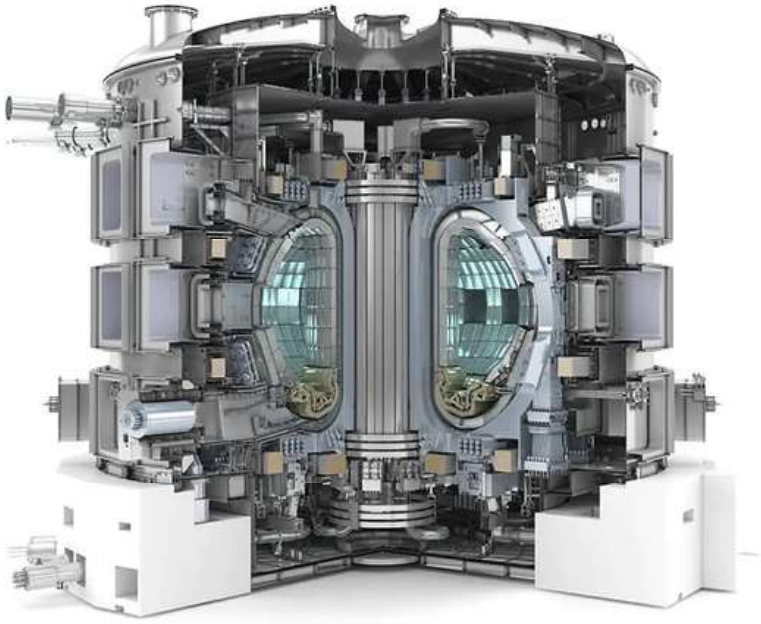
รายงานผลสัมฤทธิ์ภายใต้โครงการ

ITER RESEARCHER EXCHANGE PROGRAM 2025

หัวข้อ

MODELLING OF THE ISOTOPE SEPARATION SYSTEM





นางสาวนลิน บุญทองใหม่

การไฟฟ้าฝ่ายผลิตแห่งประเทศ

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ITER Organization

ประเทศฝรั่งเศส

Final Report

ITER Researcher Exchange Program 2025

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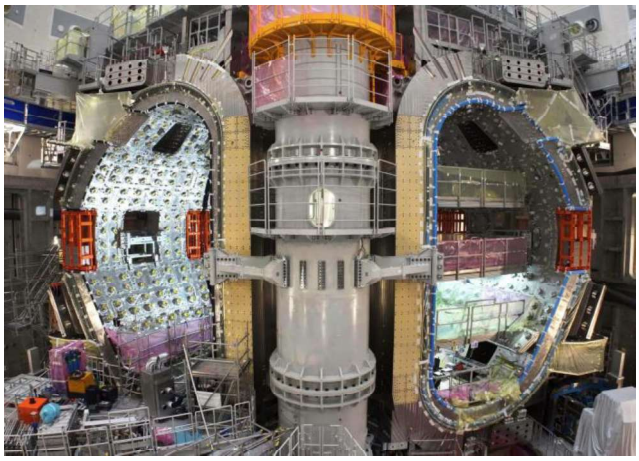
Executive Summary

This report presents an overview of ITER as an international experimental fusion facility and summarizes a two-month Visiting Researcher assignment. ITER integrates the tokamak, vacuum and cryogenic systems, plasma heating, fuel processing, isotope separation, water detritiation, and nuclear-safety systems. Together, these systems support deuterium-tritium plasma operation and the recovery and recycling of unused fuel.

The assignment was conducted within the Science & Integration Department, and Integrated Engineering Analysis framework. The first two weeks covered the Isotope Separation System and Aspen HYSYS training. A simplified helium reverse Brayton refrigeration cycle was modelled in steady-state and dynamic modes as preparation for studying the cryogenic refrigeration required for isotope separation.

The latter project focused on the Water Detritiation System using Dymola. The model represented steady-state analysis used to check hydraulic performance and dynamic simulation used to study tank levels and flow control. Radioactive substances were also tracked as water mixed and transferred between tanks.

A state machine was developed to control the sequence of operation. Transitions were based on tank levels and time delays. This work demonstrated how dynamic modelling can support component sizing, control-logic verification, operating-sequence development, and preparation for commissioning



Contruction and assembly of the ITER Tokamak within the Tokamak Complex

Taylor, A., *Photos: Building the World's Largest Fusion Reactor*, *The Atlantic*, June 2026

1. ABOUT ITER

1.1 Overview

ITER or *International Thermonuclear Experimental Reactor* is an international research project designed to demonstrate the scientific and technological feasibility of fusion energy at a reactor-relevant scale. The facility is being built as a large tokamak, in which magnetic fields confine a very hot plasma formed from deuterium and tritium. These hydrogen isotopes can fuse to produce helium and neutrons, releasing energy. ITER will not generate electricity for the grid. Instead, it will provide scientific evidence and engineering experience for the development of future fusion power plants [1].

ITER combines the tokamak with superconducting magnets, a vacuum vessel, cryostat, blanket, divertor, heating and current-drive systems, fuel-cycle equipment, diagnostics, cooling water, cryogenics, electrical power supplies, control systems and nuclear-safety systems. These systems must operate together as one integrated nuclear facility under French nuclear-safety regulations.



ITER headquarters at Saint-Paul-lez-Durance, France

1.2 Members and Contributions

The ITER collaboration comprises seven Members [1]: China, European Union, India, Japan, Republic of Korea, Russian Federation and United States.

Europe is the host Member and is responsible for approximately 45.6 percent of the construction contribution. China, India, Japan, Korea, Russia and the United States each contribute approximately 9.1 percent. Most contributions are provided in kind, meaning that the Members manufacture and deliver comp leted components, systems and buildings rather than providing only direct funding.



Member Countries

The principal contributions can be summarized as follows:

European Union: Europe supplies the ITER buildings and technical facilities. Europe also manufactures five of the nine vacuum-vessel sectors, ten toroidal-field coils, several poloidal-field coils and parts of the blanket and divertor systems.

China: China contributes to the magnet system, including poloidal-field coil PF6, magnet feeders and power-conversion equipment. China also participates in the blanket system.

India: India supplies the cryostat, including its large base and other sections. India also shares responsibility with the United States for cooling-water systems.

Japan: Japan contributes toroidal-field coils and shares responsibility for the central solenoid with the United States. Japan also contributes to divertor manufacturing and testing.

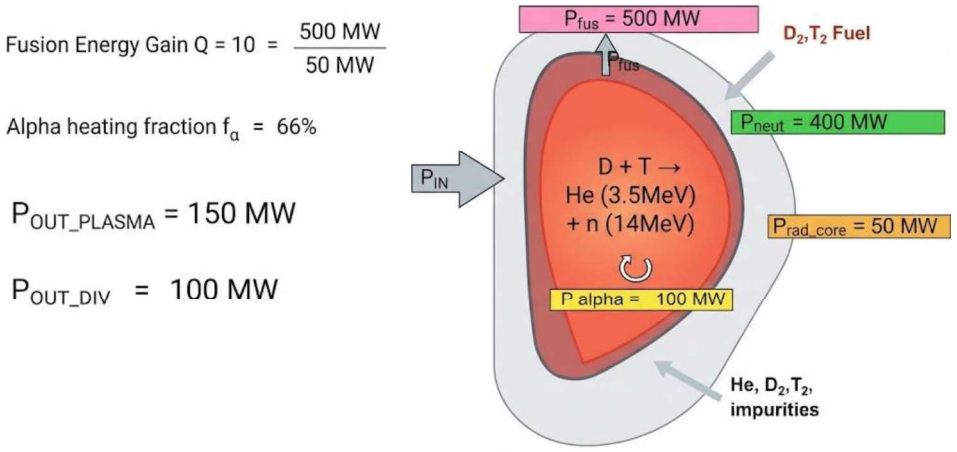
Republic of Korea: Korea manufactures four of the nine vacuum-vessel sectors, toroidal-field coils and parts of the blanket system.

