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A LAYOUT OF THE TRITIUM PLANT SUBSYSTEMS FOR THE EUROPEAN DEMONSTRATION FUSION POWER PLANT

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Master Thesis for

Mr. Federico Miguel Constantin (Matriculation # 1565426)

A lay-out of the tritium plant sub-systems for the European demonstration fusion power plant

Future fusion power plants will be based on the fusion of the hydrogen isotopes deuterium and tritium. The fuel has to be injected in surplus in order to benefit from increased reactivity. The exhausted gas then has to be processed in the fuel cycle to purify it from the helium ash and other impurities and to make it available for re-injection. Tritium hereby poses unique requirements on the employed processes and equipment due to its radiological hazards, mandating a minimization of the total tritium inventory and requiring the use of gloveboxes and secondary enclosures for confinement. The fuel cycle can be treated like a complex chemical plant. Here, all processing systems involved in handling tritium that are not part of to the reactor are housed in the tritium plant building, where they are segmented into individual rooms.

The arrangement of the sub-systems has to reflect a multitude of different integral design aspects. The operational tritium inventory (given by the connection piping and the dimension of the process units) shall be minimized. The volume and surface of the rooms shall be chosen such that in a potential safety event contamination is limited. The arrangement of the system blocks has to reflect aspects of access for reasons of reliability, maintainability and inspection. The modularity of the sub-systems shall reflect the size of the rooms in the building.

Based on a process simulation of the fuel cycle, preliminary dimensioning of its key components and characterization of primary flows between system blocks is available. In this work, the design of the tritium plant building shall be progressed further by developing the plant footprint of the fuel cycle systems, also considering the additional space requirements for ancillary equipment and secondary enclosures. In a second step, the required piping between the system blocks shall be dimensioned. Based on the developed information an optimal layout of the fuel cycle system blocks in the tritium plant shall be proposed. To achieve this, the thesis will evolve along the following steps:

- (i) Familiarization with the fusion fuel cycle and DEMO
- (ii) Collection of input information on the fuel cycle system blocks
- (iii) Cataloguing of ancillary equipment in the fuel cycle system blocks
- (iv) Estimation of the plant footprint
- (v) Dimensioning of piping connections between system blocks
- (vi) Optimization of the system layout and piping to minimize tritium inventory in process lines
- (vii) Completion of thesis writing

The work will be carried out at the ITEP at the KIT Campus Nord. The Master thesis shall be written in English language and shall comprise a clear and concise depiction of the work that has been carried out. The results of the work shall be presented orally at the Institute's Colloquium.

Start of the work: 1 October 2022 Delivery of the work: 31 March 2023

<u>Examiner:</u> Prof. Dr. Robert Stieglitz (IATF)

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Nomenclature

Symbol	Name	Value	Dimensions	Units
p_0	Reference pressure	101325	$M \cdot L^{-2} \cdot T^{-2}$	Pa
R	Universal gas constant	8.314	$L^2 \cdot T^{-2} \cdot \Theta^{-1}$	J/mol·K
T_a	Ambient / room temperature	298.15	Θ	K
T_0	Reference temperature	273.15	Θ	K

Symbol	Name	Dimensions	Units
A	Number of nucleons (neutrons + protons)	-	
c	Corrosion allowance	L	mm
D	Diameter	L	mm, m, in
$D_{n,in}$	Nominal diameter in inches	L	in
e_a	Analysis wall thickness	L	mm
E_t	Elasticity module (at design temperature)	$M \cdot L^{-1} \cdot T^{-2}$	GPa, MPa
f	Design tension	$M \cdot L^{-1} \cdot T^{-2}$	MPa
H	Height	L	mm, m
ID	Internal diameter	L	mm, m, in
ID_{req}	Required internal diameter	L	mm
ID_{std}	Standard internal diameter	L	mm
k	Safety factor	-	
K_1	K_1 - 3K method parameter	-	
K_d	K_d - 3K method parameter	$L^{0.3}$	$in^{0.3}$
K_f	K_f - 3K method parameter	-	
K_i	K_i - 3K method parameter	-	
$\left(\frac{L}{D}\right)_{eq}$	Equivalent length over internal diameter	-	
L	Length	L	mm, m
L_u	Unstiffened pipe length	L	mm, m
Mr	Molecular weight	-	g/mol, kg/kmol
n_{cyl}	Number of complete circumferential waves forming at buckling	-	
OD	Outer diameter	L	mm, m, in
OD_{req}	Required outer diameter	L	mm
OD_{std}	Standard outer diameter	L	mm
p	Pressure	$M \cdot L^{-2} \cdot T^{-2}$	Pa, bar, bar-abs, barg
p_m	Theoretical elastic buckling pressure at failure of an exactly cylindrical tube	$M \cdot L^{-1} \cdot T^{-2}$	MPa
p_r	Calculated lower failure pressure	$M \cdot L^{-1} \cdot T^{-2}$	MPa
p_y	Mean hoop stress of the cylindrical pipe at the midpoint between stiffeners reaches the yield point of the material	$M \cdot L^{-1} \cdot T^{-2}$	MPa
Q	Leak / vacuum flowrate	$M \cdot L^2 \cdot T^{-3}$	$Pa \cdot m^3/s$
Re	Reynolds number	-	
R_m	Mean radius	L	mm
$R_{p0.2}$	Yield strength at 0.2% elongation	$M \cdot L^{-1} \cdot T^{-2}$	MPa

Symbol	Name	Dimensions	Units
$R_{p0.2\,t}$	Yield strength at 0.2% elongation (at design temperature)	M·L^{-1}·T^{-2}	MPa
$R_{p1.0}$	Yield strength at 1.0% elongation	M·L^{-1}·T^{-2}	MPa
$R_{p1.0\,t}$	Yield strength at 1.0% elongation (at design temperature)	M·L^{-1}·T^{-2}	MPa
S	Flow cross section	L^2	mm^2, m^2
S_l	Elasticity limit	M·L^{-1}·T^{-2}	MPa
S_{std}	Standard pipe cross section	L	mm
T	Temperature	Θ	K, ºC
t	Thickness	L	mm
t_{min}	Minimum required thickness	L	mm
t_{nom}	Nominal required thickness	L	mm
$t_{nom,std}$	Nominal standard thickness	L	mm
$\langle v \rangle$	Mean flow velocity	L·T^{-1}	m/s
$\dot{V}$	Volume flowrate	L^3·T^{-1}	Nm^3/h, Am^3/h, Am^3/s
$\dot{w}$	Material flowrate	M·T^{-1}	mol/h, mol/s
W	Width	L	mm, m
x	Mole fraction	-	
Z	Mean radius to unstiffened pipe length ratio	-	
z	Welding factor	-	
Δp_{allow}	Allowable pressure drop	M·L^{-1}·T^{-2}	Pa, bar
$\Delta \dot{p}_{allow}$	Allowable pressure drop per length	M·L^{-2}·T^{-2}	bar/100m
$\Delta \dot{p}_{max}$	Maximum allowable pressure drop per length	M·L^{-2}·T^{-2}	bar/100m
Δp_f	Pressure drop in fittings	M·L^{-1}·T^{-2}	Pa, bar
Δp_s	Pressure drop in straight pipe	M·L^{-1}·T^{-2}	Pa, bar
$\Delta \dot{p}$	Pressure drop per length	M·L^{-2}·T^{-2}	bar/100m
Δp_T	Total pressure drop	M·L^{-1}·T^{-2}	Pa, bar
Δz	Vertical correction	L	mm, m
ε	Material roughness	L	mm
ε/D	Relative roughness	-	
λ	Fanning's friction factor	-	
λ_m	Linear mass density	M·L^{-1}	g/m
μ	Viscosity	M·L^{-1}·T^{-1}	Pa·s, cP
υ	Poisson's ratio	-	
ρ	Density	M·L^{-3}	kg/m^3

