sump

01UJA10CL001 Reactor containment sump level

01JNK10BB001 Refuelling Water Storage Tank

01JNK10CL001 Refuelling Water Storage Tank level

01JEA10BB001 SG1

01JEA20BB001 SG1

01JEA30BB001 SG1

01JEA40BB001 SG1

01JAA00BB001 Reactor vessel

01UJA10CP001 Containment pressure

01KLA10AA001 Ventilation inlet damper

01KLA10AA007 Ventilation outlet damper

01KLA10AN001 Ventilation fan

Steam Generator Overview screen;

01JEA10CL001 SG1 Level

01LBA10CP001 SG1 outlet steam pressure

01BLA10CT001 SG1 outlet steam temperature

01LBA10CF001 SG1 outlet steam flow

01LBA10AA501 SG1 outlet PORV

01JEA20CL001 SG2 Level

01LBA20CP001 SG2 outlet steam pressure

01BLA20CT001 SG2 outlet steam temperature

01LBA20CF001 SG2 outlet steam flow

01LBA20AA501 SG2 outlet PORV

01JEA30CL001 SG3 Level

01LBA30CP001 SG3 outlet steam pressure

01BLA30CT001 SG3 outlet steam temperature

01LBA30CF001 SG3 outlet steam flow

01LBA30AA501 SG3 outlet PORV

01JEA40CL001 SG4 Level

01LBA40CP001 SG4 outlet steam pressure

01BLA40CT001 SG4 outlet steam temperature

01LBA40CF001 SG4 outlet steam flow

01LBA40AA501 SG4 outlet PORV

01MAA10AA001 Turbine Emergency Stop Valve

01MAA10AA002 Turbine Control Valve

01LBA60AA251 Bypass Valve 1

01LBA60AA252 Bypass Valve 2

01MAW10AA001 Gland Steam Supply Valve

01JEA10CL001 Steam generator 1 level

01JEA20CL001 Steam generator 2 level

01JEA30CL001 Steam generator 3 level

01JEA40CL001 Steam generator 4 level

Steam Generator 1 screen;

01JEF10CL001 Pressuriser Level

01JNG60AA002 Cold Leg Accumulator 1 NRV

01JEA10CL001 SG1 Level

01JEC10CT001 Hot leg 1 temperature

01JEC60CT001 Cold leg 1 temperature

01JEC60CF001 Circuit 1 flow

01LBA10CP001 SG1 outlet steam pressure

01BLA10CT001 SG1 outlet steam temperature

01LBA10CF001 SG1 outlet steam flow

01LBA10AA501 SG1 Outlet PORV

01JEB10AP001 Reactor Coolant Pump 1

01LAC60AA501 SG 1 drain valve

01JEA10CL001 Steam generator 1 level

01JEA20CL001 Steam generator 2 level

01JEA30CL001 Steam generator 3 level

01JEA40CL001 Steam generator 4 level

Steam Generator 2 screen;

01JNG70AA002 Cold Leg Accumulator 2 NRV

01JEA20CL001 SG2 Level

01JEC20CT001 Hot leg 2 temperature

01JEC70CT001 Cold leg 2 temperature

01JEC70CF001 Circuit 2 flow

01LBA20CP001 SG2 outlet steam pressure

01BLA20CT001 SG2 outlet steam temperature

01LBA20CF001 SG2 outlet steam flow

01LBA20AA501 SG2 Outlet PORV

01JEB20AP001 Reactor Coolant Pump 2

01LAC70AA501 SG 2 drain valve

01JEA10CL001 Steam generator 1 level

01JEA20CL001 Steam generator 2 level

01JEA30CL001 Steam generator 3 level

01JEA40CL001 Steam generator 4 level

Steam Generator 3 screen;

01JNG80AA002 Cold Leg Accumulator 3 NRV

01JEA30CL001 SG3 Level

01JEC30CT001 Hot leg 3 temperature

01JEC80CT001 Cold leg 3 temperature

01JEC80CF001 Circuit 3 flow

01LBA30CP001 SG3 outlet steam pressure

01BLA30CT001 SG3 outlet steam temperature

01LBA30CF001 SG3 outlet steam flow

01LBA30AA501 SG3 Outlet PORV

01JEB30AP001 Reactor Coolant Pump 3

01LAC80AA501 SG 3 drain valve

01JEA10CL001 Steam generator 1 level

01JEA20CL001 Steam generator 2 level

01JEA30CL001 Steam generator 3 level

01JEA40CL001 Steam generator 4 level

Steam Generator 4 screen;

01JNG90AA002 Cold Leg Accumulator 4 NRV

01JEA40CL001 SG4 Level

01JEC40CT001 Hot leg 4 temperature

01JEC90CT001 Cold leg 4 temperature

01JEC90CF001 Circuit 4 flow

01LBA40CP001 SG4 outlet steam pressure

01BLA40CT001 SG4 outlet steam temperature

01LBA40CF001 SG4 outlet steam flow

01LBA40AA501 SG4 Outlet PORV

01JEB40AP001 Reactor Coolant Pump 4

01LAC90AA501 SG 4 drain valve

01JEA10CL001 Steam generator 1 level

01JEA20CL001 Steam generator 2 level

01JEA30CL001 Steam generator 3 level

01JEA40CL001 Steam generator 4 level

Criticality Estimation screen;

Fuel Age Age in days since last reactor refuelling.

CTRL Rod 1 pos Required position of control rod 1 at criticality.

CTRL Rod 2 pos Required position of control rod 3 at criticality.

CTRL Rod 3 pos Required position of control rod 3 at criticality.

CTRL Rod 4 pos Required position of control rod 4 at criticality.

Time since shutdown Time in hours since reactor SCRAM. Required to take Xenon concentration into account.

Boron concentration required Digital display of estimated boron concentration to achieve criticality with the indicated fuel age, Time since shutdown and expected rod position.

RCP pump screen;

01JEB10AP001 Reater Coolant Pump 1

01JEB20AP001 Reater Coolant Pump 2

01JEB30AP001 Reater Coolant Pump 3

01JEB40AP001 Reater Coolant Pump 4

01KAW10AA001 Seal water supply valve for RCP 1

01KAW20AA001 Seal water supply valve for RCP 2

01KAW30AA001 Seal water supply valve for RCP 3

01KAW40AA001 Seal water supply valve for RCP 4

01JEC60CF001 Circuit 1 flow

01JEC70CF001 Circuit 2 flow

01JEC80CF001 Circuit 3 flow

01JEC90CF001 Circuit 4 flow

01JEB10CS001 RCP 1 speed

01JEB20CS001 RCP 2 speed

01JEB30CS001 RCP 3 speed

01JEB40CS001 RCP 4 speed

Steam Turbine screen;

01MAB50CS901 Turbine speed

01MAG10CP901 Condenser pressure

01MAB50CE001 Generator load

01MKA10CE001 Generator Hz

01MKA10GS001 Generator Circuit Breaker

01PAC10AP001 Cooling Water Circulation pump

01MAG10CP901 Condenser pressure

01LCA10AP001 Condensate Extraction Pump 1

01LCA20AP001 Condensate Extraction Pump 2

01LCA30AP001 Condensate Extraction Pump 3

01LBA60CT001 Main steam temperature

01MAA10AA001 Turbine Emergency Stop Valve

01MAA10AA002 Turbine Control Valve

01LBA60AA251 Bypass Valve 1

01LBA60AA252 Bypass Valve 2

01MAW10CP001 Gland Steam available indication

01LBA10AA501 SG1 Outlet PORV

01LBA20AA501 SG2 Outlet PORV

01LBA30AA501 SG3 Outlet PORV

01LBA40AA501 SG4 Outlet PORV

Steam Turbine Sequence screen;

01MAA10AA001 Turbine Emergency Stop Valve

01MAA10AA002 Turbine Control Valve

01MAB50CS901 Turbine speed

01MAA10AA003 Steam chest and rotor heating steam supply valves

01MAA10AA004 Rotor heating steam supply valve

01MAA10AA501 Steam chest heating drain valve

01MAA10CT001 Steam chest temperature

01MAB10CT005 Turbine rotor metal temperature

01MAA10AH001 Turbine reset trip button

01MAA10AH002 Turbine stop button

Steam Turbine Bled Steam screen;

01LBS10AA001 LP heater 1 bled steam isolation valve

01LBS20AA001 LP heater 2 bled steam isolation valve

01LBS30AA001 LP heater 3 bled steam isolation valve

01LBS40AA001 LP heater 4 bled steam isolation valve

01LBQ60AA001 Deaerator bled steam isolation valve

01LBQ10AA001 Feedwater pumps bled steam isolation valve

01LBQ20AA001 HP heater 6 bled steam isolation valve

01LBQ30AA001 HP heater 7 bled steam isolation valve

01LBQ40AA001 HP heater 8 bled steam isolation valve

01LBQ50AA001 HP heater 9 bled steam isolation valve

Steam Turbine Lube Oil screen;

01LBA60CT001 Main steam temperature

01MAA10AA001 Turbine Emergency Stop Valve

01MAA10AA002 Turbine Control Valve

01MAB50CS901 Turbine speed

01MAK10AE001 Turning Gear motor

01MAV10AH001 Turning gear control

01MAV10CT001 Lube Oil tank temperature

01MAV10AH001 Lube Oil tank heater control

01MAV10AH002 Lube Oil pump control

01MAV10AP001 Auxiliary Lube Oil pump

01MAV20AP001 Shaft driven Lube Oil pump

01MAX10AH001 Control Oil control

01MAX10AP001 Control Oil pump

01MAX50CP001 Control Oil pressure

Steam Turbine Vacuum screen;

01MAA10AA001 Turbine Emergency Stop Valve

01MAA10AA002 Turbine Control Valve

01MAB10CT005 Turbine rotor metal temperature

01MAW10CP001 Gland Steam available indication

01MAW20AA001 Gland Steam supply isolation valve

01MAW20AA151 Gland Steam supply control valve

01MAW20CP001 Gland Steam pressure

01MAW30AN001 Gland Steam exhauster fan

01MAW10AH001 Gland Steam control

01MAG10CP001 Condenser pressure

01MAG10CP002 Condenser pressure

01MAG10CP003 Condenser pressure

01MAG10CP901 Condenser pressure

01MAJ10AH001 Condenser Vacuum control

01MAJ10AN001 Condenser Vacuum Pump 1

01MAJ10AN002 Condenser Vacuum Pump 2

01MAJ10AN003 Condenser Vacuum Pump 3

01PAC10AP001 Cooling Water Circulation pump

Generator Electrical screen;

01MKA10GS001 Generator

01BAT10GT001 21/500kV Generator Transformer

01MKA10CE001 Generator voltage

01MKA10CE005 Generator frequency

01BAA10CE001 Bus voltage

01BAA10CE005 Bus frequency

Ccondensate screen;

01MAG10CP901 Condenser pressure

01LCA10AP001 Condensate Extraction Pump 1

01LCA20AP001 Condensate Extraction Pump 2

01LCA30AP001 Condensate Extraction Pump 3

01LCA50AA001 Condensate system clean up valve

01LAA10BB001 DA storage tank

01LCA10CT001 Condenser outlet temperature

01LCA50CT001 Deaerator inlet temperature

01JEA10CL001 Steam generator 1 level

01JEA20CL001 Steam generator 2 level

01JEA30CL001 Steam generator 3 level

01JEA40CL001 Steam generator 4 level

Feedwater screen;

01LAA10BB001 DA storage tank

01LJA10AP001 Auxiliary Feedwater Pump 1

01LJA20AP001 Auxiliary Feedwater Pump 2

01LAC10AP001 Feedwater Pump 1

01LAC20AP001 Feedwater Pump 2

01LAC30AP001 Feedwater Pump 3

01LAC40AP001 Feedwater Pump 4

01LAC60AA001 Feedwater system clean up valve

01LAC10CT001 Deaerator outlet temperature

01LAC60CT001 Steam Generator inlet temperature

01LAC50CF001 Feedwater flow

01LAC50CF901P Feedwater flow percentage

01LAC50CF901C Feedwater pump capacity gauge

01JEA10CL001 Steam generator 1 level

01JEA20CL001 Steam generator 2 level

01JEA30CL001 Steam generator 3 level

01JEA40CL001 Steam generator 4 level

Cooling Water System screen;