Russian Federation: Russia supplies major magnet components, including poloidal-field coil PF1, and participates in the blanket and divertor systems.

United States: The United States supplies the central-solenoid modules, working with Japan on the overall central-solenoid system.

1.3 Scientific and engineering objectives

- Demonstrate high fusion gain. The principal operating target is $Q \geq 10$, where Q is the ratio of fusion power produced to external heating power supplied to the plasma. The reference scenario is approximately 500 MW of fusion power from 50 MW of external plasma-heating power [1].



Plasma Burn Power Balance

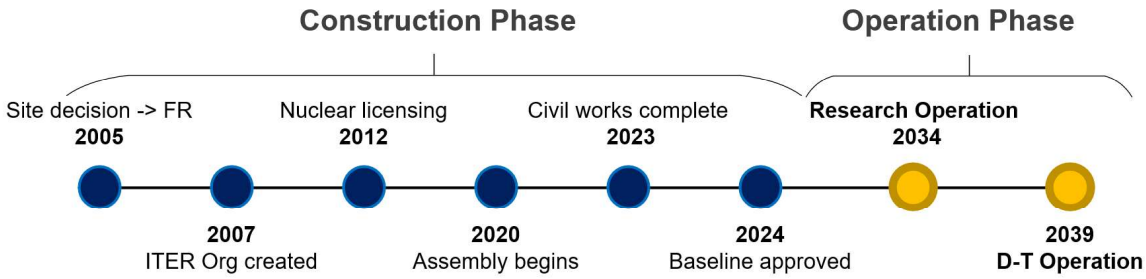
- Test integrated operation of superconducting magnets, heating, fuelling, vacuum, diagnostics, control, cooling and power systems.
- Test tritium-fuel-cycle technologies and Test Blanket Module concepts relevant to future tritium breeding and extraction.
- Demonstrate safe operation, confinement of radioactive material, radiation protection, and maintainable plant arrangements.

1.4 Timelines

ITER's construction phase runs from the 2005 decision to site the project in France through roughly 2024. Key early milestones include the 2006 signature of the ITER Agreement, formal creation of the ITER Organization in 2007, and land clearing that ran 2007–2009. Component fabrication began in 2008, followed by ground support structure and seismic foundation work for the Tokamak Complex from 2010–2014, with a nuclear licensing milestone in 2012 when ITER became

a Basic Nuclear Installation under French law. Plant and auxiliary building construction continued from 2010 - 2024, the largest components started being transported along the ITER Itinerary from 2015 onward, and machine assembly began in 2020 [1].

Cryostat closure is planned for 2033, followed by integrated commissioning in 2033–2034, and the Start of Research Operation in 2034 which is the first operational phase, using hydrogen and deuterium-deuterium plasmas. Full magnetic energy follows in 2036, and the Start of Deuterium-Tritium Operation in 2039. Relative to the 2016 reference plan, this new baseline represents a three-year delay for reaching full magnetic energy and a four-year delay for starting deuterium-tritium operation. The project is now working out detailed phase and gate milestones for project control.



Project Progress in Milestones

2. ITER INTEGRATED SYSTEM

2.1 Fusion and Fuelling

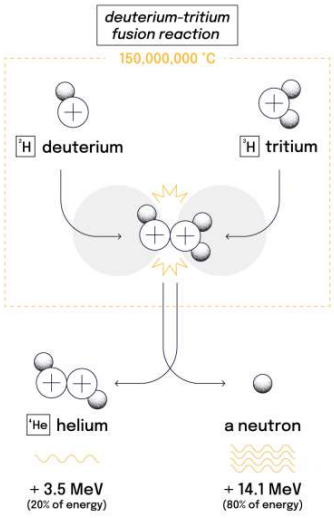
A tokamak uses strong magnetic fields to confine plasma inside a toroidal, or doughnut-shaped, vacuum vessel. ITER will initially use hydrogen and deuterium plasmas for machine commissioning and the development of plasma-control methods. The main fusion phase will use deuterium and tritium as fuel. Inside the vacuum vessel, the fuel is heated to approximately 100 to 150 million °C and ionized into plasma. The deuterium and tritium nuclei can then fuse according to the following reaction:

The basic fusion reaction is:

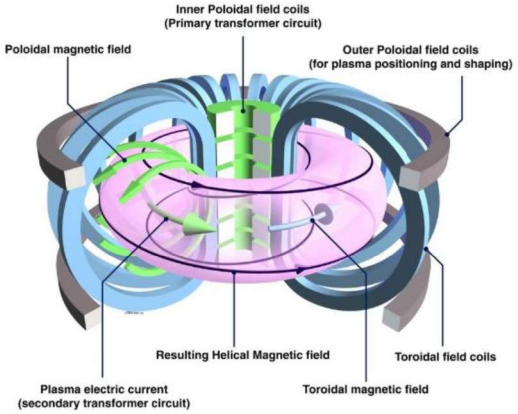
$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{T} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n} + \mathrm{Energy}$$

The helium nucleus remains in the plasma and contributes to further plasma heating, while the high-energy neutron transfers most of its energy to the surrounding components. Because only a small fraction of the injected fuel is consumed during each pass through the plasma, the unburned fuel is continuously removed, purified, separated and returned for reuse through ITER's closed fuel cycle.

Different hydrogen isotopes are used at different stages of ITER operation. Protium (H_2), the ordinary form of hydrogen, is used for early non-nuclear plasma operation, system testing and wall conditioning. Deuterium (D_2) is a stable hydrogen isotope used for later plasma experiments, neutral-beam heating and, together with tritium, fusion operation. Tritium (T_2) is radioactive and is combined with deuterium during the main fusion phase [2].



Schematic of the D-T Reaction



Magnetic Confinement Design of a Tokamak

ITER Organization, *ITER in a Few Lines*, https://www.iter.org/few-lines

Magnetic confinement alone cannot raise the plasma to fusion temperature. ITER therefore uses external heating and current-drive systems, including neutral beam injection, electron cyclotron heating, and ion cyclotron heating. The neutral beam system uses a separate supply of D_2, with H_2 used under some operating conditions. Fuel is supplied to the plasma by gas injection and solid pellet injection. At the

same time, unburned fuel, helium ash and impurities are exhausted through the divertor and transferred to the Tritium Plant for treatment and recycling [2].

2.2 Vacuum and Plasma Exhaust

The vacuum system first establishes a clean, low-pressure environment inside the vacuum vessel. This condition is important because residual gases and impurities can dilute the fuel and increase heat loss from the plasma.

During plasma operation, the vacuum system also provides continuous exhaust pumping. The divertor directs unburned deuterium and tritium, helium ash and impurities toward the torus cryopumps. The cryopumps capture these gases on very cold surfaces. The captured gases are periodically released during cryopump regeneration and transferred through the roughing pumps to the Tokamak Exhaust Processing System.