Abbreviations

Name	Abbreviation
ACI	AutoCAD color index
ABS	Equipment type: absorption
ALARA	As low as reasonable achievable
AUX	Streams: auxiliary stream
AWSS	Active water storage system
B1	Basement level 1

Name	Abbreviation
B2	Basement level 2
C	Equipment tag: compressor / vacuum pump
CB	Coldbox
CCL	Streams: cryogenic cooling fluid
CCW	Streams: cold cooling water
CD	Equipment type: cryogenic distillation
CQ_4	Tritiated methane
CVS	Conventional vacuum system
CWS	Cooling water system
D2SS	Deuterium supply system
DC	Equipment type: distillation column
DIC	DIC corporation color guide
DIN	Deutsches Institut für Normung
DIR	Direct internal recycling
DIRL	Direct internal recycling loop
DIRL-FSV	Fuel separation and torus vacuum system block
DIRL-GDCM	Gas distribution, control and monitoring system block
DIRL-GI	Gas injection system block
DIRL-PI	Pellet injection system block
DIRL-VAC	DIRL vacuum pumping system block
DP	Design pressure
DS	Equipment tag: detritiation system
DT	Design temperature
DT^+FV	DT^+ feed vessel
DT^+SS	DT^+ storage beds
DTSB	DT storage beds
DTSD	DT shut-down storage beds
DTSS	DT storage system
dU	Depleted uranium
E	Equipment tag: heat exchanger
EDS	Exhaust detritiation systems
EN	European Norm
EOS	Streams: external oxygen supply
EPVS	Exhaust processing vacuum system
EQ	Equation
EU-DEMO	European demonstration fusion power plant
FM	Equipment type: fluid machine
FT	Equipment type: filter
GB	Glovebox
GB-CS	Glovebox cooling system
GB-DS	Glovebox detritiation system
GCBS	OUTL gas collection and buffering system
G-DS	Gas detritiation system
H2SS	Protium storage system

Name	Abbreviation
HCPB	Helium-cooled pebble bed
HCW	Streams: hot cooling water
HDR	Streams: header
HE	Equipment type: heat exchanger
He3ExS	3He extraction system
HeCPS	Helium coolant purification system
HTCS	HCPB tritium conditioning system
HVAC	Heating, ventilation and air conditioning
I&C	Instrumentation and control
IGS	Streams: inert gas supply
IGSS	Inert gas supply system
INTL	Inner tritium plant loop
INTL-EP	Exhaust processing system block
INTL-IRPR	Isotope rebalancing & protium removal system block
INTL-VAC	INTL vacuum pumping system block
IPS	Impurity processing system
IRS	Impurity removal system
ISO	International Organization for Standardization
ISS	Isotope separation system
ITER	International thermonuclear experimental reactor
KTA	Kerntechnischer Ausschuss
L	Equipment dimensions: large
L1	Aboveground level 1
L2	Aboveground level 2
L3	Aboveground level 3
L4	Aboveground level 4
L5	Aboveground level 5
LPCE	Liquid phase catalytic exchange
M	Equipment dimensions: medium
MB	Metalbox
MB-DS	Metalbox detritiation system
MCC	Motor control center
MOP	Maximum operational pressure
N-EDS-OT or NEDS	Normal exhaust detritiation system once through
N-EDS-OT&R or OEDS	Normal exhaust detritiation system once through and recirculation
NOP	Normal operational pressure
NOT	Normal operational temperature
O2SS	Oxygen storage system
OBC	Optimized base case
ODS	Oxygen detritiation system
OUTL	Outer tritium plant loop
OUTL-CP	Coolant purification system block
OUTL-ED	Exhaust detritiation system block
OUTL-GS	Gas storage system block

Name	Abbreviation
OUTL-IS	Isotope separation system block
OUTL-TC	Tritium conditioning system block
OUTL-WD	Water detritiation system block
P	Equipment tag: pump
PEG	Plasma enhancement gases
PEM	Proton Exchange Membrane Electrolyzer
PKG	Equipment type: package
PLC	Programmable control logic
PRS	PEG removal system
PSS	PEG storage system
PWD	Streams: purified water
PWDS	Purified water distribution system
Q_2	Any hydrogen isotopologue
Q_2O	Tritiated water (any isotopologue)
R	Equipment tag: reactor
RAMI	Reliability, availability, maintainability, and inspectability
RC2	Streams: tritium plant building rooms
RE	Equipment type: reactor
S	Equipment dimensions: small
S	Equipment tag: separator
S-EDS-OT or SEDS	Safety exhaust detritiation system once through
SEP	Equipment type: separator
SS	Equipment type: solid storage
STCK	Streams: to stack
SVS	Service vacuum system
T	Equipment tag: column
$T_{2,eq}$	Tritium equivalent
TERS	Tritium extraction and removal systems
TG#	Streams: tritiated gas #
TK	Equipment type: tank
TKB	Tokamak building
TPB	Tritium plant building
TWH	Streams: Tritiated water (high concentration)
TWL	Streams: Tritiated water (low concentration)
U	Equipment tag: filter
V	Equipment tag: vessel
VS	Equipment type: vessel
WCLL	Water-cooled lithium lead
WCPS	Water coolant purification system
WDFT	Water detritiation feed water tanks
WDS	Water detritiation system
WTCS	WCLL tritium conditioning system

Abstract

The European demonstration fusion power plant (EU-DEMO) project intends to prove the commercial viability of nuclear fusion as a source of safe and clean energy. This fusion power plant will be fueled by a 1:1 deuterium-tritium (hydrogen isotopes) mixture that will need to be recycled for environmental and economic reasons due to the low burn-up fraction. Tritium is a radioactive isotope that requires a special design of any handling facilities to be “tritium compatible” and a series of layers of protection to prevent any release of tritium to the environment above the permitted values. Moreover, tritium is scarcely available which makes it again crucial to design the tritium systems, the so called fuel cycle, such that the inventory is minimized.

The EU-DEMO fuel cycle will be housed inside two buildings, the tokamak building and the tritium plant building. The first one will contain the reactor, its fueling systems and the direct internal recycling loop. The tritium plant building, which is the subject of this work, will accommodate an inner tritium plant loop and an outer tritium plant loop.