01PAC10AP001 Main Cooling Water Pump

01PJA10AP001 Service Water Pump

01KAA10AP001 Closed Cooling Water Pump

01MAG10CP901 Condenser pressure

01PAC10CT001 Cooling Water Inlet Temperature

01PAC60CT001 Cooling Water Outlet Temperature

B Screenshots

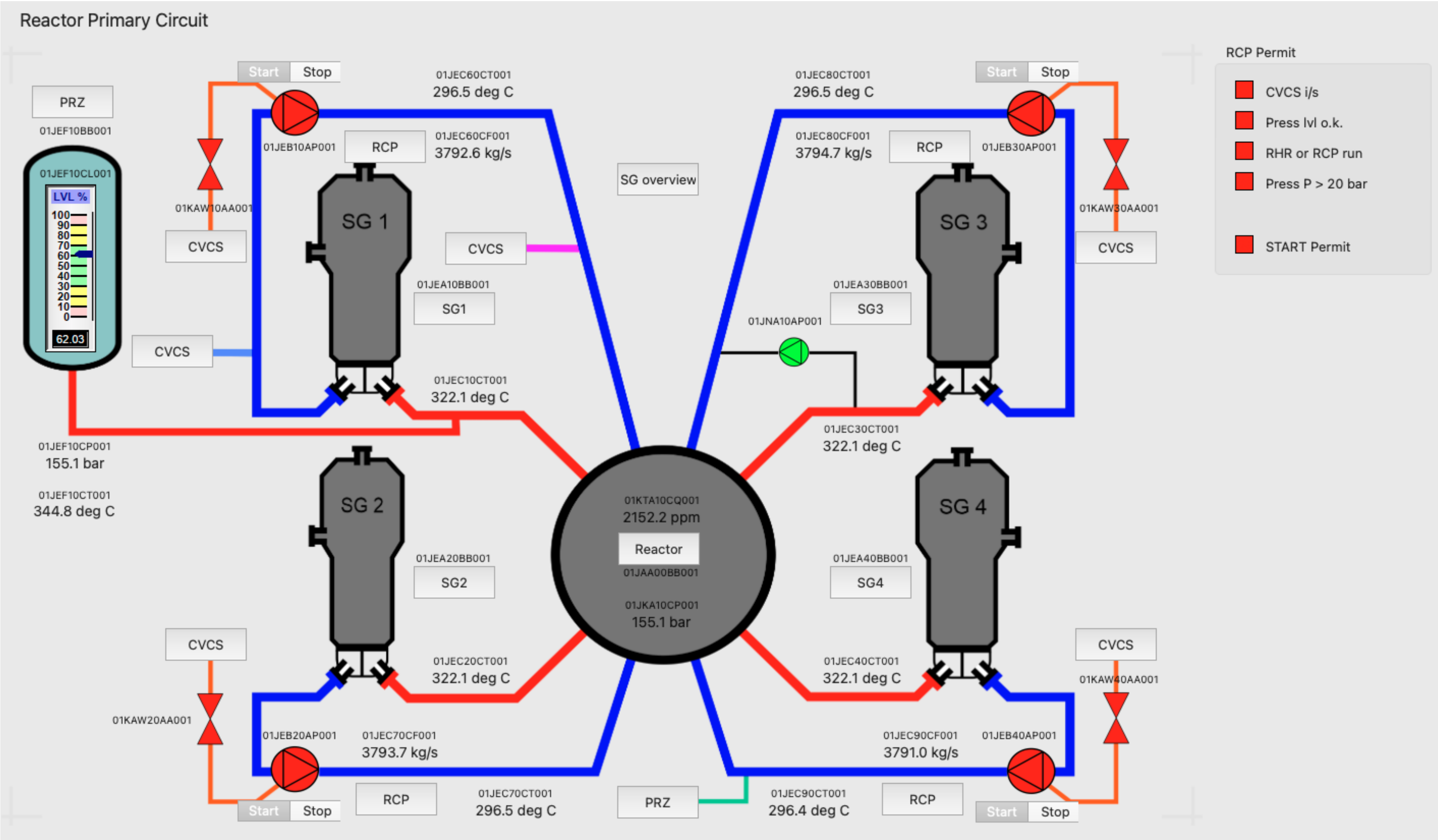


Figure 55: Reactor Primary Circuit page screenshot

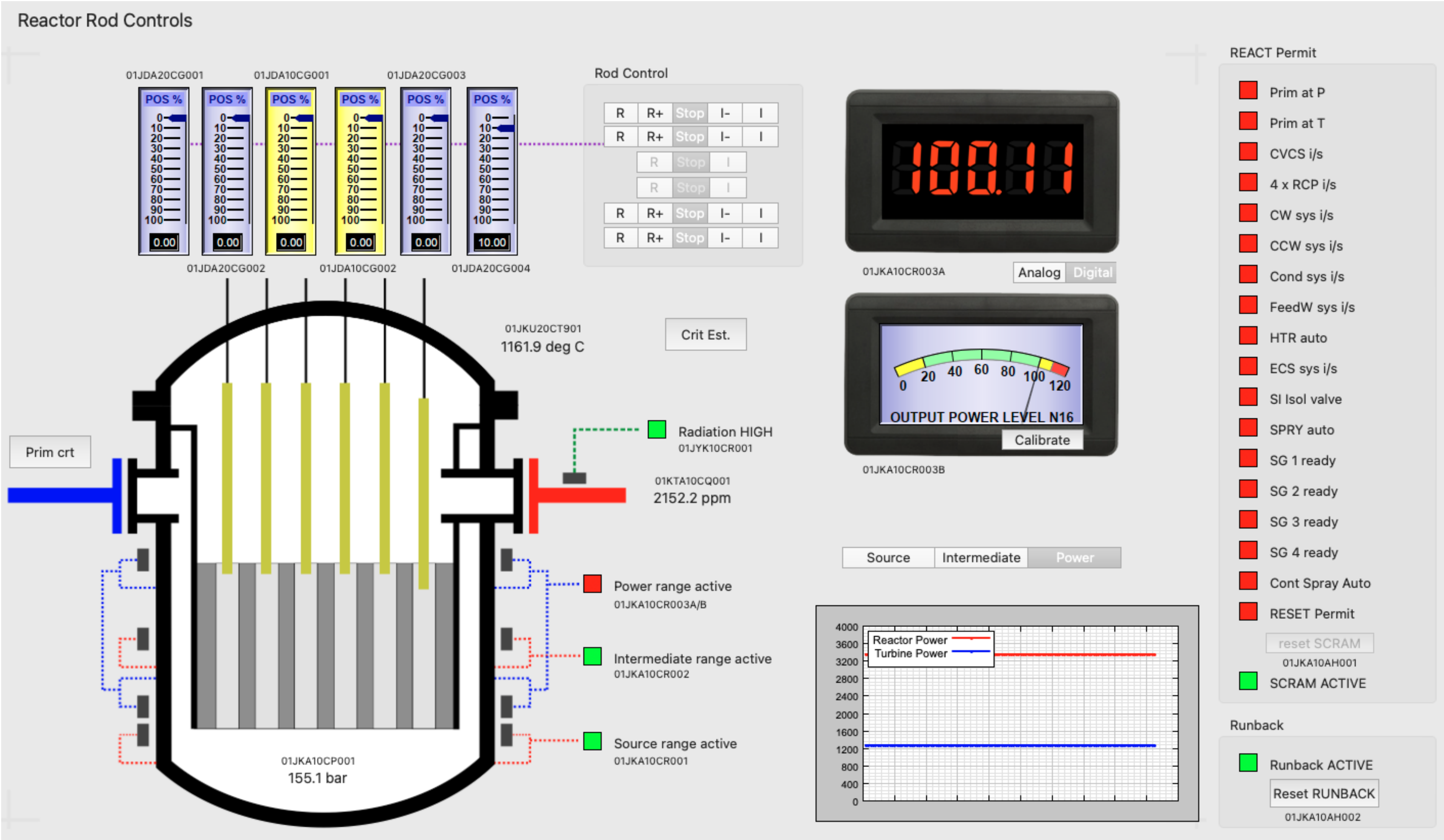


Figure 56: Reactor Rod Control page screenshot