ITER Cryopump after acceptance tests

ITER Organization, *First Cryopump Passes All Tests*, ITER Newsline, 21 May 2024

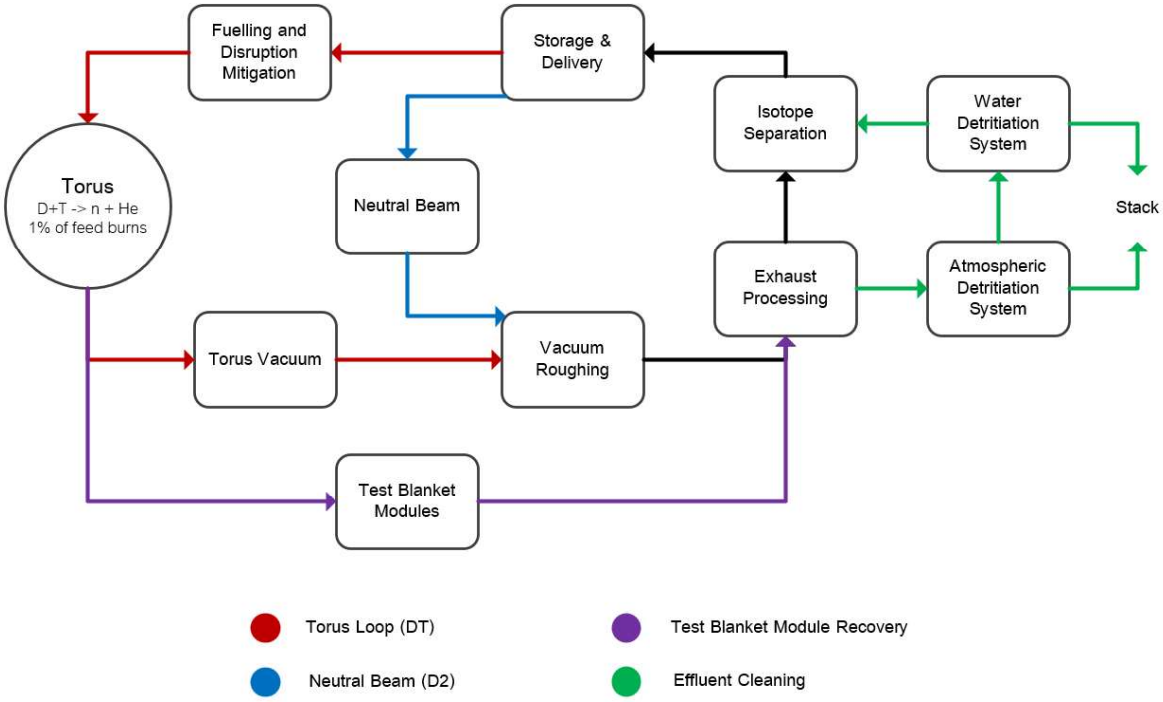
The exhaust is not a clean D-T stream. It may contain different hydrogen isotopes, helium, water, hydrocarbons, nitrogen, and other impurities. Tokamak Exhaust Processing separates the hydrogen isotopes from these impurities, recovers tritium from tritiated water and hydrocarbons, and sends the purified hydrogen-isotope stream for further separation or storage [3].

2.3 Fuel Recycling

After exhaust processing, the gas can still contain a mixture of H_2, D_2, T_2, HD, HT and DT. These substances have similar chemical properties because they are all

forms of hydrogen. Their small physical differences must therefore be used for separation.

The Isotope Separation System uses cryogenic distillation to separate hydrogen isotopes. The system recovers tritium from water-detritiation streams, recovers deuterium from neutral-beam exhaust, and separates the tokamak exhaust into suitable deuterium- and tritium-rich products. These products are returned to the Storage and Delivery System and reused for tokamak fuelling or neutral-beam operation.



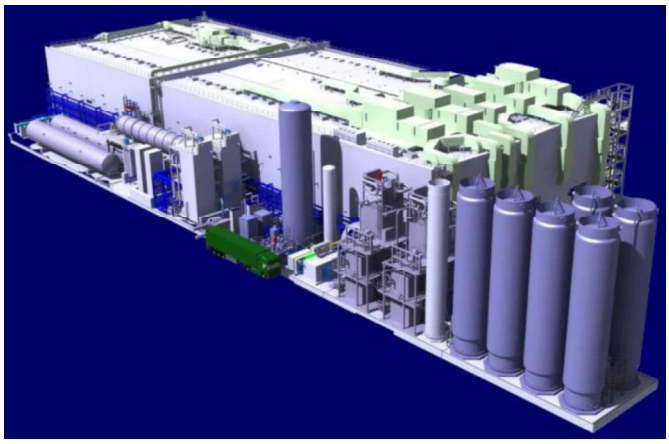
ITER Fuelling Cycle

Streams containing tritium that are not suitable for direct recycling are processed by the Detritiation System or Water Detritiation System (WDS). These systems recover tritium from process gases, room atmospheres and tritiated water. The recovered tritium is returned to the fuel cycle, while treated streams are managed under controlled conditions [4].

2.4 Cryostat and Cryogenic System

The superconducting magnets and cryopumps must operate at very low temperatures. The cryogenic system therefore provides cooling at several

temperature levels. Helium at approximately 4 K is used for the superconducting magnets and cryopumps, helium at approximately 50 K cools the current leads, and helium at approximately 80 K cools the thermal shields.



ITER Cryoplant

ITER Organization, "Cryoplant," ITER Project Construction Archives

The cryogenic system consists mainly of the cryoplant and cryodistribution system. The cryoplant produces, stores, recovers and purifies cold helium and nitrogen. The cryodistribution system transfers the cooling capacity through cryolines and cold boxes to the magnets, cryopumps and thermal shields.

The cryostat is the large enclosure surrounding the vacuum vessel and magnet system. Its vacuum reduces heat transfer from the ambient environment to the cold components. Thermal shields inside the cryostat intercept thermal radiation before it reaches the magnets. The cryostat vacuum and plasma vacuum are separate systems: the plasma vacuum provides the clean operating environment inside the vacuum vessel, while the cryostat vacuum provides thermal insulation for the superconducting equipment.



ITER Cryostat (16,000 m^3, 30 m high) is one of the world's largest vacuum chambers

ITER Organization, "Keeping it cold," *ITER Magazine*, Feb. 17, 2015

The cryogenic system also supplies the cryopumps used by the vacuum system. Therefore, vacuum performance depends directly on cryogenic availability. Before the magnets are cooled, the cryopumps are cooled first so that the vacuum vessel and cryostat can be evacuated and tested. The magnet system and thermal shields are then cooled in stages to their operating temperatures [5].

2.5 Overall Integration

Fusion energy, external heating, and electrical equipment produce large heat loads. The Tokamak Cooling Water System removes heat from the vacuum vessel, blanket, divertor, in-vessel coils, and neutral-beam injectors. Secondary cooling systems transfer this heat to the Heat Rejection System, which finally rejects to the environment.

In summary, ITER operates as one connected process. The fuelling systems supply deuterium and tritium to the tokamak. The heating systems raise fuel to plasma conditions, while the magnets confine and control the plasma. The vacuum system maintains plasma purity and removes the exhaust. The tritium plant cleans the exhaust, separates the isotopes, and returns usable fuel to storage. At the same time, the cryogenic system keeps the magnets and cryopumps cold, the cryostat limits heat transfer, and the cooling-water system removes heat from the machine.