In this thesis, a methodology for estimating the required footprint of the tritium plant and optimizing its layout is proposed. This is accomplished by identifying all the necessary equipment of the plant, estimating their physical dimensions, and allocating them into primary and secondary confinements (e.g. gloveboxes and rooms), for which their footprint and volume is obtained. By arranging these rooms inside a multistory building, the final layout is achieved. This methodology takes into consideration the fuel cycle processes and at the same time defines personnel and process safety, construction, operation and maintenance criteria to obtain an optimized layout suitable for the entire life cycle of the facility, while keeping in mind the need for minimizing the tritium inventory.

Afterwards, this work puts forward a piping dimensioning strategy, defining design basis and calculation sequences supported on European Norms as well as optimization criteria to achieve a reasonably low tritium inventory in piping required to connect confinements and rooms. The presented tritium inventory determination focuses on the piping under normal operation of the plant, while the inventory inside the units is out of the scope of this work, even though it is taken into account for the development of the layout.

The application of the developed methodologies resulted in the identification of 627 process equipment which have been grouped into 29 gloveboxes, 2 coldboxes and 19 metalboxes. These confinement structures can be housed inside a compact seven-story-building design, with a projected footprint of 2200 m^2, a cumulative footprint of 11240 m^2, an external volume of 57030 m^3 and external dimensions of 35.8 m of height, 74.0 m of length and 30.9 m of width. Lastly, the resulting tritium inventory inside interconnecting pipes under normal operation is found to be in the order of 0.2 g with only 10 pipe types (outer diameter and thickness combinations).

Zusammenfassung

Das europäische Demonstrationsprojekt für ein Fusionskraftwerk (EU-DEMO) soll die kommerzielle Nutzbarkeit der Kernfusion als sichere und saubere Energiequelle beweisen. Dieses Fusionskraftwerk wird mit einem Deuterium-Tritium-Gemisch (Wasserstoffisotope) im Verhältnis 1:1 betrieben, das aufgrund der geringen Reaktionsumsatz aus umwelt- und wirtschaftlichen Gründen recycelt werden muss. Tritium ist ein radioaktives Isotop und erfordert als solches besondere Auslegung der Anlagen, um „tritium-kompatibel" zu sein, sowie eine Reihe von Schutzschichten um jegliche Freisetzung von Tritium in die Umwelt über die zulässigen Grenzwerte hinaus zu verhindern. Darüber hinaus ist Tritium nur begrenzt verfügbar, so dass auch aus diesem Grund der Brennstoffkreislauf so konzipiert werden muss, dass das Betriebsinventar möglichst gering ist.

Der EU-DEMO-Brennstoffkreislauf wird in zwei Gebäuden untergebracht sein, dem Tokamak-Gebäude und dem Tritiumanlagen-Gebäude. Das erste Gebäude wird den Reaktor, die Brennstoffzufuhrsysteme und den direkten internen Rezyklierungskreislauf (DIRL) enthalten. Das Tritiumanlagen-Gebäude, das Gegenstand dieser Arbeit ist, wird den inneren Tritiumanlagen-Kreislauf und den äußeren Tritiumanlagen-Kreislauf beherbergen.

In dieser Masterarbeit wird eine Methode zur Abschätzung des Platzbedarfs des Tritiumanlagen-Gebäude sowie einer optimierten Gebäudeaufteilung vorgeschlagen. Dies erfordert die Identifizierung der erforderlichen Ausrüstung der Anlage sowie die Schätzung ihrer Abmessungen und anschließende zur Gruppierung in primäre und sekundäre Umschließungen (z. B. Handschuhboxen und Räume). Für diese wird dann die benötigte Grundfläche und Volumina ermittelt und eine Anordnung der Räume in einem mehrstöckigen Gebäude vorgeschlagen. Diese Methode berücksichtigt die Prozesse des Brennstoffkreislaufs und legt gleichzeitig Kriterien für Personal- und Prozesssicherheit, Bau, Betrieb und Wartung fest, um ein optimiertes Layout zu erhalten, das für den gesamten Lebenszyklus der Anlage geeignet ist, wobei die Notwendigkeit der Minimierung des Tritiuminventars berücksichtigt wird.

Anschließend wird in dieser Arbeit eine Strategie für die Dimensionierung von Rohrleitungen vorgeschlagen, wobei Auslegungskriterien und Berechnungssequenzen auf der Grundlage europäischer Normen sowie Optimierungskriterien festgelegt werden, um ein angemessen niedriges Tritiuminventar in Rohrleitungen zu erreichen. Die vorgestellte Bestimmung des Tritiuminventars konzentriert sich auf die Rohrleitungen bei normalem Betrieb der Anlage, während das Inventar innerhalb der Prozesssysteme nicht Gegenstand dieser Arbeit ist. Es findet jedoch Einfluss in der vorgeschlagenen Raumaufteilung.

Die Anwendung der entwickelten Methoden führte zur Identifikation von 627 Prozessausrüstungen, die in 29 Handschuhboxen, 2 Kältekammern und 19 Metallboxen gruppiert sind und in einem kompakten siebenstöckigen Gebäude mit einer projizierten Grundfläche von 2200 m^2, einer kumulativen Grundfläche von 11240 m^2, einem Außenvolumen von 57030 m^3 und Außenmaßen von 35.8 m Höhe, 74.0 m Länge und 30.9 m Breite untergebracht sind. Das resultierende Tritiuminventar in den Verbindungsrohren bei Normalbetrieb liegt in der Größenordnung von 0.2 g bei nur 10 möglichen Rohrtypen (Kombinationen aus Außerdurchmesser und Dicke).

Resumen

El proyecto europeo de central eléctrica de demostración de la fusión nuclear (EU-DEMO) pretende probar la viabilidad comercial de la fusión nuclear como una fuente de energía segura y limpia. Esta planta de fusión nuclear será alimentada por una mezcla 1:1 de deuterio y tritio (isótopos de hidrógeno) que deberá ser reciclada por razones ambientales y económicas debido a la baja fracción de combustión. El tritio es un isótopo radiactivo que requiere un diseño especial de cualquier instalación de manipulación para que sea “compatible con el tritio” y una serie de capas de protección para evitar cualquier liberación de tritio al medio ambiente por encima de los valores permitidos. Además, el tritio es escaso lo que hace que sea crucial diseñar los sistemas de tritio, el llamado ciclo de combustible, de modo que se minimice el inventario.

El ciclo de combustible de EU-DEMO estará alojado dentro de dos edificios, el edificio del tokamak y el edificio de la planta de tritio. El primero contendrá el reactor, sus sistemas de alimentación y el circuito de reciclaje directo interno. El edificio de la planta de tritio, que es el tema de este trabajo, albergará los circuitos interior y exterior de la planta de tritio.