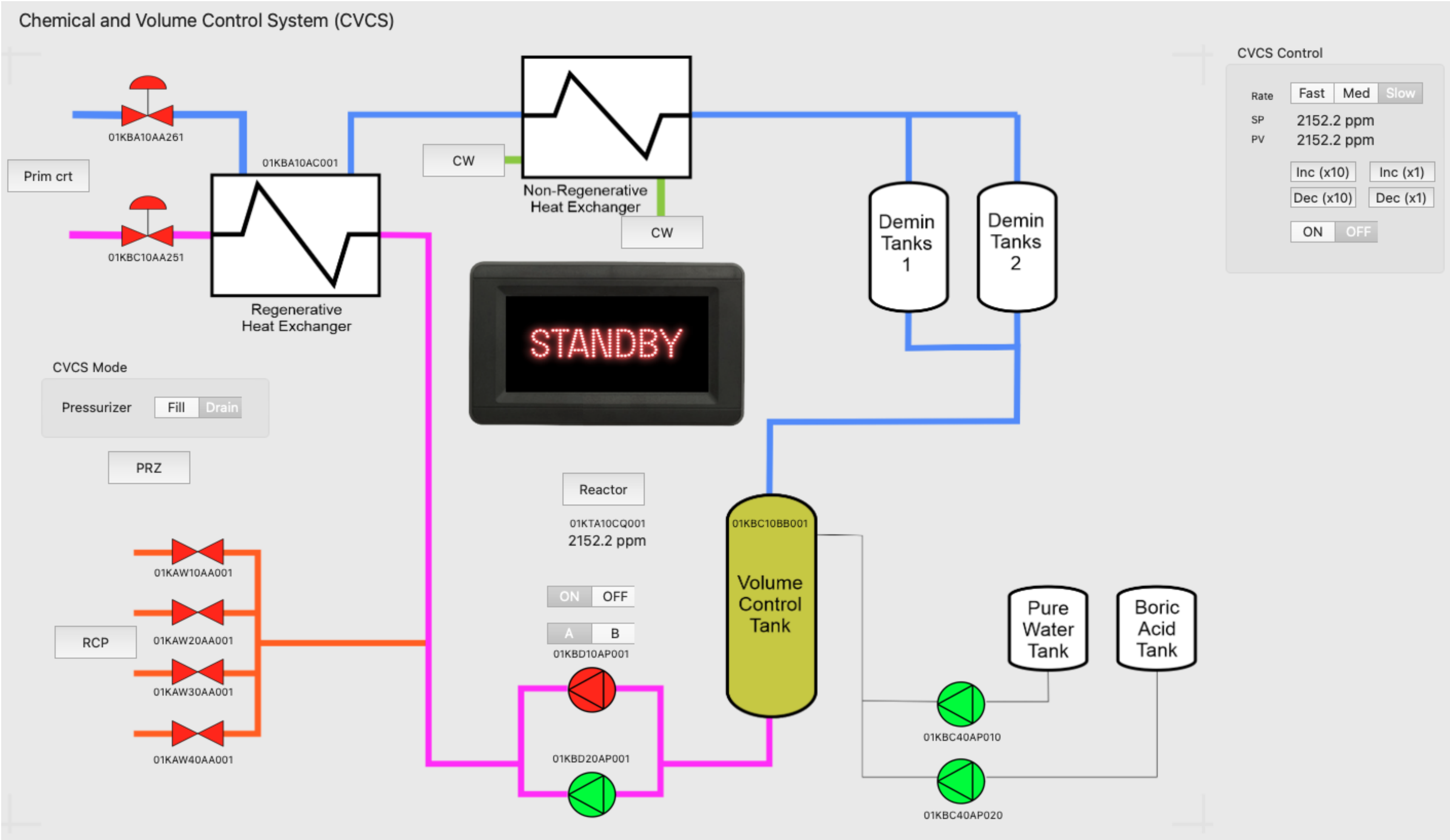


Figure 57: Chemical and Volume Control System page screenshot

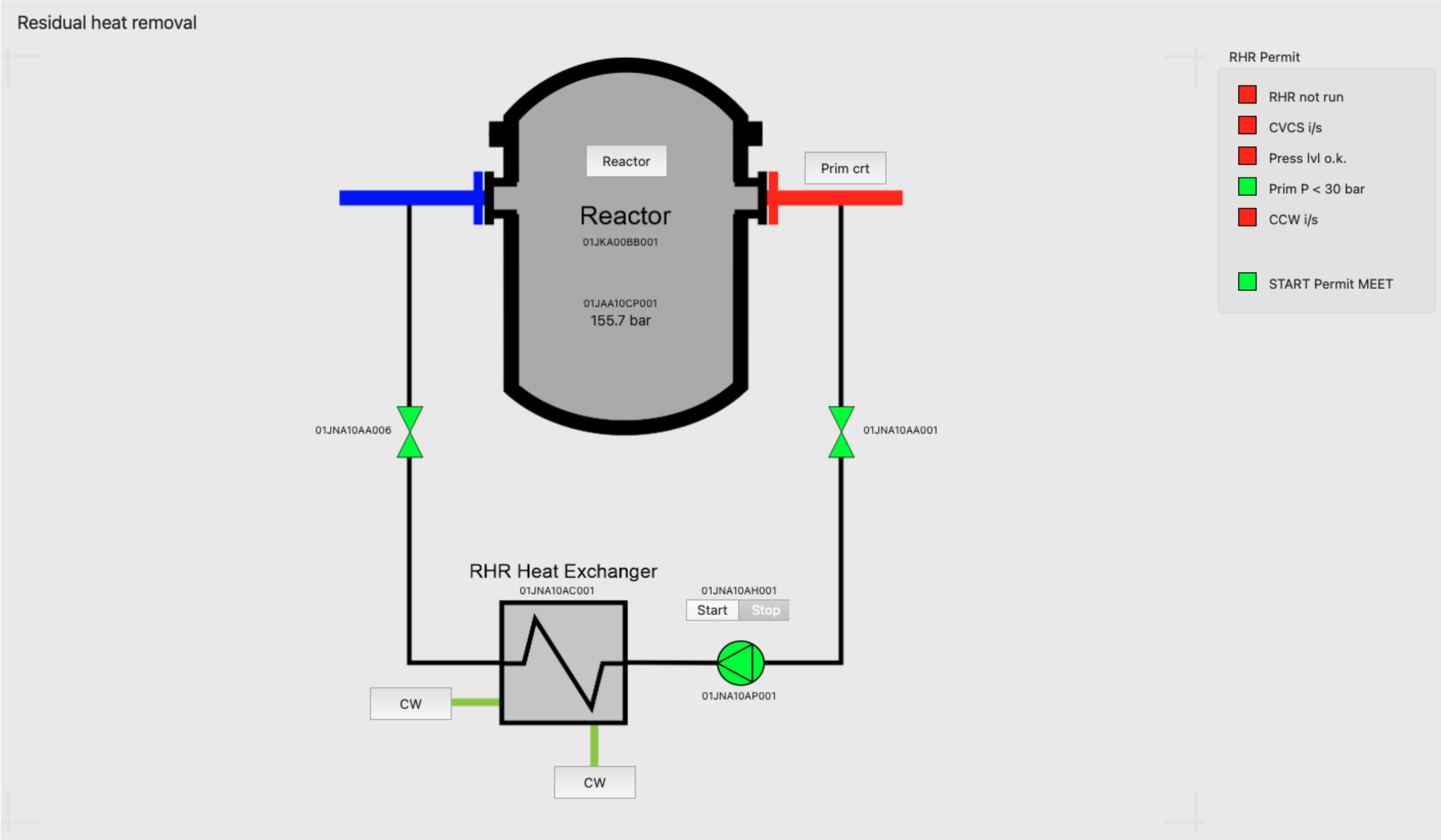


Figure 58: Residual Heat Removal page screenshot

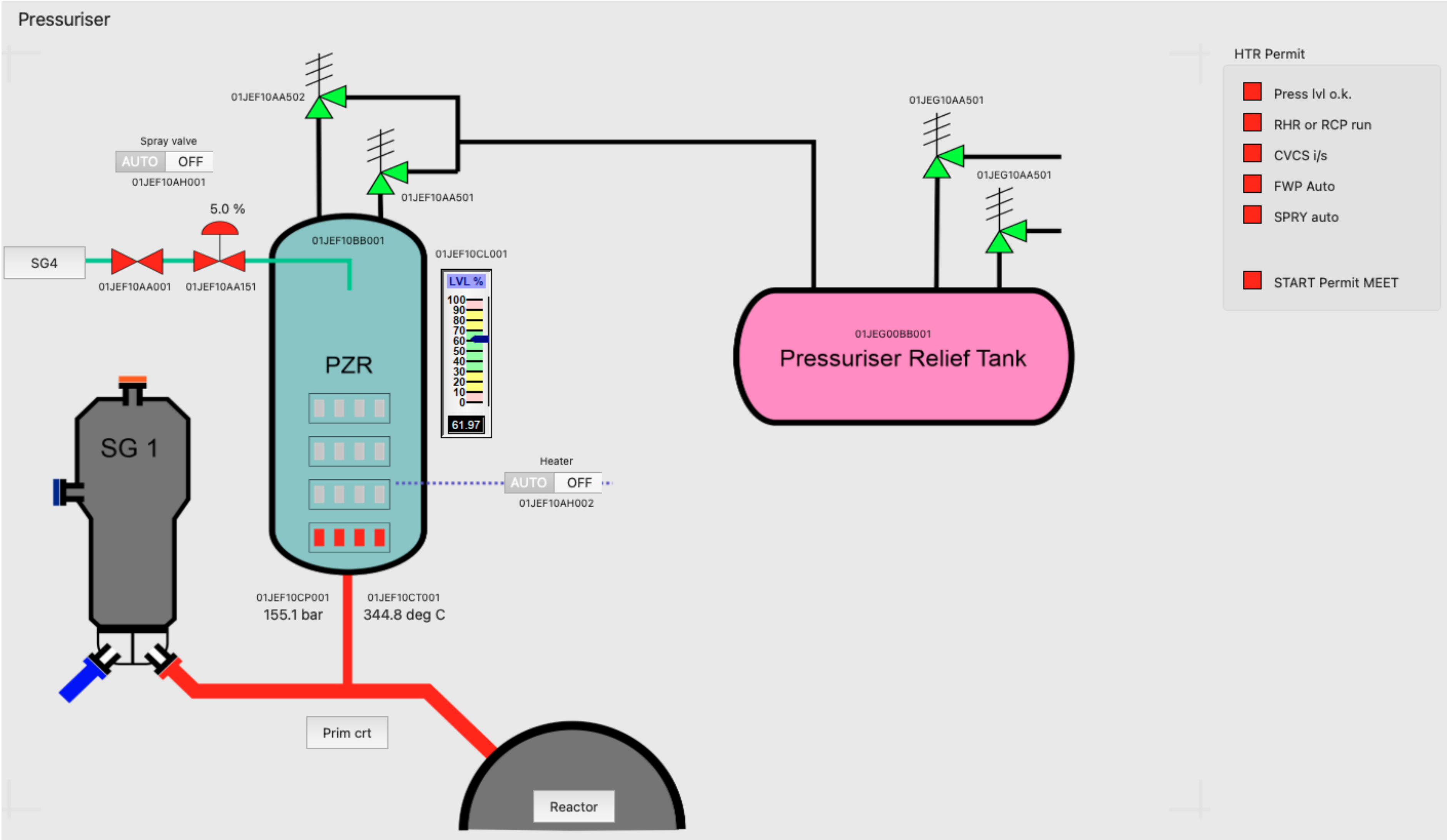


Figure 59: Pressuriser page screenshot

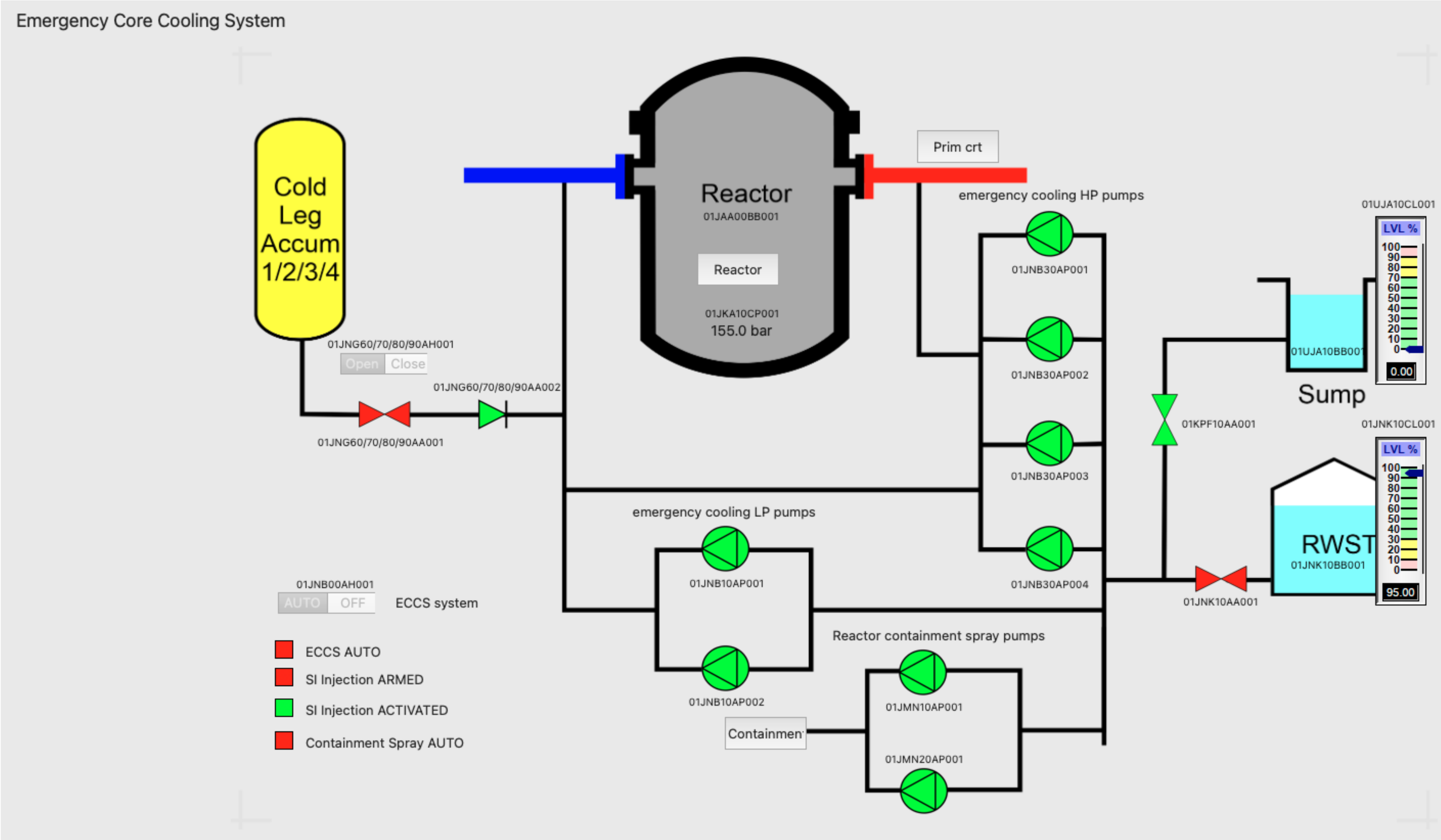


Figure 60: Emergency Core Cooling System page screenshot

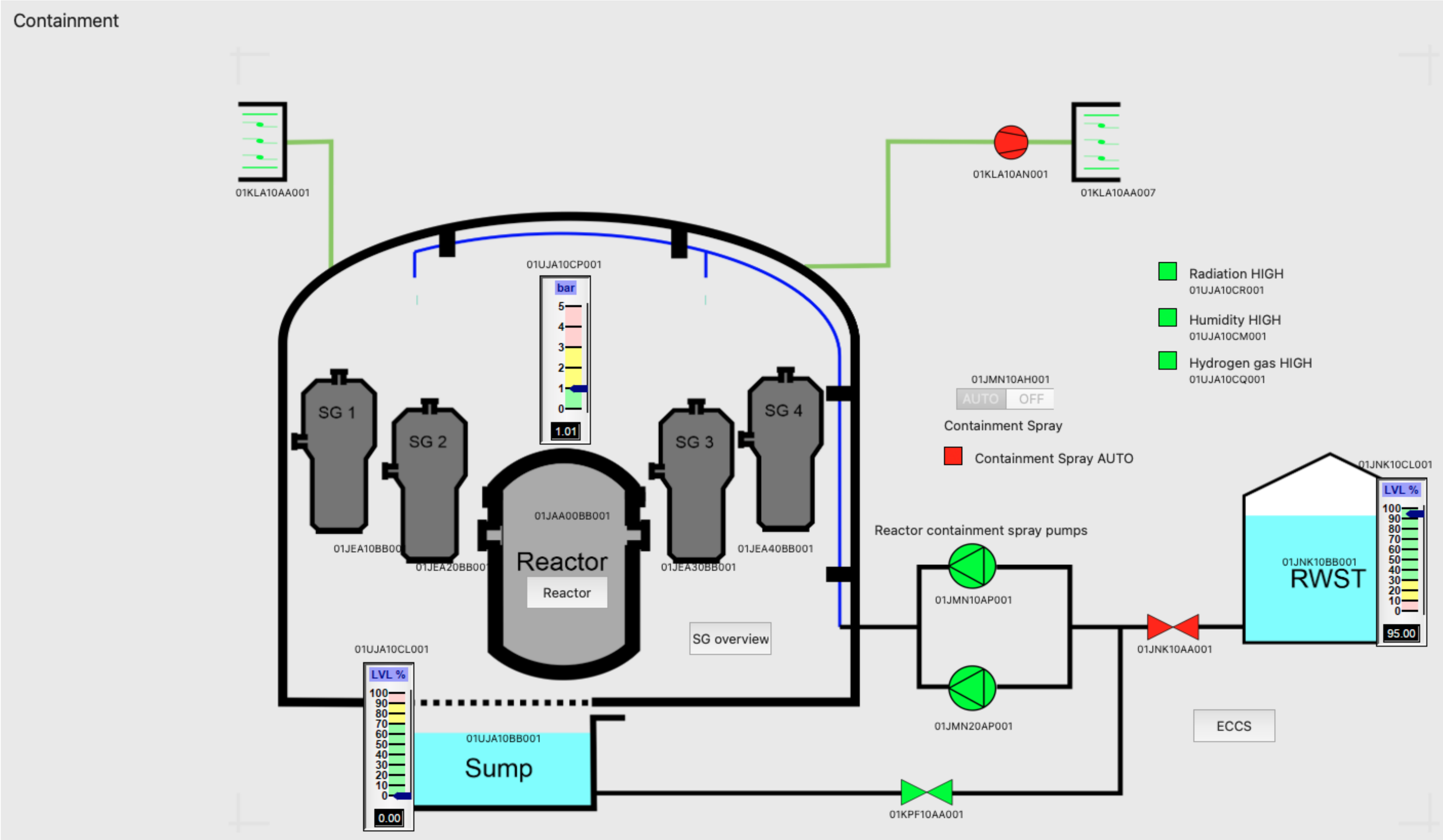