3. SID, CID AND IEA

Within the ITER Organization, engineering and scientific integration are organized through several hierarchical levels. For the work discussed in this report, the relevant organizational chain is Science & Integration Department (SID) → Central Integration Division (CID) → Integrated Engineering Analysis (IEA). The current ITER organizational chart identifies the same principal functions within SID's Central Integration organization.

The Science & Integration Department (SID) is responsible for ITER's scientific and technical integration framework. Its responsibilities include development of the ITER Research Plan, coordination of scientific activities, establishment of system architecture and functional requirements, configuration control, and technical integration throughout the development and operation of the ITER facility.

Within SID, the Central Integration Division (CID) serves as the overall system architect and design integrator. CID establishes and maintains project and system requirements, engineering processes, integration methodologies, and technical standards. Its purpose is to ensure that many ITER systems, structures, and components are developed consistently and operate together as an integrated plant.

Within this integration framework, Integrated Engineering Analysis (IEA) provides specialized engineering-analysis capabilities. ITER describes IEA's activities including the definition and assessment of different types of loads, such as seismic, electromagnetic, and transient thermal loads. IEA also provides guidance on engineering-analysis methodology and best practices and supports designers in addressing specific analysis problems.

During my two-month assignment at ITER as a Visiting Researcher, I worked under the supervision of Dr. Andrey Ocharov, a System Engineer. In ITER's matrix organization, my work was associated with Integrated Engineering Analysis (IEA) through the SID-CID structure, while my supervisor also belonged to the Engineering Services Department (ESD). This matrix arrangement allows engineering expertise and resources from ESD to support

technical activities across different parts of the ITER organization, enabling close collaboration between system integration and specialized engineering functions.

4. PROGRESS REPORT

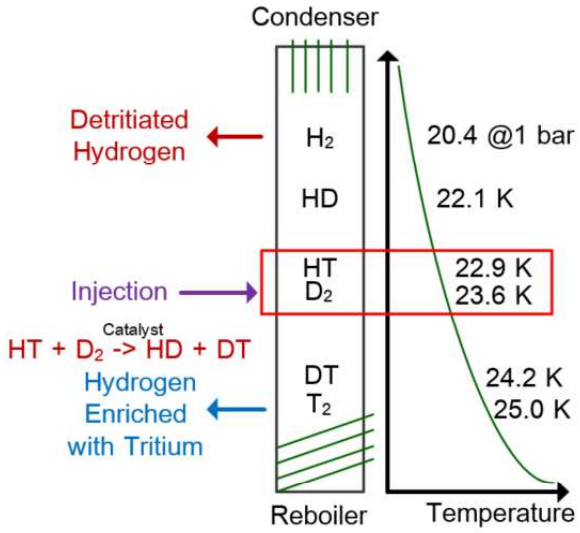
4.1 Isotope Separation System and Initial Aspen HYSYS Training

4.1.1 Isotope Separation System

The Isotope Separation System (ISS) is part of ITER's closed fuel cycle. During plasma operation, hydrogen isotopes are supplied separately but leave the tokamak and neutral-beam systems as mixed gases. After non-hydrogen impurities are removed by the Tokamak Exhaust Processing System, ISS separates the remaining mixture into protium-, deuterium-, and tritium-rich product streams. The recovered products are then returned to the Storage and Delivery System or Water Detritiation System for reuse.

As previously mentioned in item 2.3, ISS mainly uses cryogenic distillation, based on the small differences in boiling points among H_2, HD, HT, D_2, DT, and T_2. The lighter and more volatile components move toward the top of the distillation columns, while the heavier components, particularly T_2, tend to collect near the bottom. The system uses six cryogenic distillation columns. Columns CD1 to CD4 produce isotope streams for recycling, while CD5 and CD6 remove residual tritium from excess protium and deuterium before controlled discharge.

The distillation columns require cryogenic helium for cooling. The ISS Helium Refrigerator System compresses helium, cools it through heat exchange, and then expands it through a turbine to produce cold helium at approximately 16 K. The helium is distributed to the column condensers and feed coolers before returning to the refrigerator [4].

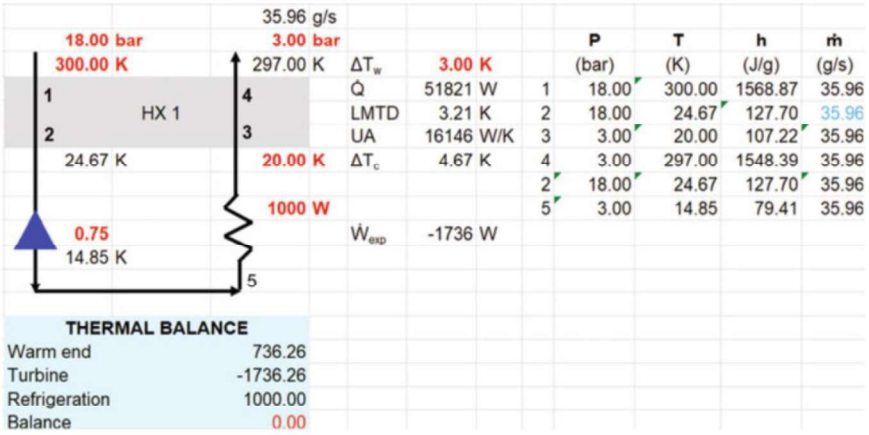


A cryogenic distillation column, or CD column, separates the six molecular forms of hydrogen according to their different boiling temperature, found in the ITER fuel cycle

4.1.2 Initial Two-week Training

During the first two weeks, I studied the main functions and process arrangement of ISS and became familiar with Aspen HYSYS. Aspen HYSYS is widely used in the energy and process industries to model fluid properties, process equipment, heat and material balances, and complete plant systems. It supports both steady-state design and dynamic studies of control response, start-up, shutdown, and other transient conditions. For ITER, Aspen HYSYS was evaluated for modelling the low-temperature helium refrigeration and distribution loops supporting the ISS.

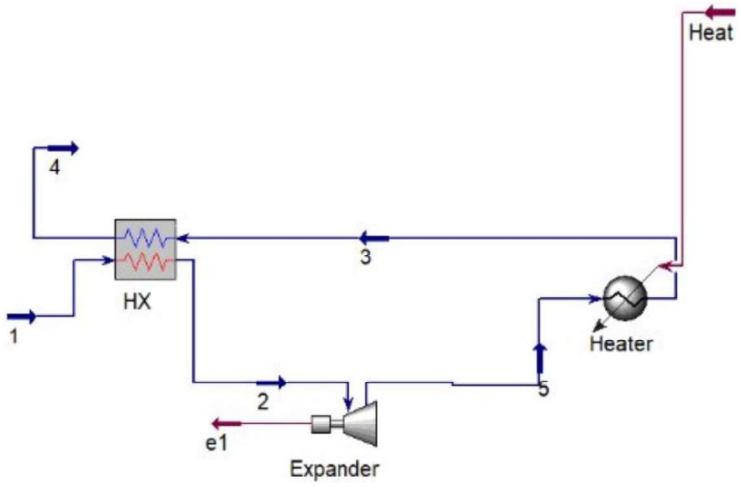
The initial exercise was based on the reverse Brayton refrigeration cycle in Section 3.4 of the book *Cryogenic Helium Refrigeration for Middle and Large Powers* [6]. This refrigeration cycle transfers heat from a low-temperature region to a warmer environment by using external work. Its main processes are helium compression, heat rejection, cooling through heat exchangers, and expansion through a turbine. In real process, the ISS cryogenic distillation columns require cold helium to cool the feed streams and condense hydrogen isotopes at approximately 20–25 K.