En esta tesis se propone una metodología para estimar el espacio requerido por la planta de tritio y optimizar su distribución. Esto se logra mediante la identificación de todo el equipo necesario de la planta, estimando sus dimensiones físicas y asignándolos a confinamientos primarios y secundarios (por ejemplo, cajas de guantes y salas), para lo cual se obtiene un área proyectada y volumen. Al acomodar estas salas dentro de un edificio de varios pisos, se logra obtener la disposición final. Esta metodología tiene en cuenta los procesos del ciclo de combustible y al mismo tiempo define criterios de seguridad del personal y del proceso, de construcción, de operación y de mantenimiento, para obtener un diseño optimizado y adecuado para todo el ciclo de vida de la instalación, teniendo en cuenta la necesidad de minimizar el inventario de tritio.

Posteriormente, este trabajo plantea una estrategia de dimensionamiento de cañerías, definiendo bases de diseño y secuencias de cálculo soportadas en Normas Europeas, así como criterios de optimización para lograr un inventario de tritio razonablemente bajo en las cañerías requeridas para conectar confinamientos y salas. La determinación del inventario de tritio presentada se enfoca en las cañerías bajo operación normal de la planta, mientras que el inventario dentro de las unidades está fuera del alcance de este trabajo, aunque se toma en cuenta para el desarrollo del diseño.

La aplicación de las metodologías desarrolladas dio como resultado la identificación de 627 equipos de proceso los cuales han sido agrupados en 29 cajas de guantes, 2 cajas frías y 19 cajas metálicas. Estas estructuras de confinamiento pueden albergarse dentro de un diseño de edificio compacto de siete pisos, con un área proyectada de 2200 m^2, un área de pisos acumulada de 11240 m^2, un volumen externo de 57030 m^3 y unas dimensiones externas de 35.8 m de altura, 74.0 m de largo y 30.9 m de ancho. Por último, se encuentra que el inventario de tritio resultante dentro de las cañerías de interconexión en operación normal es del orden de 0.2 g con sólo 10 tipos de cañerías (combinaciones de diámetro exterior y espesor).

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1 Introduction

1.1 The demonstration fusion power plant

The transition to a sustainable energy matrix must involve not only the phase out of fossil fuels, but also of the traditional nuclear power plants whose fission by-products disposal (long-term storage) represent a risk to the environment for extended periods of time. The development of nuclear fusion technologies for providing a reliable base load power to the grid with only short lived radioactive waste is part of the goals of the International Thermonuclear Experimental Reactor (ITER) and the EUropean DEMOnstration fusion power plant (EU-DEMO) projects.

Whereas ITER will be an experimental device which has been designed for a wide operational window to allow the variation of physics and technology parameters during experimental campaigns [1], the EU-DEMO project is meant to be the step between ITER and future fusion power plants [2] by proving the commercial viability of this technology for supplying electricity to the grid. A goal of the project is therefore to achieve an overall availability of at least 30% between commissioning and decommissioning, so that a derived future power plant will be able to have at least 60% availability in its lifetime, which is considered a requirement for economic attractiveness [3].

The EU-DEMO intends to produce 2 GW of fusion power, with an expected power output of 300 to 500 MW of electricity to the grid by operating at one single operational point [4]. On the other hand, the ITER research fusion reactor is designed for 500 MW of fusion power and is not intended to generate any electricity [2].

Both reactors are designed to burn a deuterium-tritium fuel, resulting in a key requirement for EU-DEMO to be self-sufficient in tritium due to its limited natural abundancy. This means that the plant must be able to breed tritium to replenish the burnt fuel and ideally also produce a surplus of tritium to allow future power plants to start up. As a demonstration reactor, EU-DEMO is intended to achieve the resolution of all remaining physics and engineering issues foreseen in the operation of a fusion power plant and integrated demonstration of all relevant technologies.

The EU-DEMO plan design approach must always keep in mind safety and environmental sustainability. Great effort is put on containing tritium within the process, thus minimizing its presence in open areas of buildings and avoiding the release of tritium to the environment. The materials used need to be able to withstand radiation doses over periods of several years [1] and there must also be a focus on reducing the tritium content in components extracted for disposal and the identification of appropriate disposal and recycling routes [2].

For these reasons, one of the most important challenges of the EU-DEMO is to scale ITER fusion power by 400% without increasing the plant tritium inventory proportionally. As explained by Day and Giegerich [5], adopting the ITER fuel cycle architecture and extrapolating it for the EU-DEMO requirements, results in a tritium inventory 3.75 times higher than the ITER one, that is, around 10 kg [6], which is considered not viable under the requirement of transferring the EU-DEMO approach to a wider number of future power plants. Instead, the EU-DEMO fuel cycle is based around the “direct internal recycling” concept, which is expected to keep the inventory required to operate the fuel cycle below 2 kg [7] by recirculating 80% of the exhaust unburnt fuel from the tokamak back to the fueling systems and sending only the remaining 20% to the tritium plant building (TPB), whose size is reduced accordingly.

1.2 The fuel cycle of the EU-DEMO fusion power plant

Due to its limited availability, nuclear licensing constraints, and cost of tritium it is critical that the EU-DEMO fusion power plant is designed in such a way that the required tritium inventory for start-up and in the fuel cycle is as low as possible. Furthermore, in the tokamak reactor, only 0.6% of the injected tritium is expected to be burned [4], meaning that the exhaust stream still contains 99.4% of the tritium injected which must be purified before re-injection and kept in a closed loop since it cannot be released to the environment due to its radioactive properties and cost.

The tokamak exhaust gas is a multi-species mixture, composed mainly of deuterium and tritium in a 1:1 ratio but expected to contain all six hydrogen isotopologues (H_2, HD, HT, D_2, DT and T_2). Inert gases will also be present as plasma enhancement gases (PEG), which in this case are Ar and Xe, ^{3}He, from tritium decay, and ^{4}He, as a product of the fusion reaction. Next to hydrogens and inert gases there are also impurities expected, mainly by the interaction of tritium with the stainless steel walls (forming tritiated water Q_2O, tritiated methane CQ_4, as well as CO/CO_2), activated isotopes and decay products, mainly from plasma enhancement gases, plus air and water that leak into the fuel cycle loops. Additionally, protium and other matter can be leached out of the tokamak walls, blanket first wall and limiter [4].

The EU-DEMO proposed fuel cycle is depicted in Figure 1.