Figure 61: Containment vessel page screenshot

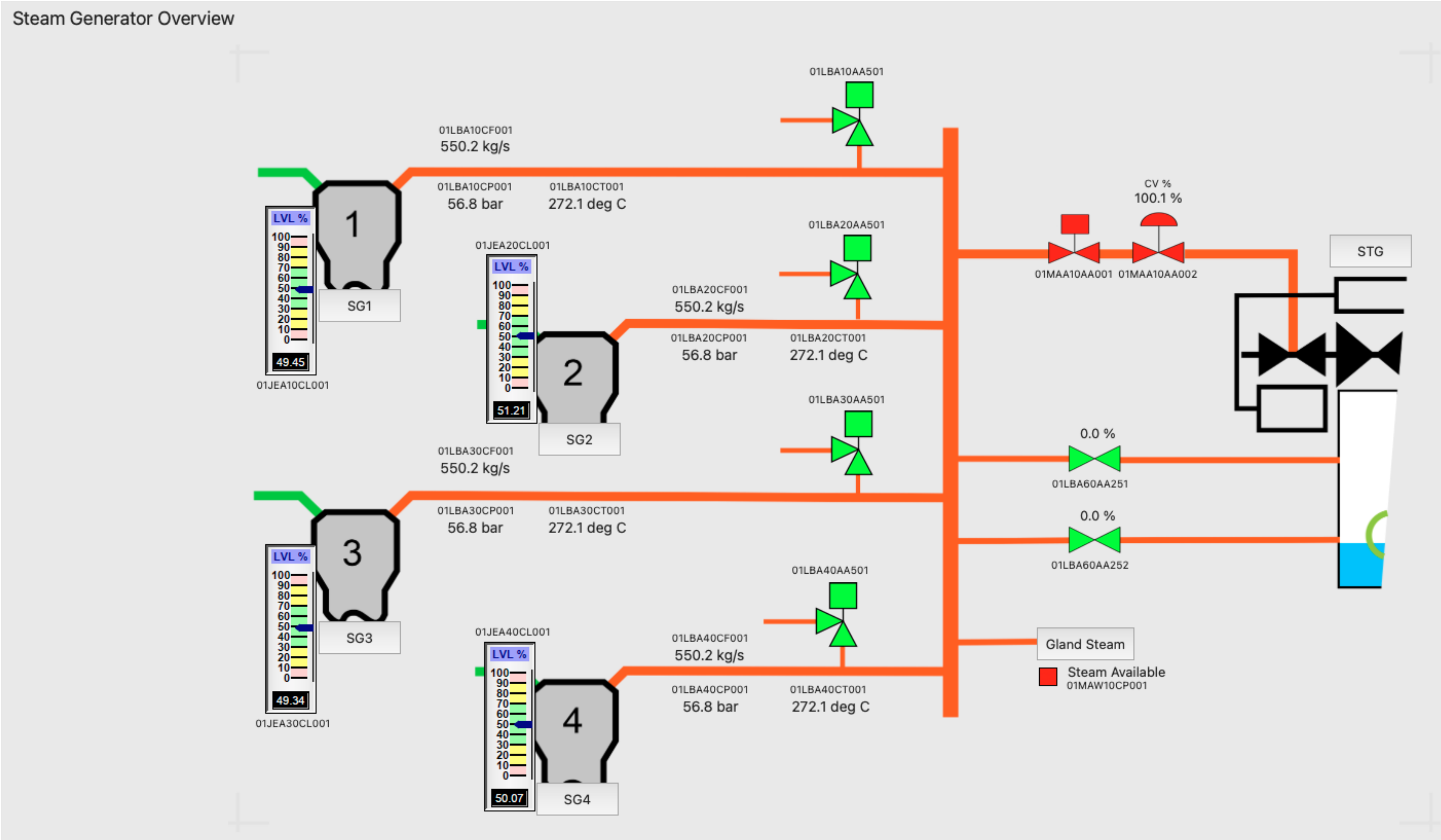


Figure 62: Steam Generator Overview page screenshot

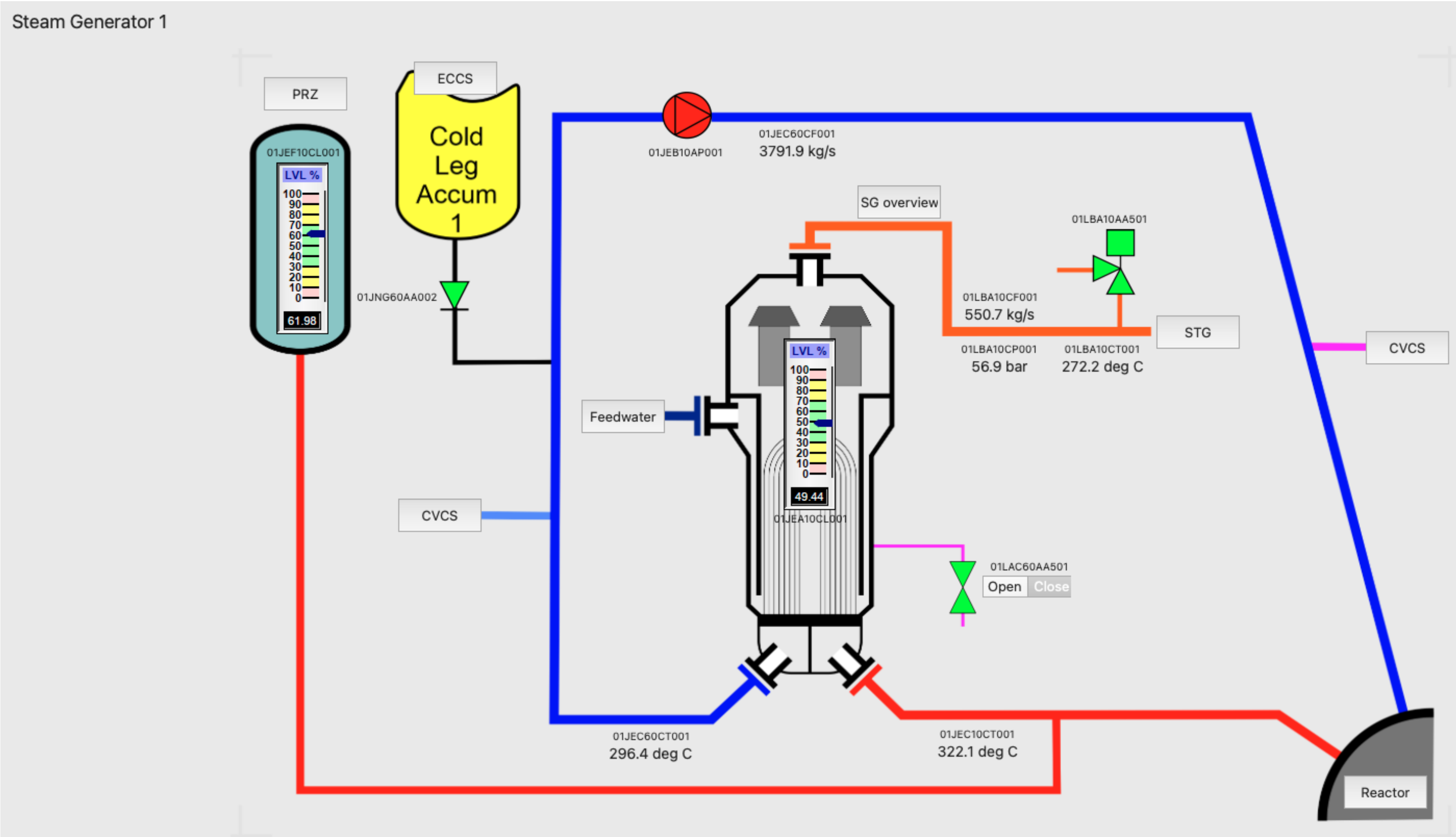


Figure 63: Steam Generator 1 page screenshot

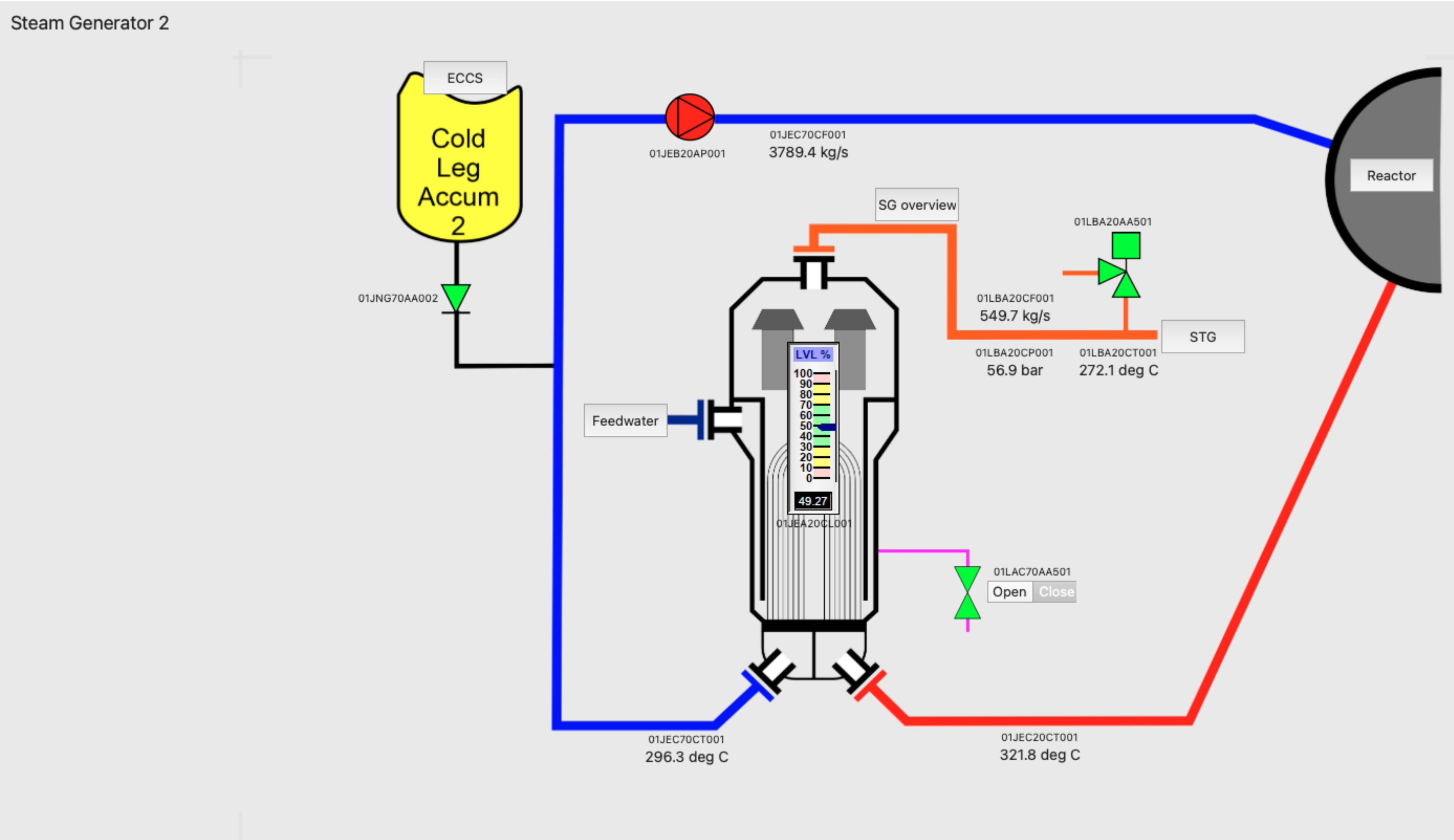


Figure 64: Steam Generator 2 page screenshot

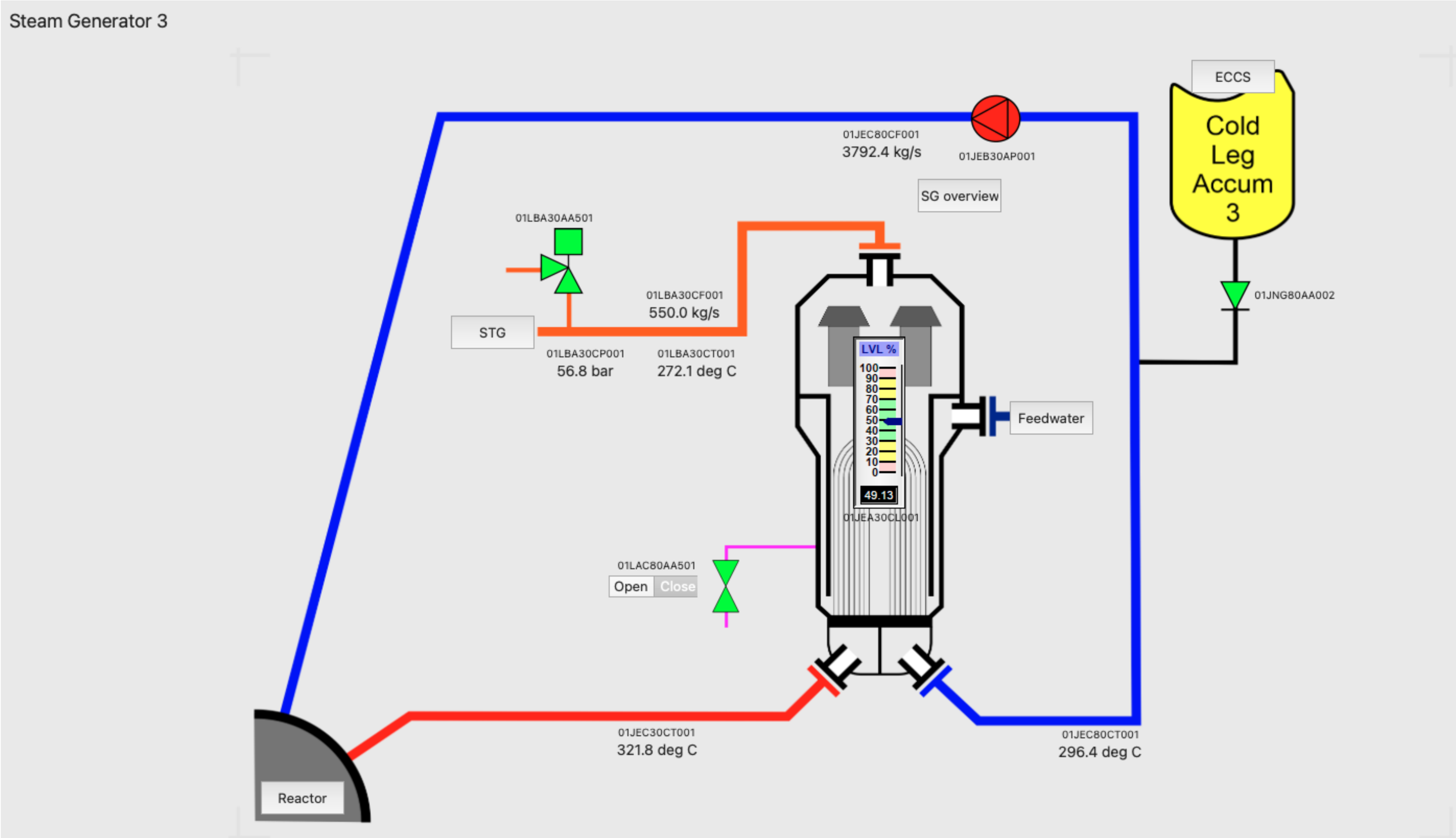


Figure 65: Steam Generator 3 page screenshot