Calculation of a Brayton pure refrigeration cycle

The given conditions included a high pressure of 18 bar, a low pressure of 3 bar, a warm inlet temperature of 300 K, a refrigeration load of 1,000 W, and a maximum cold-side temperature of 20 K. The turbine isentropic efficiency was set to 0.75, while the heat exchanger was defined using its warm-end temperature difference and overall heat-transfer conductance [7].

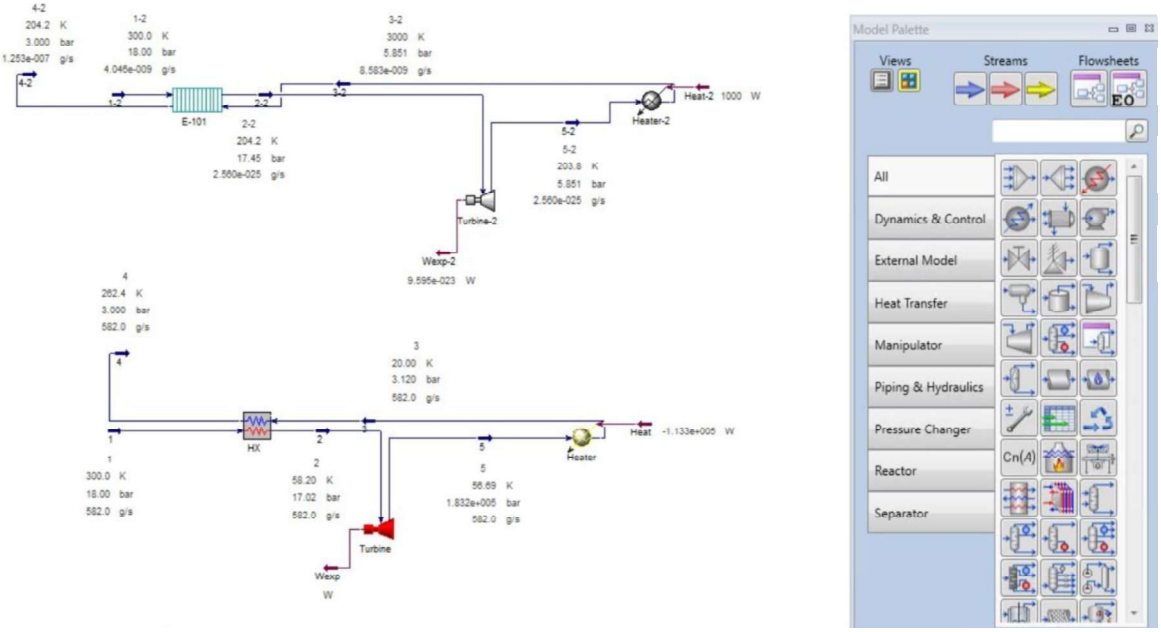
The steady-state model was used to determine the helium mass flow rate and calculate the outlet temperatures, turbine work, heater duty, heat-exchanger (plate type) duty, overall heat transfer coefficient, and log mean temperature difference (LMTD).



Aspen Hysys model for a steady state thermal balance

The same process was then prepared in dynamic mode to observe changes in temperature, pressure, and flow with time. Unlike the steady-state model, the

dynamic model requires equipment sizing, pressure-flow relations, and suitable boundary specifications. This exercise provided initial experience in both steady-state and transient simulation before developing the larger ISS helium refrigeration model, with a target cooling duty of approximately 2,000 W at 18 K, including the associated distribution loops.



Aspen Hysys screen showing dynamic model execution and simulation tools

After the first two weeks, several limitations of Aspen HYSYS were identified. Developing the transient model requires detailed, component-level configuration and extensive manual input. However, the model did not provide results comparable to those obtained from Aspen Plus, which is already used by ITER. Therefore, considering the limited duration of the assignment, my advisor and the Head of IEA recommended changing the modelling software and research topic to provide a more practical and valuable learning experience.

4.2 Dynamic Modelling of the Water Detritiation System Using Dymola

Following the initial two-week study using Aspen HYSYS, the remaining period of my Visiting Researcher assignment focused on the Water Detritiation System (WDS). The main task was to develop a process model of the WDS water

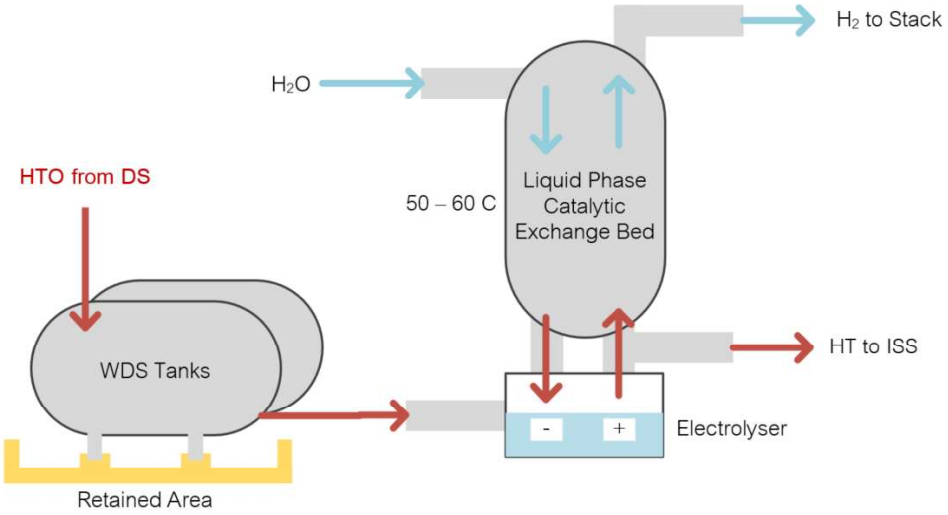
distribution network using Dymola and the Modelica modelling language. The work covered equipment sizing, steady-state verification, dynamic simulation, flow control and tracking of radioactive substances throughout the system.

4.2.1 Water Detritiation System

The WDS is part of the ITER Tritium Plant. Its main purpose is to receive and process tritiated water produced by the atmospheric detritiation systems and other ITER systems. The WDS provides an important barrier for tritium confinement by recovering tritium from water before treated streams are reused or released under controlled conditions. The main treatment process is based on Combined Electrolysis Catalytic Exchange (CECE) technology. Tritiated water is converted into gaseous hydrogen by electrolysis, after which isotopic exchange takes place in a Liquid Phase Catalytic Exchange column. Part of the hydrogen isotope stream is also transferred to the ISS system for further separation and recovery [4].

The water distribution network includes effluent tanks, feed tanks, batch tanks, emergency tanks, a drain tank, connecting pipes, isolation and control valves, and feeding, sampling, effluent and recycle pumps. The tanks receive water from different systems and at different activity levels. The water may then be stored, mixed, sampled, transferred for purification or sent to the main WDS process. Emergency tanks provide additional capacity for abnormal inflow or tank-overfilling conditions.

The WDS tanks had already been sized and installed, while the connecting piping, pumps and valves remained part of the continuing system-design work. The approved tank procurement included water holding tanks, high-level holding tanks, feeding tanks and emergency tanks.