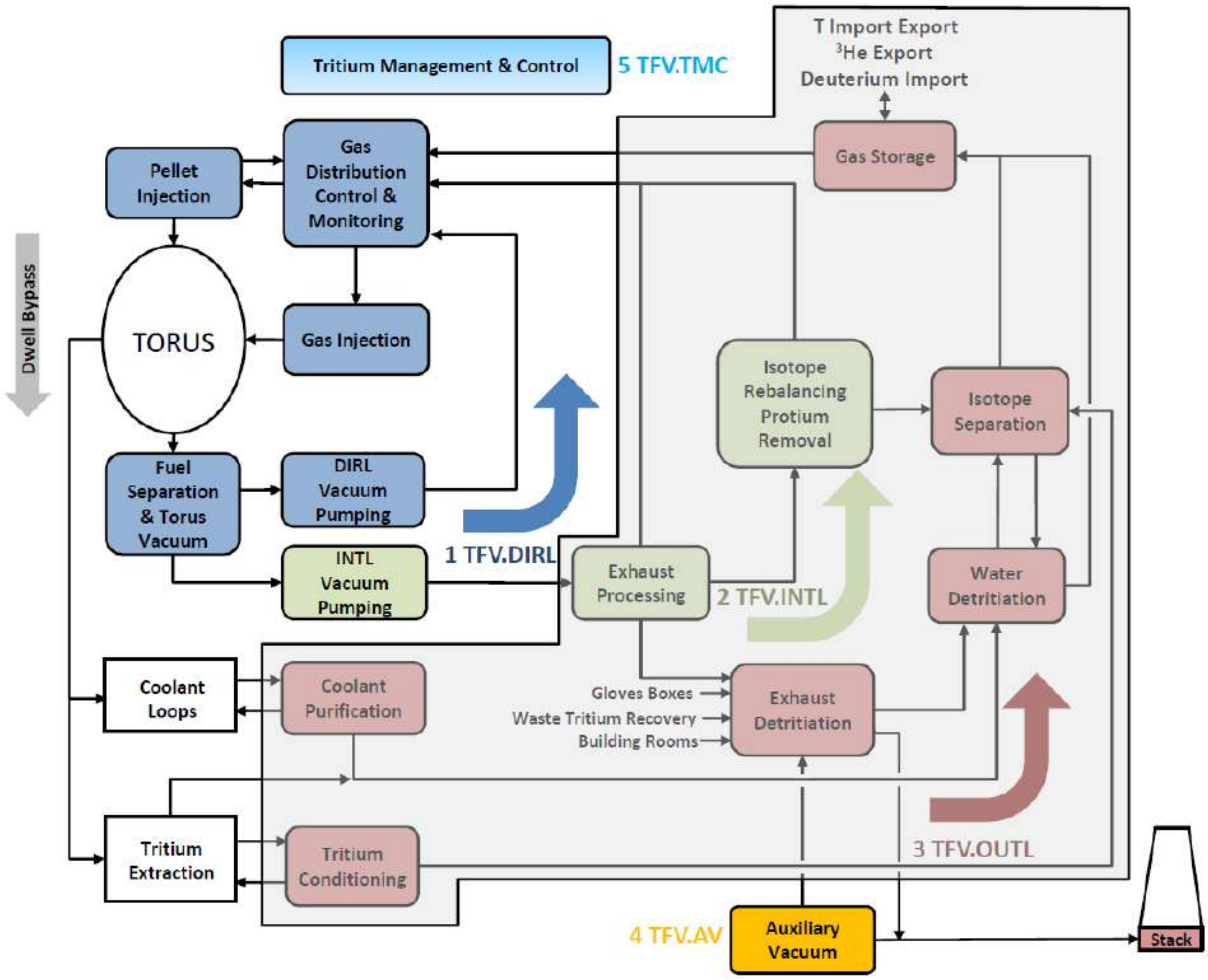

Figure 1 – EU-DEMO fuel cycle. The greyed out area marks the process units inside in the Tritium Plant Building [8].

The direct internal recycle loop (DIRL) allows, as its name indicates, to continuously recycle 80% of the hydrogens contained in the tokamak exhaust directly. The remaining 20% of the exhaust hydrogens as well as all ash and impurities is then sent to the inner tritium plant loop (INTL) extracting the remaining unburnt fuel and processing impurities while also maintaining the isotopic balance of the fuel. Lastly, the outer tritium plant loop (OUTL) includes large-scale systems for isotope separation and water detritiation and provides the function of recovering any trace of tritium from the INTL or in the building air in the exhaust detritiation systems. The OUTL also contains the coolant purification and the tritium conditioning systems, which are not directly related to the main process but support the operation of the breeding blankets.

The DIRL has the greatest impact on the minimization of the tritium inventory in the fuel cycle since only 20% of the exhaust tritium is processed in the tritium plant. The DIRL is located inside the tokamak building (TKB) and composed by five system blocks, namely, the fuel separation and torus vacuum (DIRL-FSV); the DIRL vacuum pumping (DIRL-VAC); the gas distribution, control and monitoring; the gas injection and the pellet injection. None of these are located in the TPB and as such, are not within the scope of this work.

The INTL receives the gases that are not being recycled to the fusion reactor, and consists of three functional blocks; the INTL vacuum pumping (INTL-VAC), which is still located in the TKB near the DIRL-FSV; the exhaust processing system (INTL-EP), which is the first system block in the tritium plant; and the isotope rebalancing & protium removal system (INTL-IRPR).

The INTL-VAC and the DIRL-VAC have the tasks of keeping the required pressure level in the subdivertor at the throughput to be pumped during the plasma burn; and in the dwell period, to pump down the torus to a vacuum level required for the start of the next pulse in a given time.

The INTL-EP separates hydrogens from the PEG, fusion ash, and impurities in a first stage and then the PEG from ash and impurities. The INTL-EP in total contains six subsystems. The impurity removal system (IRS) has the function to separate hydrogen from non-hydrogens. The impurity processing system (IPS) recovers hydrogen from compounds such as CQ_4 and Q_2O, and separates the hydrogens. The gas detritiation system (G-DS) captures the remaining hydrogens from the exhaust gas that had not been successfully separated in the two previous systems. The exhaust processing vacuum system (EPVS) generates sufficient vacuum for the proper functioning of permeators in the IRS, IPS and G-DS, while sending the hydrogens to the INTL-IRPR. The PEG and impurities leaving the G-DS are sent to the PEG removal system (PRS) which recovers the PEG via cryogenic distillation and sends them to the PEG storage system (PSS), from where they are sent back to the TKB. The remaining impurities are then sent to exhaust detritiation in the OUTL.

The INTL-IRPR is a single subsystem by itself and is also identified as IRPRS. Its function is to adjust the isotopic composition in the DT fuel mixture to the desired value and at the same time to remove excess protium and route it to the isotope separation system (ISS) in the OUTL.

The OUTL is responsible for processing all tritiated streams that do not constitute the circulated fuel, extracting any contained tritium to make it available for reuse and assuring the safe discharge of the detritiated streams with as low as reasonable achievable (ALARA) tritium levels. There are four major sources for these steams; the processing of the bred tritium extracted from the breeding blankets; the continuous purification of a fraction of the tokamak primary coolant; the detritiation of air from the TKB rooms and the TPB rooms and gloveboxes, and finally the waste streams leaving the INTL which require further processing before being discharged. The OUTL includes six system blocks which are exhaust detritiation (OUTL-ED), water detritiation (OUTL-WD), isotope separation (OUTL-IS), tritium conditioning (OUTL-TC), coolant purification (OUTL-CP) and gas storage (OUTL-GS).