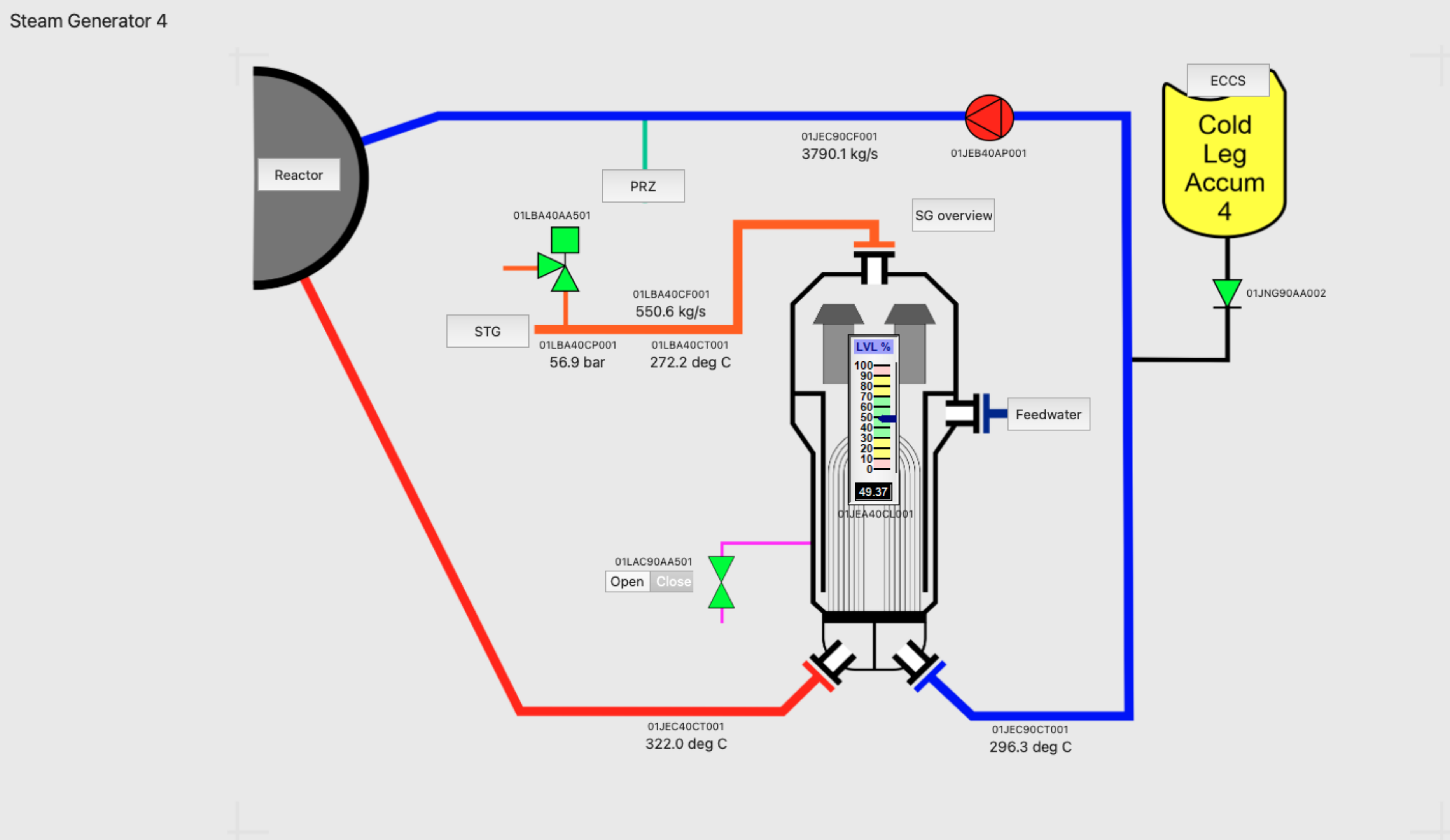


Figure 66: Steam Generator 4 page screenshot

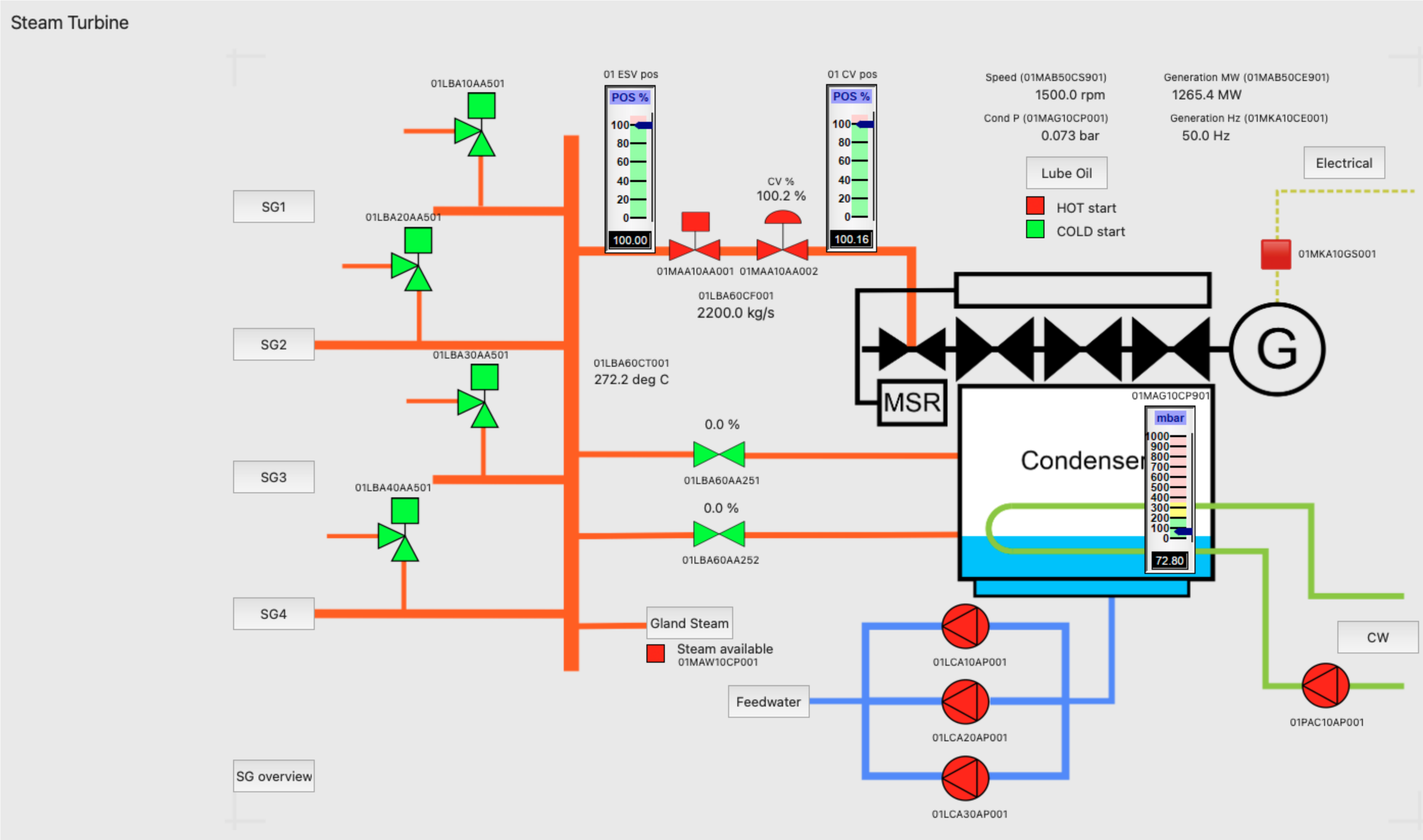


Figure 67: Steam Turbine page screenshot

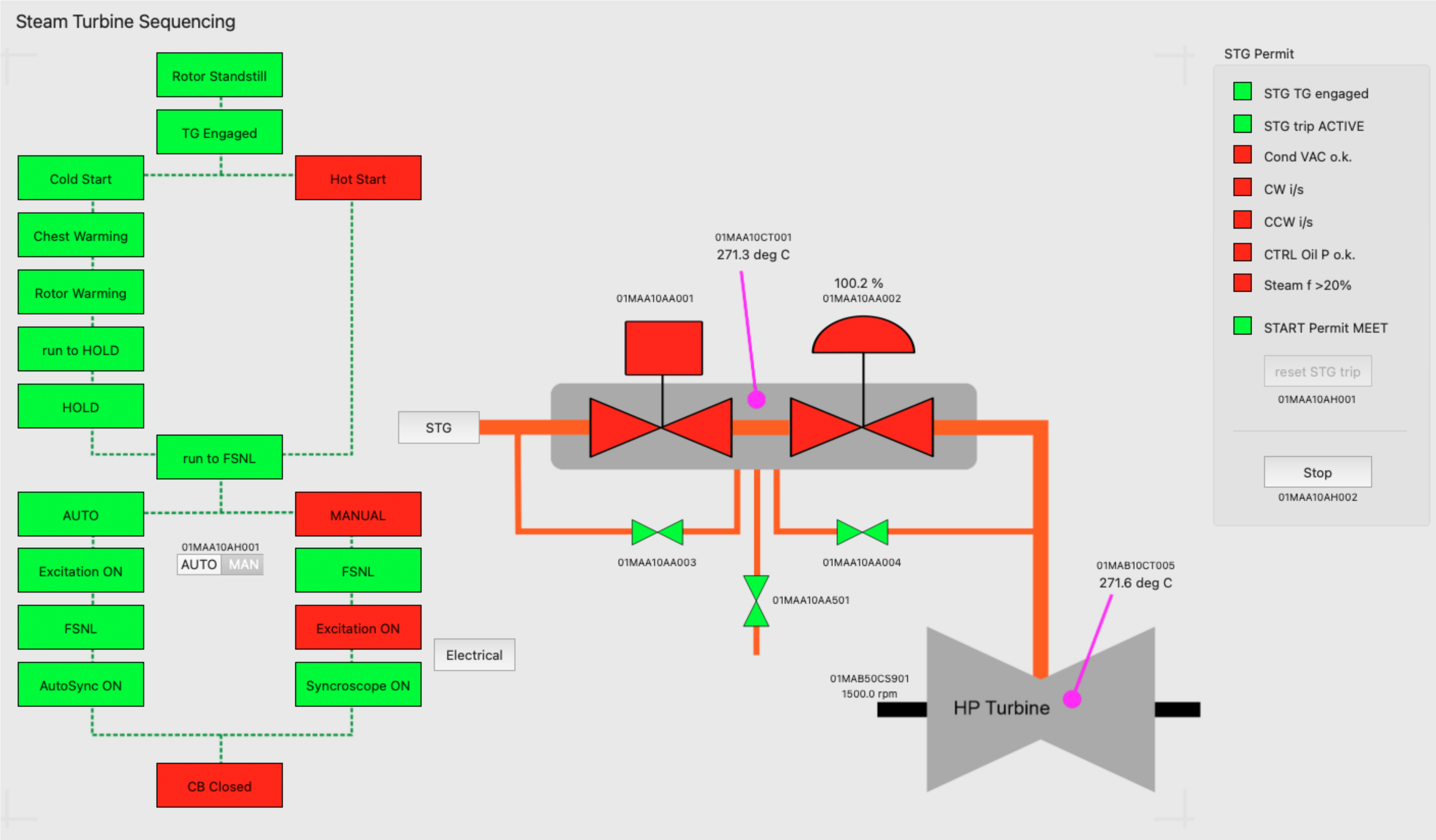


Figure 68: Steam Turbine Sequence page screenshot

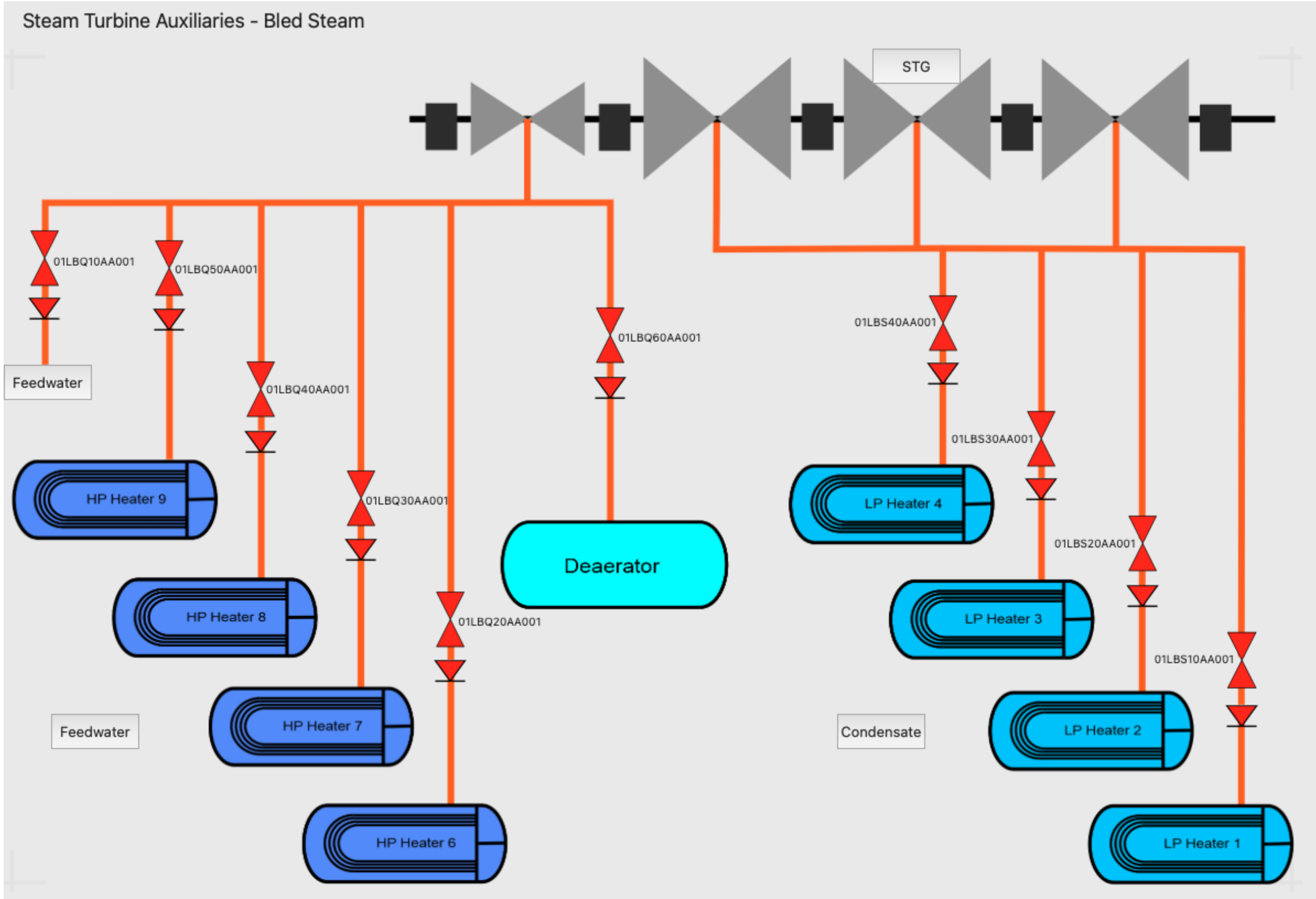


Figure 69: Steam Turbine Bleed Steam page screenshot

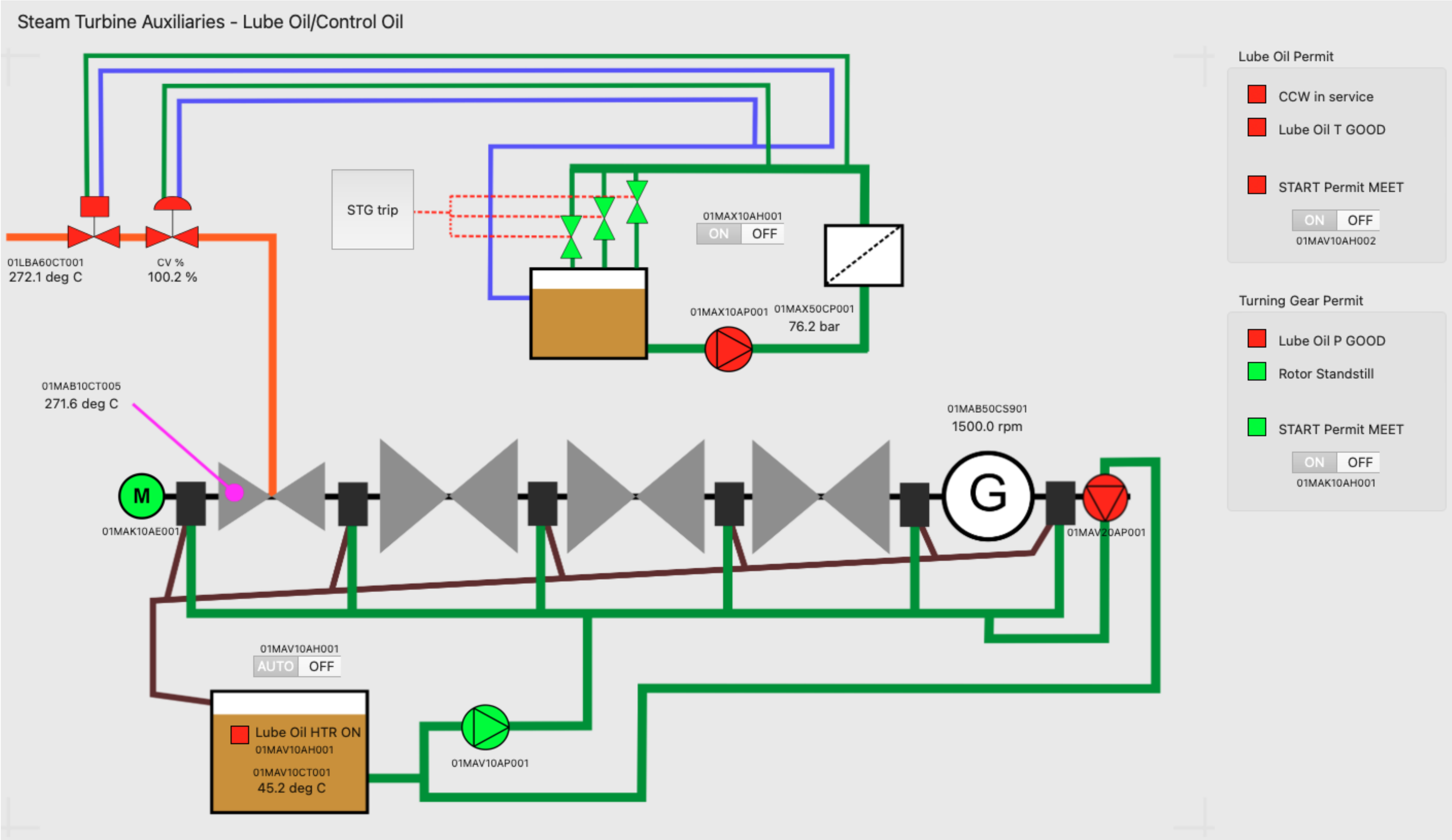