The Combined Electrolysis and Catalytic Exchange (CECE) process, converts tritium contained in water (HTO) into gaseous tritium (HT) so it can be sent to the ISS.

The design approach is different from that of a conventional water-transfer system in a power plant. The transported water may contain tritium and other radioactive substances, so the design must consider nuclear-safety classifications, confinement, seismic requirements, traceability, leak prevention, material selection and controlled operating sequences. The applicable design documents refer to ITER nuclear-safety requirements, the ITER Tritium Handbook, seismic requirements and recognized mechanical design codes.

4.2.2 Dymola and Modelica

Dymola is a modelling and simulation environment for integrated engineering systems. It can combine fluid, thermal, mechanical, electrical and control-system models within one simulation. Dymola uses Modelica, an equation-based and object-oriented modelling language in which physical components are represented by mathematical equations and connected according to their actual engineering relationships.

This modelling method is suitable for dynamic simulation because pressure, flow, tank level, valve position, pump operation and fluid composition can all change with time. A component model can represent an individual tank, pipe, valve or pump, while several component models can be connected to form a subsystem and finally the complete plant model. Dymola can therefore be used to study interactions between process equipment and control logic under normal and transient conditions.

```
model FourTanks6
package Medium =
    Modelica.Media.CompressibleLiquids.LinearWater_pT_Ambient(extraPropertiesNames={"T2","D2","ACP"},C_default={2E-3,2E-3,2E-3},C_nominal={2E-3,2E-3,2E-3});
package Medium2 = Modelica.Media.CompressibleLiquids.LinearWater_pT_Ambient(extraPropertiesNames={"T2","D2","ACP"},C_default={0.2E-3,0.5E-3,0.7E-3},C_nominal={0.2E-3,0.5E-3,0.7E-3})
                                                                                                                                                    a ;
  inner Modelica.Fluid.System system(energyDynamics=Modelica.Fluid.Types.Dynamics.FixedInitial)
    a ;
  Modelica.Fluid.Vessels.OpenTank Efftank2(
    level_start=0.2*Efftank2.height,
    height=3.5,
    crossArea=1.92,
    portsData={Modelica.Fluid.Vessels.BaseClasses.VesselPortsData(diameter=0.07, height=3.2),Modelica.Fluid.Vessels.BaseClasses.VesselPortsData(diameter=0.1, height=3.5),
        Modelica.Fluid.Vessels.BaseClasses.VesselPortsData(diameter=0.1, height=0),Modelica.Fluid.Vessels.BaseClasses.VesselPortsData(diameter=0.1, height=3.5)},
    redeclare package Medium = Medium,
    nPorts=4) a ;
  Modelica.Fluid.Vessels.OpenTank Efftank1(
    level_start=0.2*Efftank1.height,
    height=3.5,
    crossArea=1.92,
    portsData={Modelica.Fluid.Vessels.BaseClasses.VesselPortsData(diameter=0.1, height=3.5),Modelica.Fluid.Vessels.BaseClasses.VesselPortsData(diameter=0.1, height=0),
        Modelica.Fluid.Vessels.BaseClasses.VesselPortsData(diameter=0.07, height=3.2),Modelica.Fluid.Vessels.BaseClasses.VesselPortsData(diameter=0.1, height=3.5)},
    redeclare package Medium = Medium,
    nPorts=4) a ;
```

Modelica language in Dymola

When developing a Modelica model, the modeller must understand both the physical system and the equations used by each component. Correct boundary conditions, initial values, pressure-loss relations, equipment parameters and control logic are required for the model to solve reliably. A large system may also become difficult to debug because a problem in one component or connection can prevent the whole model from converging.

4.2.3 Scope of My Modelling Project

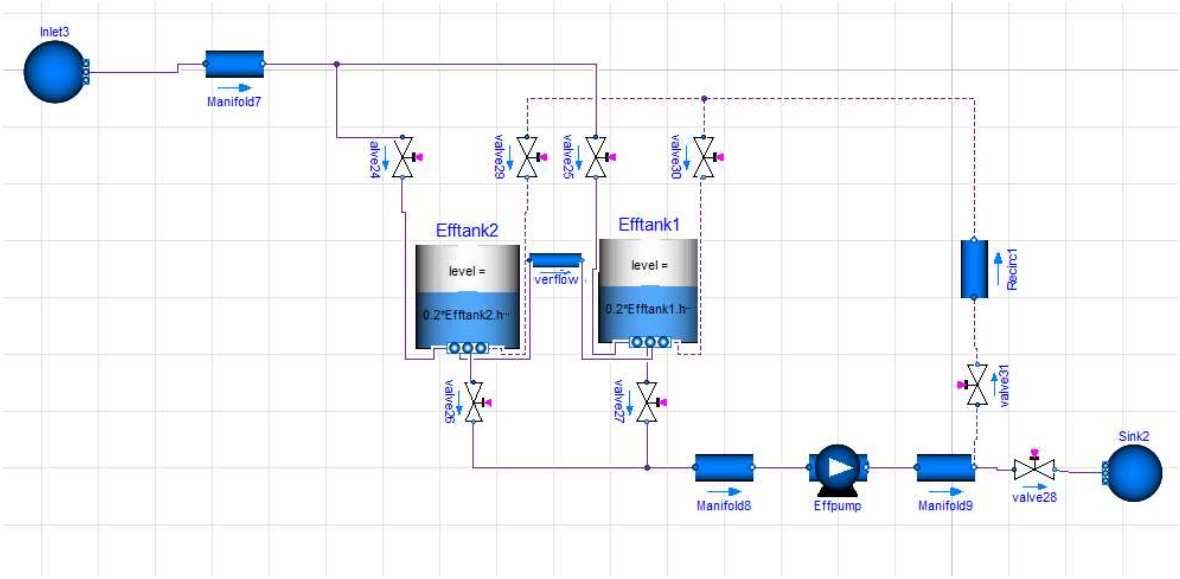
My project focused on the WDS tank, water distribution system and mass-balance scheme. The network includes several flow paths for continuous and batch inflows, purification, sampling, recycling and transfer to the main processing system. Different operating scenarios use different tank combinations and flow routes.

The first task was to define the hydraulic basis and size the main transfer equipment. This included:

- Establishing the required flow rates for each operating route

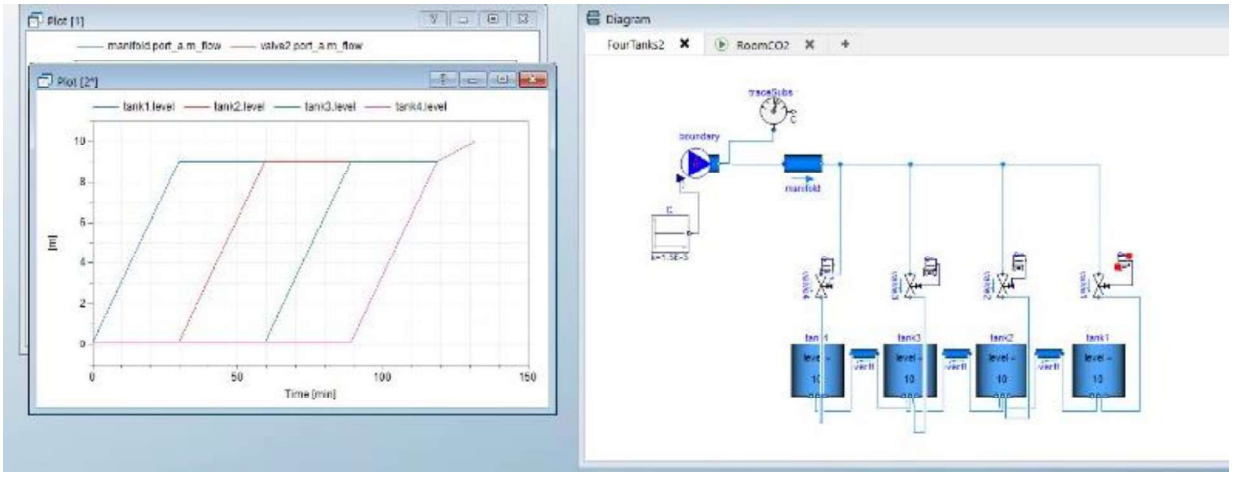
- Defining pipe sizes and pressure losses
- Selecting suitable valve parameters
- Determining pump flow and head requirements
- Checking available suction pressure and pump cavitation margin
- Confirming that each tank could be filled, drained, sampled and transferred as required