The OUTL-ED encompasses all the exhaust detritiation systems (EDS), which are the only systems that discharge to the atmosphere through a stack. They receive gaseous streams with trace amounts of tritium and recover it. There are three kinds of EDS in the tritium plant. The normal exhaust detritiation system once through (N-EDS-OT) captures tritium from air of building areas, glovebox detritiation systems, service vacuum system, and the ashes from the PRS and maintains a pressure cascade in the required rooms & volumes. The normal exhaust detritiation system once through and recirculation (N-EDS-OT&R) is activated to capture trace tritium from building areas when needed, for example substituting the heating, ventilation, and air conditioning (HVAC) operation in a room during an open-box maintenance, with the ability to recirculate the treated air to the rooms or send it to the stack depending on contamination level. Lastly, the safety exhaust detritiation system once through (S-EDS-OT) captures the tritium from the ventilation systems in case of accidents in the plant. The tritiated water produced in these systems is sent to the OUTL-WD.

The OUTL-WD receives all liquid aqueous streams that arise in all areas of the fuel cycle and produces high purity protium, high purity oxygen and a bleed stream of gaseous protium and tritium that is sent to the OUTL-IS. The OUTL-WD contains four subsystems. The water detritiation feed water tanks (WDFT), collect tritiated water from different clients (their main contributors are the OUTL-ED and the OUTL-CP) during normal operation, including maintenance. The active water storage system (AWSS) provides safe storage for active water that arises during off-normal operation, including drained water. The core of the OUTL-WD is the water detritiation system (WDS) whose function is to purify and detritiate water and provide pre-enrichment for the ISS. In this subsystem also the final scrubbing of the protium from the ISS is carried out before storage. The oxygen produced in the WDS electrolyzers is sent to the oxygen detritiation system (ODS) where tritiated water in form of humidity is removed from the oxygen stream and recirculated back to the WDS.

The OUTL-IS is comprised of two subsystems. The OUTL gas collection and buffering system (GCBS) which collects hydrogen streams from OUTL-IRPR, OUTL-WD and OUTL-TC in vessels and serves as a buffer against intermittent flows to ensure steady state operation of the ISS, and the isotope separation system (ISS) which produces a tritium free protium stream to be sent to the WDS and a protium free tritium stream (with some deuterium) returned to the TKB for fueling.

The OUTL-TC has the function to recover tritiated hydrogens from the tritium extraction and removal systems (TERS) exhaust and reflux the cleaned streams. At this time, two technologies for breeding blankets, and thus, for tritium extraction systems are being considered both of which will be mounted in the TKB. These technologies are the water-cooled lithium lead concept (WCLL) and the helium-cooled pebble bed (HCPB). The tritium conditioning subsystems are then called WCLL tritium conditioning system (WTCS) and HCPB tritium conditioning system (HTCS) and will be housed in the tritium plant building.

The OUTL-CP has the goal to keep a target tritium concentration in the primary tokamak coolant by continuously processing a fraction thereof. At this time, the two breeding blanket concept use different primary coolants (water and helium), both with associated purification systems in the tritium plant. The corresponding subsystems will be the water coolant purification system (WCPS) and the helium coolant purification system (HeCPS).

The OUTL-GS is comprised of five subsystems. The DT storage system (DTSS) houses all storage vessels and beds for tritiated hydrogens, providing sufficient storage capacity for hydrogen isotopologues when the reactor is in maintenance or shut-down modes, for tritium import and export out of the fuel cycle, as well as 50/50 DT fuel mixture required for burn make-up. The ^{3}He extraction system (He3ExS) recovers ^{3}He from stored tritium decay to be exported. The protium storage system (H2SS) collects and stores the tritium free protium produced in the WDS. The oxygen storage system (O2SS) collects and stores the oxygen generated in the WDS. The deuterium supply system (D2SS) supplies deuterium to make up for any deuterium burnt in the fusion reaction or exhausted to the stack.

Additionally, the fuel cycle requires several auxiliary support systems, connected to multiple subsystems of the plant. The glovebox / metalbox detritiation system (GB-DS / MB-DS), captures trace tritium leaked from the process to the boxes atmosphere and sends it to the EDS. The service vacuum system (SVS) provides vacuum to clients that might be tritiated or see tritium when taken out of service. Both subsystems are also located inside the TPB. This building also features a tritium vault, a safe room dedicated to the secure storage of excess bred tritium to be exported.

Next to these tritium processing systems, the fuel cycle also interfaces to more generic plant infrastructure systems. The cryo-distribution system supplies the TKB and the TPB from the cryoplant compressor building with helium at 4 K and 80 K [9]. The cooling water system (CWS) supplies chilled cooling water for the tritium plant. The inert gas supply system (IGSS) supplies makeup nitrogen for glovebox and metalbox atmospheres. The purified water distribution system (PWDS) supplies purified water to the EDS trains and the WDS. The conventional vacuum system (CVS) provides vacuum for clients that will never see tritium (e.g. transfer lines). The stack, whose function is to protect workers and the environment from tritium discharges and to keep dose rates ALARA when releasing treated gases to the atmosphere. All these systems are considered as “outside battery limits” from the point of view of the tritium plant as they are not required to be housed in a nuclear rated building.

A detailed explanation of the equipment and technologies adopted or being considered for each subsystem can be found in Ref. [4].

1.3 Challenges of tritium handling

Tritium (^{3}H or T) is an unstable (radioactive) isotope of hydrogen, with an atomic mass of 3 amu (2 neutrons and 1 proton) [10]. It has a decay half-life of 12.32 years and is generated naturally only in trace amounts in the upper atmosphere by cosmic rays [10], making it impossible to harvest. Thus, it must be artificially produced to be available for research or industrial purposes. In the present times, tritium is mainly produced in fission reactors that burn natural uranium and are moderated by heavy water (D_2O) which can absorb neutrons and become tritiated.

The other two isotopes of hydrogen are protium (^{1}H or H), also known as ordinary hydrogen, with an atomic mass of 1 amu (one proton); and deuterium (^{2}H or D) which makes up about 0.015% of the natural hydrogen, with an atomic mass of 2 amu (one neutron and one proton). In this thesis, the letter Q is used to denote any of these three hydrogens without specifying the isotope.

Gaseous hydrogen is always found in diatomic form (Q_2), having six possible combinations called isotopologues: H_2, D_2, T_2, HD, HT and DT. Due to the radioactive properties of tritium, a mixture of pure H_2 or pure D_2 with pure T_2, moves towards a thermodynamic equilibrium also producing HT and DT respectively.

All isotopological hydrogen gases behave similar with respect to physical properties, they are colorless, odorless and tasteless. They have a high coefficient of diffusion and readily diffuse through porous substances such as rubber and can also diffuse through metals. Additionally, they all form explosive mixtures with air, which means that leak detection and explosion protection are major safety design considerations for any hydrogen processing plant [10].

The chemical properties of tritium are largely the same as the other isotopes, with the particularity that the energy provided by the radioactive decay provides the activation energy required for some reactions that would not occur with protium or deuterium. Tritium in contact with any material containing hydrogen will exchange a hydrogen atom to form a tritiated molecule of the material by radiolysis. Carbon containing compounds (e.g. organic compounds, carbon dioxide, carbon steel) will be degraded by tritium to release tritiated methane and, when in contact with water or air, tritium will produce tritiated water and even react with nitrogen to produce tritiated ammonia. As a consequence, the tritium purity in a closed system decreases over time due to isotopic exchange and radiolysis, which makes purification crucial.