Figure 70: Steam Turbine Oil Systems page screenshot

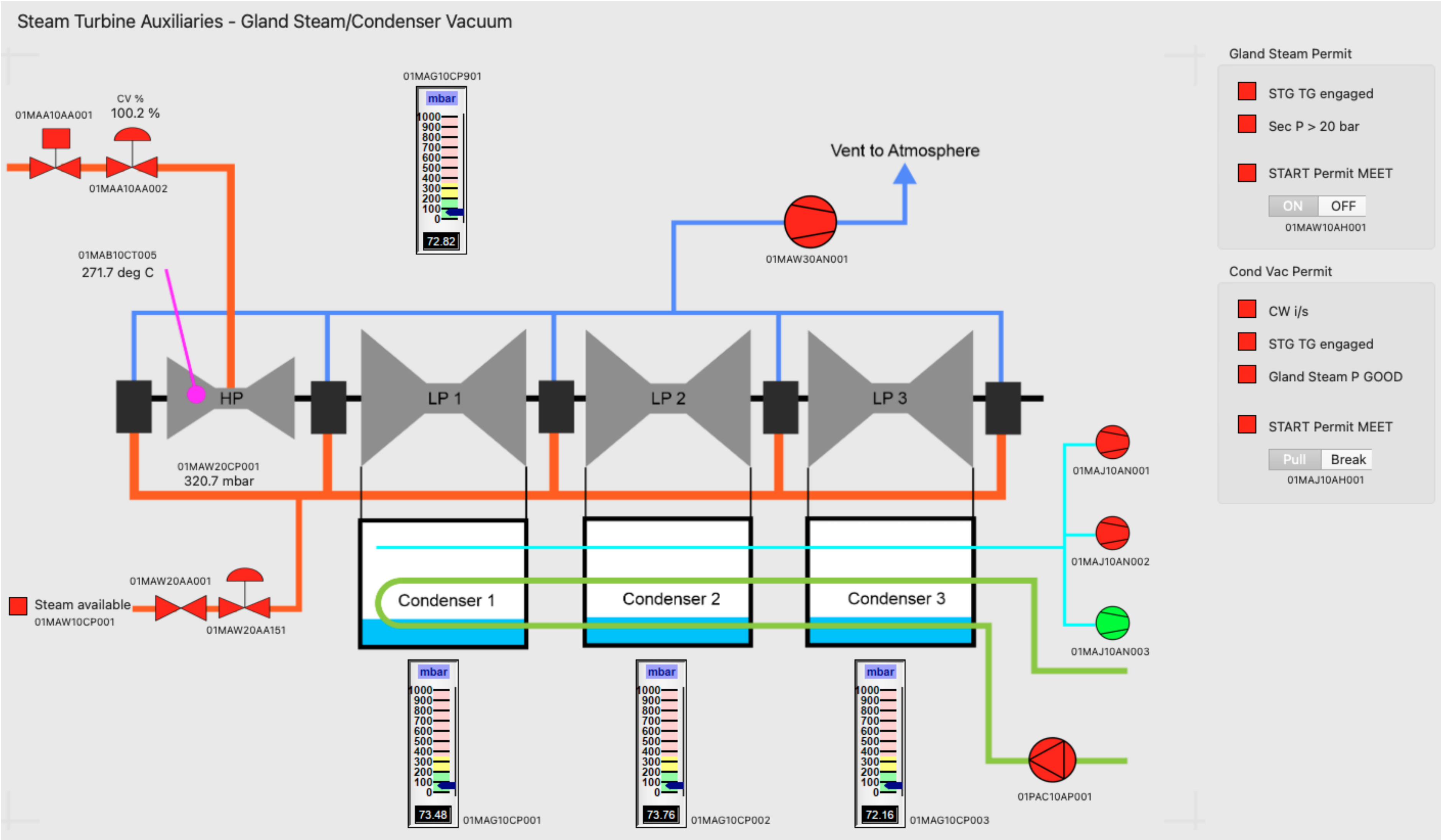


Figure 71: Steam Turbine Vacuum and Gland Steam page screenshot

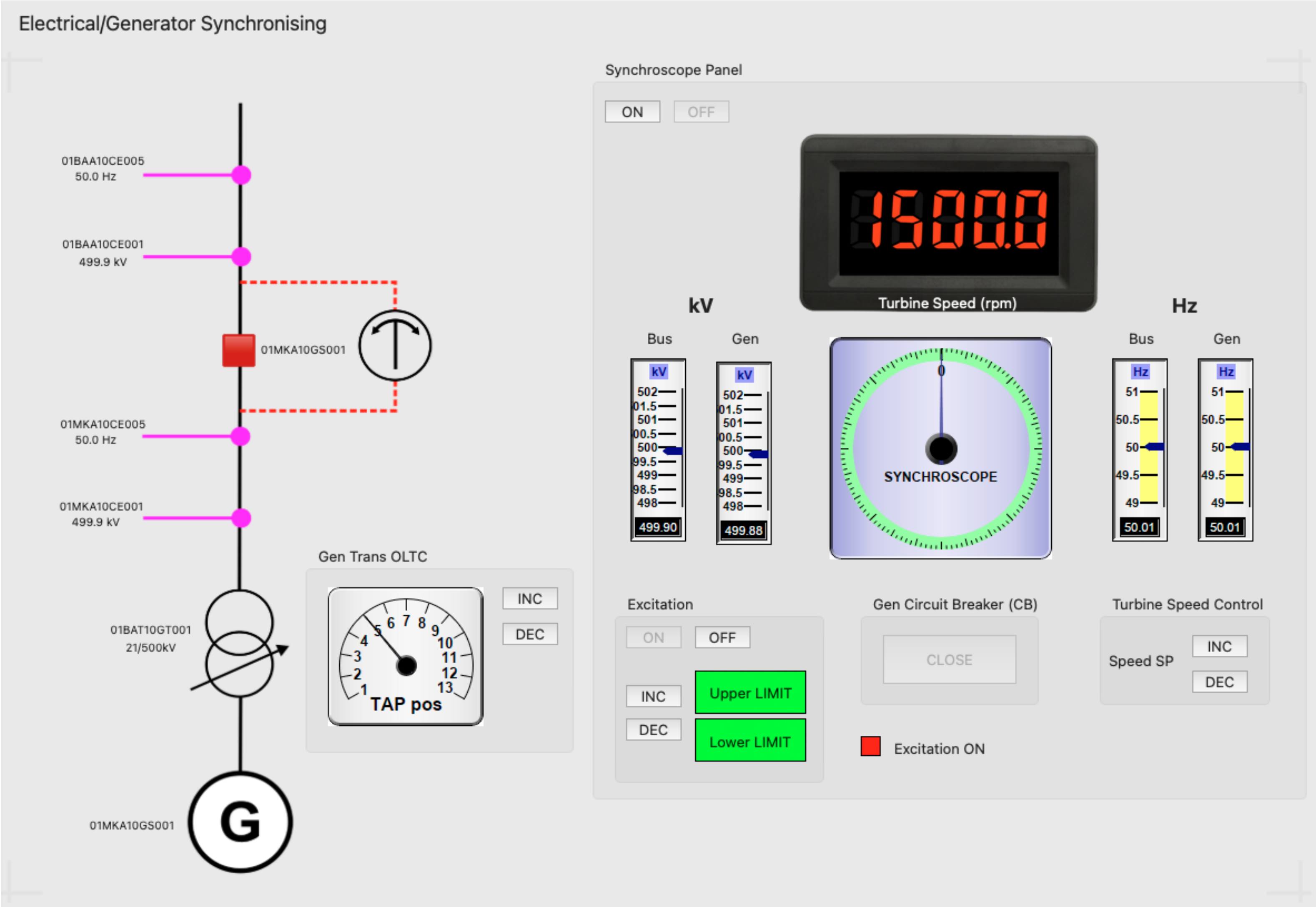


Figure 72: Generator Synchronising page screenshot

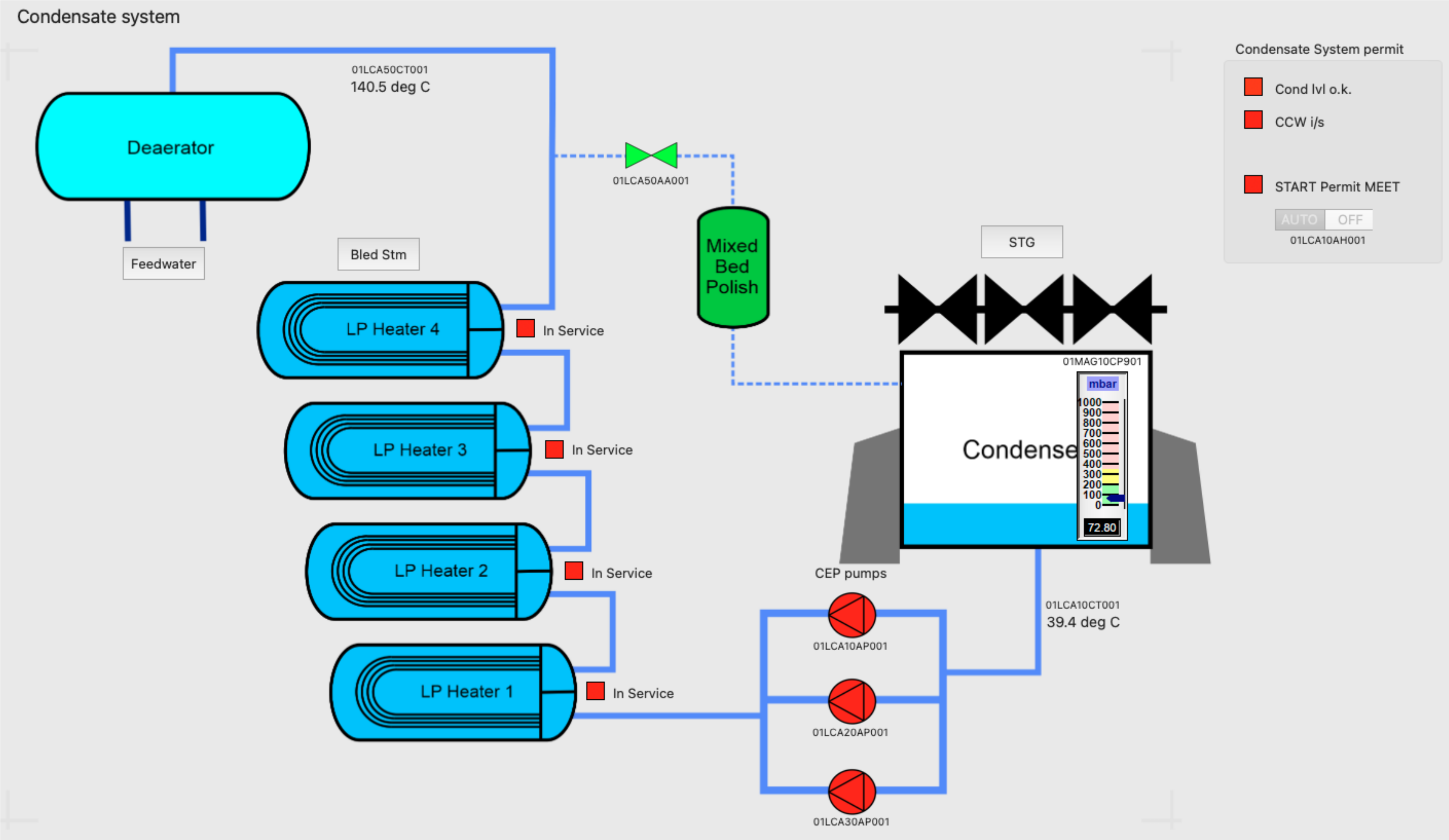


Figure 73: Condensate page screenshot

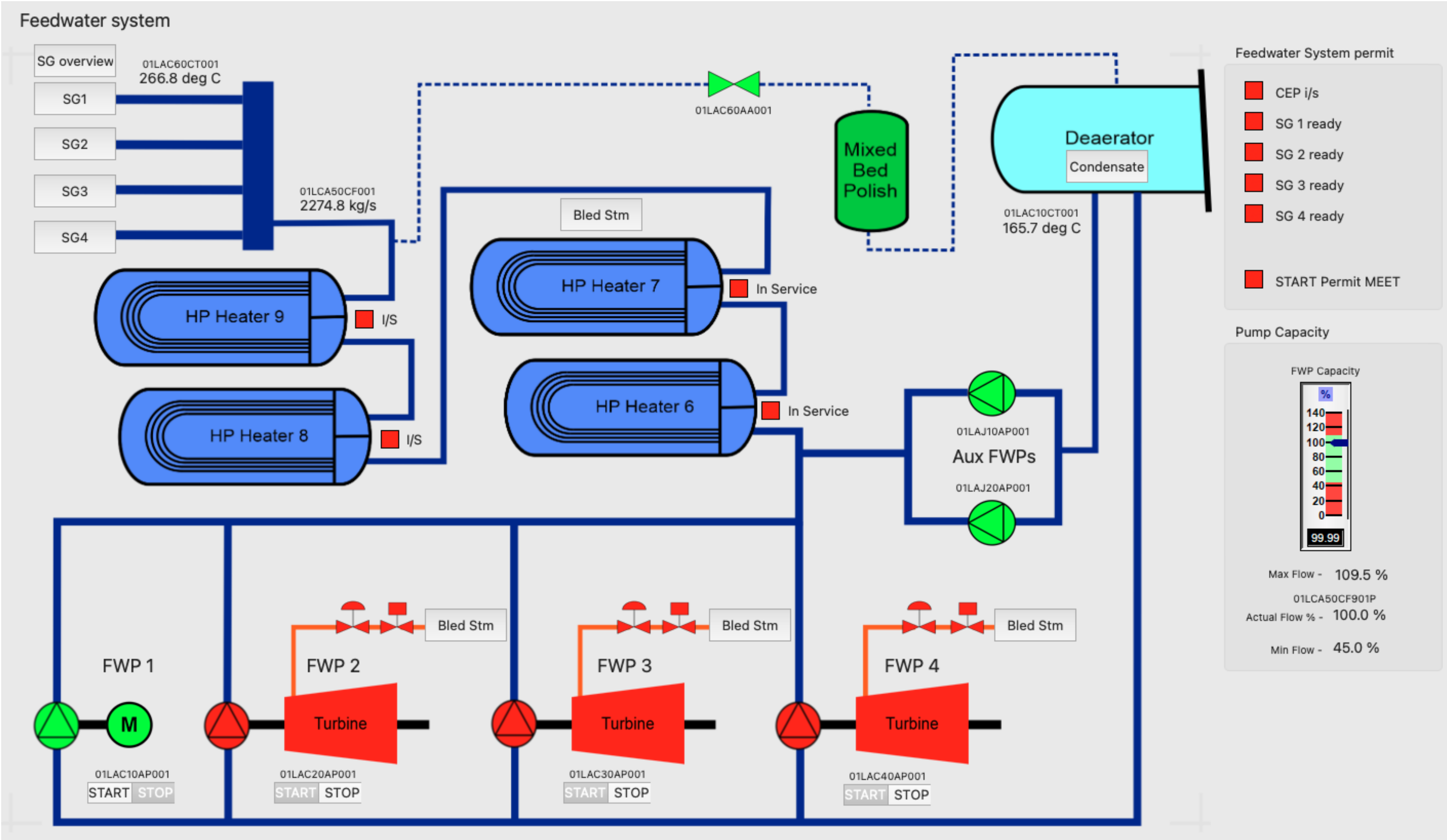


Figure 74: Feedwater page screenshot