After the equipment parameters were established, a steady-state model was prepared to confirm that the selected pipes, valves and pumps could deliver the required flow rates. This stage was used to check the overall hydraulic balance, pressure distribution, pump operating conditions and consistency of the flow paths before introducing time-dependent operation.



Dymola model of the effluent storage and transfer system

The model was then converted into a dynamic simulation. The purpose was to verify that water could be transferred between tanks in a controlled manner and that the system responded correctly when pumps started or stopped and valves opened or closed. The dynamic model was also used to check tank-level changes, flow stability, transfer time, valve sequencing and the possibility of low pump-suction pressure or cavitation during transient operation.



Water level in each tank as a function of time during the simulation period

4.2.4 Radioactive-Substance Tracking

An important part of the project was the tracking of radioactive and hydrogen-isotope content as water entered, mixed and transferred between tanks. The model was intended to follow components identified in the project model, including ACP (Activated Corrosion Product), D_2 and T_2, together with the total water inventory.

When streams with different concentrations entered the same tank, the model calculated the resulting mixed concentration based on the incoming mass and the existing tank inventory. The updated composition was then carried with the outlet stream to the next tank or process route. This made it possible to follow how radioactive content moved through the system under different transfer scenarios.

The tracking function was particularly important before any stream was routed toward an environmental discharge path. The model needed to preserve the material balance and provide the calculated composition after mixing, sampling, recycling and transfer.

4.3 State Machine

4.3.1 State Machine and Its Importance

A state machine is a control model that divides an operating process into a set of defined states. Each state represents one operating condition, such as Start, Filling, Recirculation, Holding, or Draining. The model changes from one state to another only when a specified transition condition is satisfied. These conditions may be based on process measurements, logical signals, or time delays.

In Modelica, blocks connected by transitions form a state machine, with one block defined as the initial state. A transition may occur immediately when its condition becomes true or may be delayed until the next control step. State-machine models can also include priorities, reset functions, synchronized operations, and parallel sequences [8].

For a system engineer, a state machine provides a clear description of how the plant should operate before commissioning. It converts the operating philosophy into a testable sequence and identifies the required conditions for starting, stopping, filling, holding, recirculating and draining the system. It also defines the required valve positions, pump commands, level limits and waiting periods for each step.

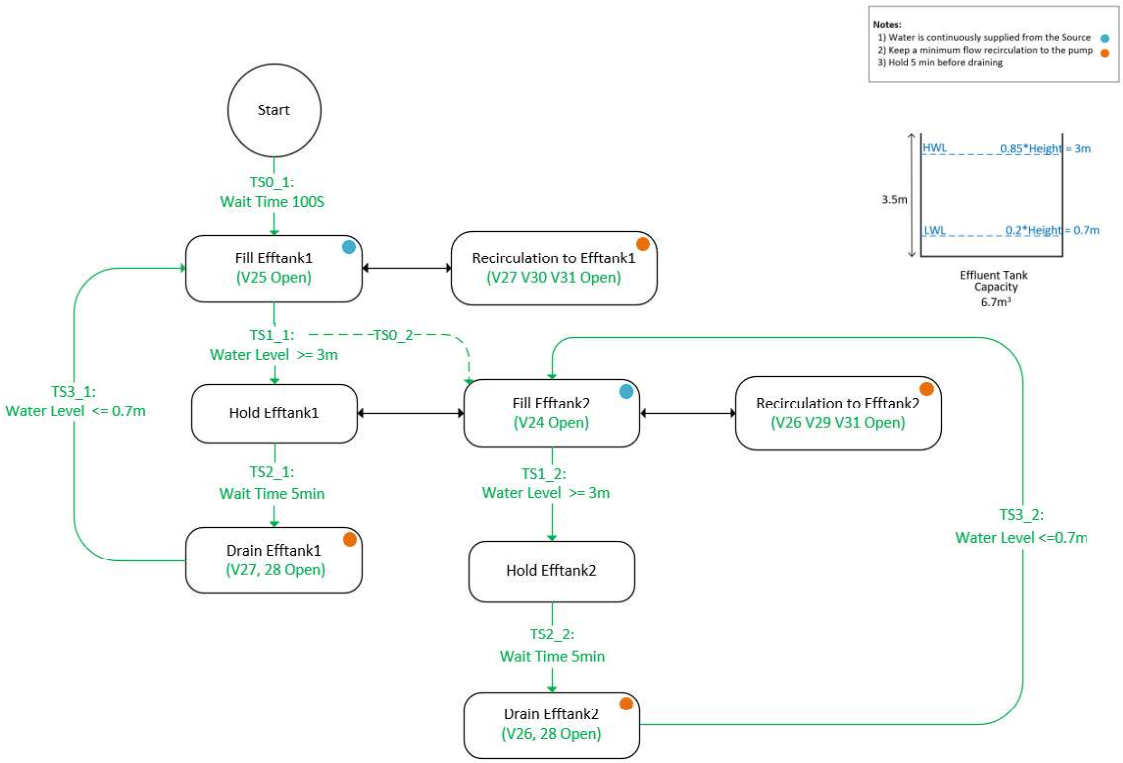
The state-machine model can be connected to the dynamic physical model so that control commands act directly on the simulated valves, pumps, tanks and piping. This allows the proposed operating sequence to be tested before it is applied to the actual plant. The model can also support future operator training by showing the current operating state, the active equipment and the condition required for the next transition. However, the simulation should be treated as an engineering verification and training tool. The final operating logic must still be reviewed against the approved control philosophy, safety requirements and commissioning procedures.

4.3.1 Application to the WDS Model

For my WDS model, the state machine was applied to the operation of two effluent tanks. The sequence was developed to maintain continuous receipt of incoming water while allowing each tank to pass through filling, holding and draining operations. A recirculation path was included so that water could continue circulating in the pipeline when the normal filling path was not available.