Tritium decays to helium-3 (^3He) and emits low energy beta radiation (maximum energy: 18.6 keV). This kind of radiation is easily shielded by common materials such as paper, glass, plastic or metal, and even the external layer of skin. On the other hand, should tritium be inhaled, ingested or incorporated via skin or wounds in the form of water (HTO, DTO or T_2O), it is absorbed and retained in the body for a biological half-life of approximately 10 days which has hazardous effects in the order of 10000 times more than the same exposure to gaseous tritium (HT, DT or T_2) [10].

Tritium handling thus combines the challenges of hydrogen handling with the challenges of radioactive materials handling. As such, traditional containment strategies are not valid for tritium, and careful material selection and better leak tightness than usually employed for protium and deuterium are a must when dealing with this isotope. Fulfilling the leak tightness requirements include the use of metallic sealing and wetted materials to only be metallic or ceramic. In addition, no organic materials such as pump oils can be present, and materials like hydrocarbons (e.g. oils, plastics, O-rings) and materials containing fluorine (formation of HF/TF which attacks glass) must be avoided [10]. Even when using stainless steel, tritium will eventually be lost due to wall interactions (and tritiated methane will be produced). Thus, a single wall of containment is not enough and as best practice a tritium confinement strategy and leak control of three layers is used for safety reasons:

1. First layer:

   This layer is also referred to as “primary containment” and is a passive barrier that includes equipment and piping enclosing tritium gas operations. Leakage should be kept below values of $1 \cdot 10^{-7}$ to $1 \cdot 10^{-8}$ $Pa \cdot m^3/s$ per system [10].

2. Second layer:

   This layer is also referred to as “primary confinement”, since it is the first active system, and is designed to protect workers by limiting releases of radioactive materials into the accessible working areas. These are secondary enclosures filled with an inert gas atmosphere (e.g. N_2) and maintained at a negative pressure to the environment to avoid leakage to the room spaces, with a dedicated detritiation system to continuously clean said atmosphere (e.g.: gloveboxes + glovebox detritiation systems). Oxygen concentration due to in-leakage should be kept below 2.0%, to avoid excessive formation of tritiated water and prevent the formation of ignitable mixtures.

3. Third layer:

   This layer is also referred to as "secondary confinement" is another active layer and prevents releases to the working areas accessible by non-radiological-authorized workers, the general public and/or the environment (i.e.: Room / Building Sector + Exhaust Detritiation System).

All the rooms of the EU-DEMO Tritium Plant building that contain primary confinement systems are considered as C2 contamination class according to ISO 17873 [11]. This means that during normal operation, active species should not be present above the allowable threshold outside the second layer and so, the HVAC exhaust will be directly sent to the stack without treatment. In the event of off-normal operation (e.g. opening of a glovebox for maintenance, component replacement/movement), controlled areas with moderate levels of surface or airborne contamination are expected and the air of the building sector will be sent to the N-EDS-OT&R. Table 1 offers an overview of the different classifications for rooms according to ISO 17873.

Class	Expected normal and/or occasional contamination
C1	Means a clean area free from normal radioactive contamination, whether surface or airborne. Only in exceptional situations, a low contamination level can be accepted.
C2	Means an area that is substantially clean during normal operation. Only in exceptional circumstances, resulting from an incident or accident situation, is a medium level of surface or airborne contamination acceptable, so appropriate provisions must be made for its control.
C3	Means an area in which some surface contamination could be present but it is normally free from airborne contamination. In some cases, resulting from an incident or accident situation, there will be a potential for surface or airborne contamination at a level higher than in C2 areas, so that suitable provisions must be made for its control.
C4	Means an area in which permanent, as well as occasional, contamination levels are so high that there is normally no access permitted for personnel, except with appropriate protective equipment.

Table 1 – Classification of containment classes taken from ISO 17873:2004.

The fact that permeation cannot be avoided affects the design of equipment and piping geometry as minimizing their sizes not only reduces the tritium inventory but also the external area through which tritium can escape. Furthermore, permeation through hot structural materials starts to become significant at temperatures above 150ºC, and a "vacuum jacket", which stays at room temperature and acts as a first layer is used to recover the tritium permeated through the equipment wall.

Regarding safe tritium storage while it is possible as gas or liquid, metal hydrides are preferable due to safety reasons as tritium is actively bound. Hydrides provide the highest density and most stable alternative. A typical technology is the use of depleted uranium getter beds (dU-beds), which can fit 3 hydrogen atoms per atom of uranium (forming UQ_3) at 27ºC.

1.4 Objective & structure of this work

As has been established, the minimization of tritium inventories in the fuel cycle is crucial for safety and economic reasons. This directly transfers to the pipe network used inside the tritium plant, which can carry tritiated streams, calling for the minimization of the pipes volumes.

The first objective of this work is therefore to identify and estimate the dimensions of all the tritium plant equipment, group them into secondary enclosures and obtain the required footprint and volume. Afterwards, an optimized layout must be proposed in which the operational tritium inventory found inside the pipes that interconnect subsystems can be minimized, followed by a dimensioning of said piping and calculation of the inventory.

The footprint of the plant must include all the fuel cycle equipment plus any ancillary equipment required for the proper function of the plant and consider the need of spare (stand by) equipment for reliability reasons. Understanding of the footprint requirement is critical since the facility, due to the presence of tritium, will be nuclear rated and significantly more expensive than a comparable inactive facility.

While the layout and piping must minimize the operational tritium inventory, it must also focus on arranging the subsystems in a way that considers accessibility for operation, maintenance and inspection, as well as containing and limiting any potential safety event.

This work will be aimed at establishing a calculation methodology and serve as a guideline for further development of the Tritium Plant engineering, since the project is still in a conceptual stage and the input parameters are likely to change as the project evolves.

This thesis is divided into 4 sections. Section 1, “Introduction”, has described the context in which it has been developed, namely, the European demonstration fusion power plant project, its fuel cycle, the challenges of tritium handling and the objectives of this work. Section 2, “Development of a design basis & layout optimization method”, introduces the assumptions, simplifications, properties and design criteria defined. Section 3, “Optimized tritium plant layout & piping”, presents and discusses the final sizing and grouping of equipment, the required footprint and volume for the groups and their rooms, the optimized layout, a comparison to the ITER tritium plant building, the pipe sizing and tritium inventory estimation, and a sensitivity analysis on the tritium inventory contained in piping. Finally, Section 4, “Summary & conclusions”, summarizes the work done and proposes future improvements for the engineering stage.

2 Development of a design basis & layout optimization method

2.1 Block size definition

The first step in determining the plant layout is to develop and understand the space requirements of the individual subsystems.