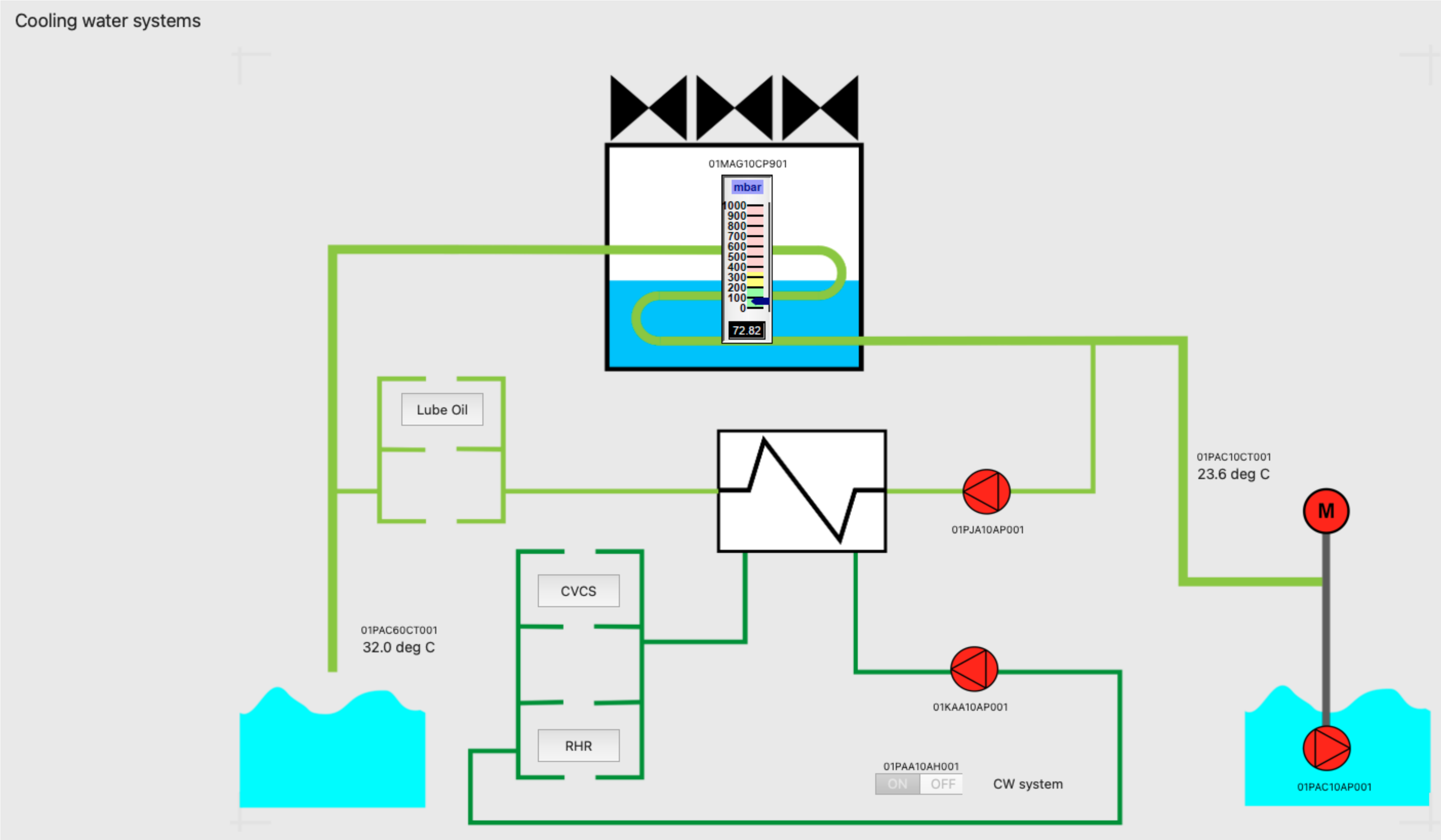


Figure 75: Cooling Water System page screenshot

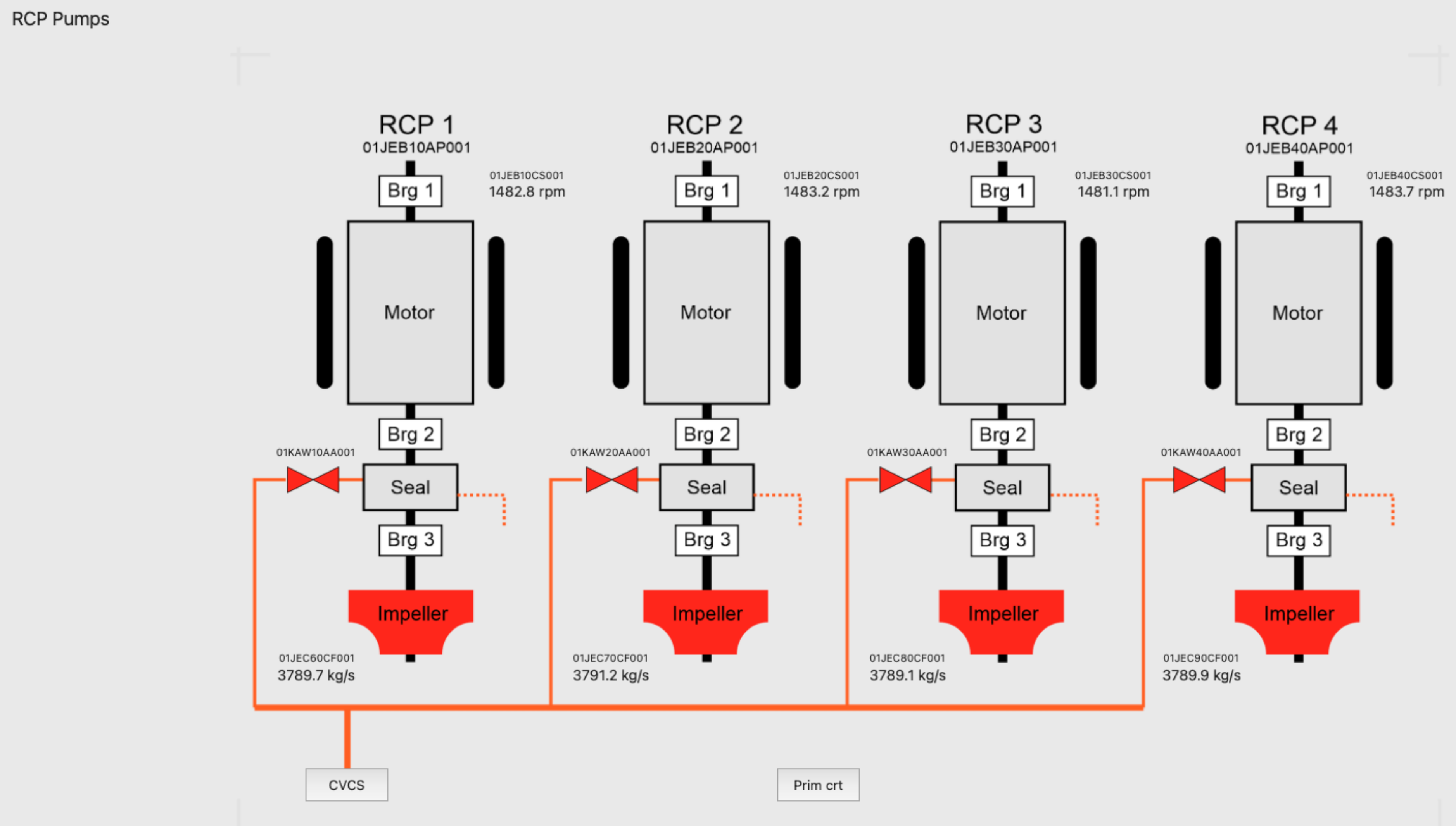


Figure 76: Reactor Coolant Pump monitoring page screenshot

C Plant drawing

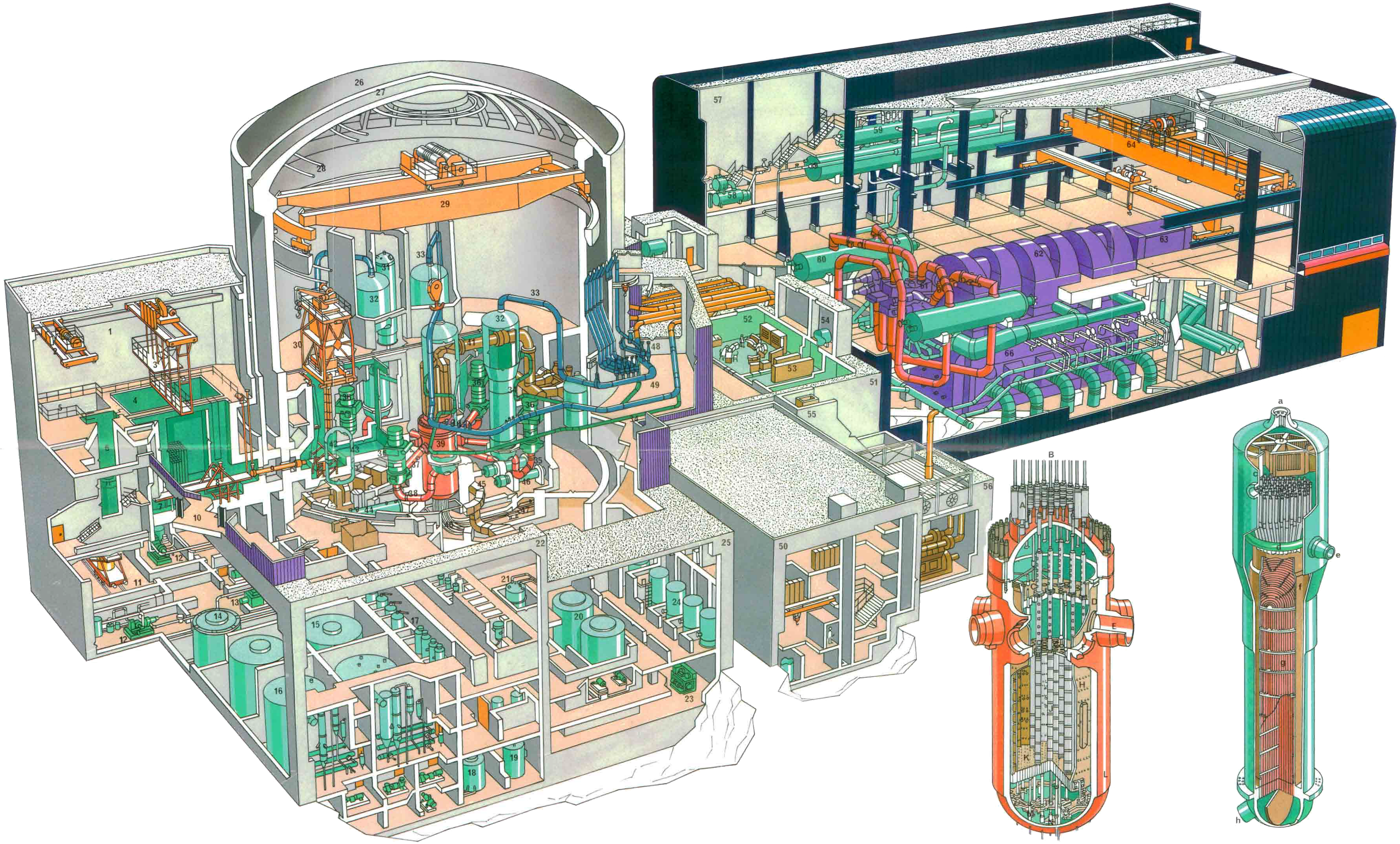


Figure 77: ACME NucPower Unit 1 cutaway drawing

D Thermodynamics

The thermodynamic cycle modelled in this simulation is shown below. It consists of a Rankine cycle with reheat.