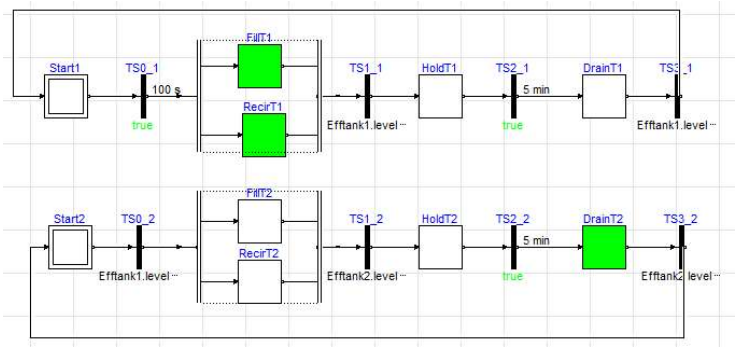
The main operating states were:

- Start: The model remains in the initial state for a defined start-up delay before water transfer begins.
- Fill Effluent Tank 1: The inlet path to Tank 1 is opened, and the tank receives water continuously.
- Recirculation to Tank 1: The associated valves establish a recirculation path to maintain water movement in the line.
- Hold Tank 1: When Tank 1 reaches the high-level condition, filling stops and the tank remains in a holding period.
- Drain Tank 1: After the specified holding time, the outlet path opens and Tank 1 is drained.
- Fill, Recirculate, Hold and Drain Tank 2: The same sequence is applied to Tank 2, allowing the tanks to operate alternately.



Control Logic for alternating operation of the two effluent tanks

The sequence begins after a 100-second start delay. During filling, the selected tank inlet valve is open. When the water level reaches approximately 3 m, the state machine changes from filling to holding. The holding period is set to 5 minutes, after which the corresponding drain valves open. When the water level decreases to approximately 0.7 m, the draining step ends and the sequence returns to filling.



State Machine

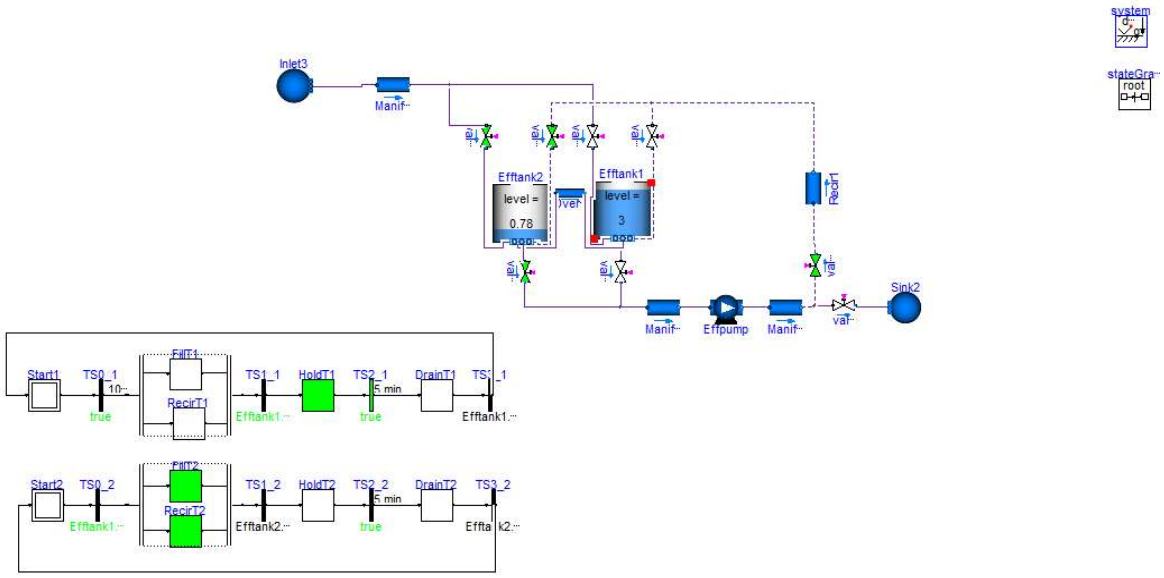
An important requirement was that a tank must not continue filling while the same tank is being drained. Therefore, the filling valve is closed before the drain state becomes active. At the same time, the second tank or the recirculation path must

remain available so that the incoming water does not create an uncontrolled interruption or accumulation in the upstream line.

The state transitions were based on two main types of conditions:

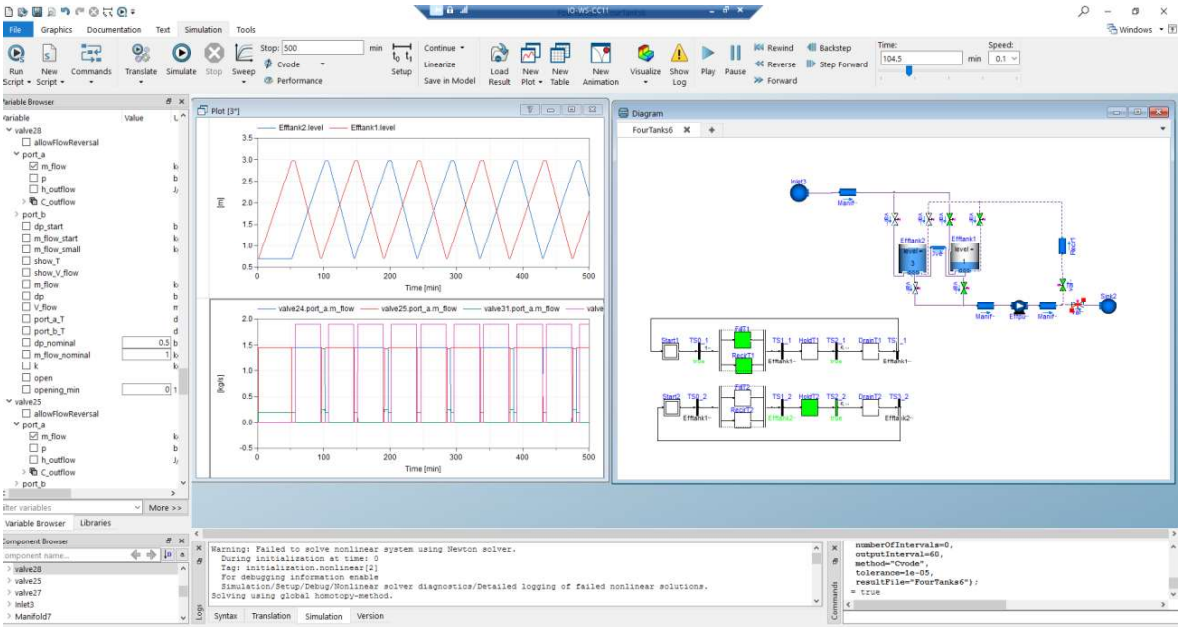
- Level-based transitions: Tank level determines the change from filling to holding and from draining back to filling.
- Time-based transitions: Defined delays are used before initial filling and between holding and draining.

The Modelica implementation links each active state to the required valve commands. For example, the filling state opens the selected inlet valve, the recirculation state opens the designated recirculation valves, and the draining state opens the tank outlet and common discharge valves. Only the commands associated with the active state are applied to the fluid model.



Integration of the state machine with the transient Dymola model

The state machine was connected to the Dymola model containing the two effluent tanks, manifolds, piping, valves and effluent pump. The simulation was then used to observe tank levels and confirm that the active state changed according to the defined level and time conditions.



The simulation results show the water level profile and radioactive tracer behavior during the state machine controlled and transient operation

Overall, the state-machine model provided a structured connection between the WDS operating philosophy and the dynamic hydraulic model. It enabled verification of the tank sequence, recirculation path, valve operation, filling interruption during draining and time-delayed transitions before plant commissioning. This approach can support the preparation of control logic and operator procedures by showing how the physical system responds to each operating command.

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