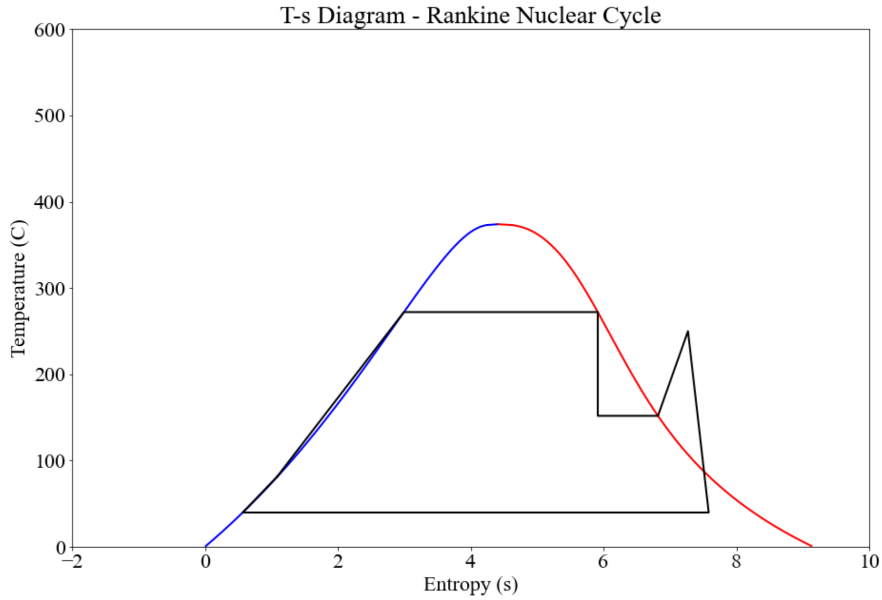


Figure 78: Temperature-Entropy diagram

The code to generate this curve is provided below using the Python programming language.

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
@date: 16 January 2025 (update)

This source code is provided by Richard J Smith 'as is' and 'with all faults'. The provider
    makes no
representations or warranties of any kind concerning the safety, suitability, inaccuracies,
typographical errors, or other harmful components of this software.
"""

import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)

print('Rankine nuclear cycle analysis')

p1 = 56.9 #steam generator outlet pressure (bar)
p2 = 5 #Wet steam pressure at inlet to seperator (bar)
p4 = 0.0728 #Condenser pressure (bar)
t3 = 250 # low pressure turbine inlet temperature (deg C)
p10 = (1+0.05)*p1 #feedwater supply pressure (bar)
eff_HPC = 0.89 #HPC isentropic efficiency
eff_LPC = 0.86 #LPC isentropic efficiency
eff_Pump = 0.8 # pump efficiency

def wspHEXPANSIONPPEFF(p0,p1,eff):
    t0 = steamTable.tsat_p(p0)
    h0 = steamTable.h_tx(t0,1)
    s0 = steamTable.s_ph(p0,h0)
    s1 = s0
    t1 = steamTable.tsat_p(p1)
    x1 = steamTable.x_ps(p1,s1)
    h1 = steamTable.h_tx(t1,x1)
    return h0-(h0-h1)*eff

def wspHEXPANSIONPTPEFF(p0,t0,p1,eff):
    h0 = steamTable.h_pt(p0,t0)
```

```
    s0 = steamTable.s_pt(p0,t0)
    s1 = s0
    t1 = steamTable.t_ps(p1,s1)
    # need to determine if single phase or two phase
    x1 = steamTable.x_ps(p1,s1)
    h1 = steamTable.h_tx(t1,x1)
    return h0 - (h0 - h1)*eff

def wspHCOMPRESSIONPPEFF(p0,p1,eff):
    h0 = steamTable.h_px(p0,0)
    s0 = steamTable.s_ph(p0,h0)
    s1 = s0
    h1 = steamTable.h_ps(p1,s1)
    return h0+((h1-h0)/eff)

def wspHCOMPRESSIONPTPEFF(p0,t0,p1,eff):
    h0 = steamTable.h_pt(p0,t0)
    s0 = steamTable.s_pt(p0,t0)
    s1 = s0
    h1 = steamTable.h_ps(p1,s1)
    return h0+((h1-h0)/eff)

def find_a_sh(quality,hwater1,hwater2,enthalpy1,enthalpy2,enthalpy3):
    for x in range(100):
        y = ((1-quality)*hwater2)+((x/100)*hwater1)+(quality*enthalpy3)
        z = y-((x/100)*enthalpy1)
        if z < enthalpy2:
            for p in range(100):
                y = ((1-quality)*hwater2)+((((x-1)/100)+(p/10000))*hwater1)+(quality*enthalpy3)
                z = y-((((x-1)/100+(p/10000)))*enthalpy1)
                if z < enthalpy2:
                    return ((x-1)/100)+((p-1)/10000)

def find_h9(sh,hwater1,enthalpy8):
    for x in range(500):
        y=(sh*hwater1)+enthalpy8
        z=(1+sh)*x
        if z > y:
            for p in range(100):
                y=(sh*hwater1)+enthalpy8
                z=(1+sh)*(x-1)+(p/100)
                if z > y:
                    return ((x-1)+((p-1)/100))


#extra for trend
t1a = steamTable.tsat_p(p1)
h1a = steamTable.h_px(p1,0)
s1a = steamTable.s_ph(p1,h1a)

#inlet to HPC
t1 = steamTable.tsat_p(p1)
h1 = steamTable.h_px(p1,1)
s1 = steamTable.s_ph(p1,h1)
print('\nPoint 1 - main steam (HP turbine inlet) conditions')
print(f"P1: {round(float(p1),1)} bar")
print(f"T1: {round(float(t1),1)} degC")
print(f"H1: {round(float(h1),1)} kJ/kg")
print(f"S1: {round(float(s1),3)} kJ/kg K")

#water from superheater
hw1 = steamTable.h_px(p1,0)

#steam inlet to seperator
t2 = steamTable.tsat_p(p2)
hw2 = steamTable.h_px(p2,0)
s2 = s1
h2 = wspHEXPANSIONPPEFF(p1,p2,eff_HPC)
x2 = steamTable.x_ph(p2,h2)
print('\nPoint 2 - HP turbine outlet (seperator inlet) conditions')
print(f"P2: {round(float(p2),1)} bar")
print(f"T2: {round(float(t2),1)} degC")
print(f"H2: {round(float(h2),1)} kJ/kg")
print(f"S2: {round(float(s2),3)} kJ/kg K")
```

```
#extra for trend
t2a = t2
p2a = p2
h2a = steamTable.h_tx(t2a,1)
s2a = steamTable.s_ph(p2a,h2a)

#inlet to LPC
p3 = p2
h3 = steamTable.h_pt(p3,t3)
s3 = steamTable.s_ph(p3,h3)
print('\nPoint 3 - LP turbine inlet conditions')
print(f"P3: {round(float(p3),1)} bar")
print(f"T3: {round(float(t3),1)} degC")
print(f"H3: {round(float(h3),1)} kJ/kg")
print(f"S3: {round(float(s3),3)} kJ/kg K")

#outlet of LPC
t4 = steamTable.tsat_p(p4)
h4 = wspHEXPANSIONPTPEFF(p3,t3,p4,eff_LPC)
x4 = steamTable.x_ph(p4,h4)
s4 = steamTable.s_ph(p4,h4)
print('\nPoint 4 - LP turbine exhaust conditions')
print(f"P4: {round(float(p4),4)} bar")
print(f"T4: {round(float(t4),1)} degC")
print(f"H4: {round(float(h4),1)} kJ/kg")
print(f"S4: {round(float(s4),3)} kJ/kg K")

#outlet of condenser
p5 = p4
h5 = steamTable.h_px(p5,0)
t5 = steamTable.tsat_p(p4)
s5 = steamTable.s_ph(p5,h5)
print('\nPoint 5 - Condenser outlet before pump')
print(f"P5: {round(float(p5),4)} bar")
print(f"T5: {round(float(t5),1)} degC")
print(f"H5: {round(float(h5),1)} kJ/kg")
print(f"S5: {round(float(s5),3)} kJ/kg K")

#percentage steam flow to seperator to reheat HP exhaust
a_sh = find_a_sh(x2,hw1,hw2,h1,h2,h3)
print('\nPoint X - percentage main steam flow to seperator')
print(f"a_sh : {round(float(a_sh*100),2)} %")

#putlet of CEP 1
h6 = wspHCOMPRESSIONPPEFF(p5,p2,eff_Pump)
s6 = steamTable.s_ph(p5,h6)

#inlet of CEP 2
h7 = (x2*h5)+((1-x2)*hw2)
t7 = steamTable.t_ph(p2,h7)
s7 = steamTable.s_ph(p5,h7)

#outlet of CEP 2
h8 = wspHCOMPRESSIONPTPEFF(p2,t7,p1,eff_Pump)
t8 = steamTable.t_ph(p1,h8)
s8 = steamTable.s_ph(p1,h8)

#inlet of feedpump
h9 = find_h9(a_sh,hw1,h8)
t9 = steamTable.t_ph(p1,h9)
s9 = steamTable.s_ph(p1,h9)

#outlet of feedpump
h10 = wspHCOMPRESSIONPTPEFF(p1,t9,p10,eff_Pump)
t10 = steamTable.t_ph(p10,h10)
s10 = steamTable.s_ph(p10,h10)
print('\nPoint 10 - Feedpump outlet')
print(f"P10: {round(float(p10),4)} bar")
print(f"T10: {round(float(t10),1)} degC")
print(f"H10: {round(float(h10),1)} kJ/kg")
print(f"S10: {round(float(s10),3)} kJ/kg K")

print('\nSummary')
#pump work
w_pump=((x2/100)*(h6-h5))+(h8-h7)+((1+(a_sh/100))*(h10-h9))

```

```python
#HPC work
w_HPC = 1*(h1-h2)
print(f"Work generated by HP turbine: {round(float(w_HPC),1)} kJ/kg")

#LPC work
w_LPC = x2*(h3-h4)
print(f"Work generated by LP turbine: {round(float(w_LPC),1)} kJ/kg")

#Specific work of SG
w_SG = (1+(a_sh))*(h1-h7)
print(f"Heat input by Steam Generator: {round(float(w_SG),1)} kJ/kg")

#cycle efficiency
eta_th = (w_HPC+w_LPC-w_pump)/w_SG
print(f"Thermal efficiency is: {round(float(eta_th*100),2)} %")

HRcycle = 3600*100/(eta_th*100)
print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")

font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('T-s Diagram - Rankine Nuclear Cycle')
plt.rc('font', **font)

plt.ylabel('Temperature (C)')
plt.xlabel('Entropy (s)')
plt.xlim(-2,10)
plt.ylim(0,600)

T = np.linspace(0, 373.945, 400) # range of temperatures
# saturated vapor and liquid entropy lines
svap = [s for s in [steamTable.sL_t(t) for t in T]]
sliq = [s for s in [steamTable.sV_t(t) for t in T]]

plt.plot(svap, T, 'b-', linewidth=2.0)
plt.plot(sliq, T, 'r-', linewidth=2.0)

plt.plot([s10, s1a, s1, s2, s2a, s3, s4, s5, s10],[t10, t1a, t1, t2, t2a, t3, t4, t5, t10], '
    black', linewidth=2.0)

plt.savefig('rankine_nuclear_cycle-TSdiagram.png')
```

E Revision History

15 Oct 2024 Simulation at initial release stage.

16 April 2025 Simulator BETA release v1.32.

- Turbine Hot start/Cold start run up sequence added.
- Control rod visual representation on screen now moves in 1% increments (previously it was in 10% steps).
- Steam generator draining rate has been reduced.
- Pressuriser draining/filling rate also reduced.
- Turbine cold start runup rate reduced (i.e. it now takes longer to reach synchronise speed).
- Primary coolant heating when in mode 5 or mode 4 is slowed down.

2 May 2025 Simulator BETA release v1.33

- Turbine lube oil (tank heater, cooling loop, lube pump, turning gear).
- Turbine CTRL oil.
- Turbine gland steam system.
- Turbine metal temperature.
- Primary coolant heating when in mode 5 or mode 4 is slowed down further. Approx. 12 minutes to 100 deg C and 12-20 minutes to design P and T.
- RCP spin up/down slower - approximately 2x.
- Turbine - prep - heating lube oil, starting lube oil, jacking oil, turning gear
- Seal steam manual start

11 May 2025 Simulator BETA release v1.34

- Turbine sequence page added (used for starting/stopping steam turbine, selecting AUTO/Manual runup, etc).
- Electrical page added (used to start/stop excitation and manually synchronise generator to grid).
- If turbine is COLD (<150 deg C rotor temperature) during startup the turbine and steam chest (ESV and CV valve bodies) will go through some warming steps before turbine starts.
- If turbine HOT (>150 deg C rotor temperature) these steps will be bypassed.
- Generator can now be manually synchronised to the electrical grid.
- Spray valve on the pressurizer can be shut down if reactor mode 4 or 5.

27 May 2025 Simulator BETA release v1.35

- Added main turbine bled steam system for feedwater heaters and running turbine driven feedpumps.
- Separated Condensate and feedwater systems onto two pages. Included feedwater heaters and direct control of electric and turbine driven feedwater pumps.
- Reduced turbine load increase/decrease rate.
- Reduced turbine speed run down rate after trip

9 June 2025 Simulator BETA release v1.36

- Added program About menu item.
- Changed opening about screen
- Improved trending - now looks much better.
- General screen tidy up.

25 July 2025 Simulator RELEASE CANDIDATE release v1.37

- bug removal.

30 July 2025 Simulator RELEASE CANDIDATE release v1.38

- compiled for Windows in addition to macOS.

F Known issues

A number of plant system do not work as well as I would like. They are listed below;

1. When program run on Windows computer, screen updates can be slow and can take a second or so to display complete image when new page selected.

2. Criticality Estimator is not fully functional. Currently Time since shutdown is not taken into account when calculating estimated boron concentration (so the potential effect of Xenon is ignored in calculation).

G Figures

List of Figures