The determination of the space requirements for the plant systems can be divided into two tasks. The first one consists of identifying and sizing all the required equipment, and the second, of grouping the identified equipment into assemblies that can be housed in a confinement structure and sizing them.

For each of the fuel cycle system blocks, the EU-DEMO project team has already identified subsystems as outlined in section 1.2 and essential equipment for the process. Based on that input, each subsystem and equipment needs to be assessed in order to identify the requirement of spare equipment, additional heat transfer equipment or turbomachinery, and ancillary equipment to support the systems operation. It is worth mentioning that it was decided that each confinement structure would have its own distributed detritiation system instead of having a centralized unit for the whole plant. This allows the use of standardized packaged equipment each of which discharges the generated tritiated water directly to the WDFT.

Since two breeding blankets technologies and two TERS are being considered in the EU-DEMO project, the tritium plant must include two operational modes, A and B. Mode A contains the OUTL-TC and OUTL-CP associated with the WCLL TERS. Mode B contains the OUTL-TC and OUTL-CP associated with the HCPB TERS. Equipment for both operational modes are taken into consideration when sizing the facility.

Table A-1, Table A-2 and Table A-3 in the annex list all the equipment required for each system. Some of the originally identified equipment was already pre-sized (shown in bold), although most of the identified auxiliary components required a size estimation. The criteria used in identifying and sizing additional equipment is given in the following subsections.

2.1.1 Equipment identification

Sparing philosophy

Redundancy for specific equipment must be considered analyzing whether or not the equipment can be bypassed during operation. The sparing philosophy goes as follows:

i. Critical equipment has been considered to have a spare (1+1, 2+1, etc.). In the case of EDS, complete trains are considered under this philosophy.

ii. Should there be any equipment that could operate at reduced capacity for a short period of time without affecting the operation of the plant, then instead of adding a full size spare, the possibility of mounting two equipment in parallel with 50% capacity (2+0 or 2x50%) must be assessed.

iii. Compressors, pumps and filters are considered to have a higher rate of failure than vessels, columns and heat exchangers, so at least one spare equipment needs to be mounted in order to secure the process operation.

iv. Primary confinement detritiation systems (GB-DS / MB-DS) are considered to be highly reliable packages and thus only one per confinement volume will be installed, considering that there will be some spare skids in stock ready for replacement.

v. Even though each confinement volume contains only one detritiation package, should it fail, the design flowrate of these skids is such that they can support the detritiation of the atmosphere of another box until the out-of-service skid can be replaced.

Heat exchangers

The plant requires a large amount of heat exchangers, most of which have not yet been sized by the EU-DEMO project team. For this reason, some design parameters have been defined.

For the systems in which cooling water is required, an arrangement of two water loops is considered [10]. There will be an inner loop serving the main equipment and in which the water might be exposed to tritium since only one wall separates the fluids (water-to-gas-exchanger), and a second, outer loop in which the tritiated cooling water exchanges heat with an open cooling water loop (water-to-water-exchanger). Cooling water from the inner loop is circulated with dedicated pumps for each glovebox in order to minimize the transport of this water. Cooling facilities (CWS) for the outer cooling water are considered to be outside battery limits, so the piping in and out will only be accounted for in terms of space inside the rooms but not dimensioned (see section 2.3.3). An inlet temperature of 5 ºC is considered to be achievable by the use of cooling towers plus a chilling step, thus enabling a minimum temperature for the process streams of around 15 ºC to 25 ºC considering pitch temperatures of 5 ºC to 10 ºC for each step.

A cryogenic cooling system is required for the cryogenic distillation units in the ISS. It is assumed that helium at 4 K and 80 K is readily available from the cryoplant building. The required space for this piping system will also be accounted for but not dimensioned (see section 2.3.3). Cryogenic distillation in the PRS is done by the use of cryocoolers [12] eliminating the need for cryogenic cooling fluid. Finally, some streams of low flowrate and temperature are considered to be cooled down by dissipation of the heat to the environment along their routing.

Regarding the heating, most of the requirements are met by electric heating and, when hot water or oil is needed, it is supplied in-situ by electrical heaters and pumps (IRPRS, WCPS).

2.1.2 Equipment sizing

After the identification of all the process equipment expected to be found in the plant, they need to be classified by whether or not they fit inside standard 60 m^3 gloveboxes for primary confinement [13]. For equipment that can fit inside gloveboxes, three sizes categories have been defined: small (S), medium (M), and large (L) whenever there was no available pre-size information.

- Small equipment refers to table-top equipment with a maximum volume of 0.1 m^3,
- Medium equipment refers to equipment up to 2 m^3,
- Large equipment accounts for equipment up to 4 m^3.

These sizes are based on commercially available equipment. For example, the Eumeca Model 15 m^3/h scroll pump with 0.06 m^3 (365 mm x 460 mm x 350 mm) [14], which is a tritium compatible vacuum pump, belongs to the “small equipment” category.

An example of a medium size equipment is a packaged nitrogen generator such as the Atlas Copco NGM 3 with 1.32 m^3 (820 mm x 772 mm x 2090 mm) [15]. In combination with the Atlas Copco oil free compressor LFx 2.0 standard unit with 0.37 m^3 (890 mm x 828 mm x 505 mm) [16] they provide similar equipment as needed for the primary confinement detritiation systems, namely absorber beds and compressor.

Lastly, the Atlas Copco oil free blower ZL3000 standard unit [17] is the reference taken for the large size category, with 3.65 m^3 (1643 mm x 1320 mm x 1687 mm), which, with a flowrate of 3000 m^3/h has the expected dimensions for the EDS trains compressors (two in parallel would be required to achieve the 5000 Nm^3/h flowrate).

Additionally, some equipment has been specifically sized:

- Filters after bed reactors were considered as 0.5 m extra length of the vessel.
- Dimensions for water electrolyzers in the WDS (D=1.5 m; L=2.5 m) were obtained from McPhy McLyzer 200-30 electrolyzers [18] [19], which each produces 200 Nm^3/h. Even though this is an alkaline electrolyzers, which requires an additional electrolyte system whose fluid (aqueous KOH) would get tritiated, it is safe to assume that the space requirement in the eventual selection of PEM technology will be the same or smaller. Due to the electrolyte system tritium incompatibility, its space requirement has not been considered.
- In the case of gas storage for oxygen, hydrogen and deuterium, 50 L gas cylinders were considered. Standard supply of these cylinders can be found in 12-cylinder bundles with the dimensions: 1.00 m x 0.77 m x 1.90 m [20] (1 m x 1 m x 2 m has been considered in this work).
- Permeators were sized by grouping the tubes in 10-tubes bundles inside a shell pipe. A 10-cm-diameter shell pipe can fit between 10 and 15 1-cm-diameter tubes.
- dU-beds for DT and T_2 storage, were sized based by extrapolating the information on [21] which states that a 5.2 kg dU-bed can hold 33 mol Q_2 (around 200 g T_2) and the dimensions of a commercially available dU-bed from Torion Plasma Corporation [22] which contains 80 g dU-bed in a 1.24 L vessel. This means that a vessel for 5.2 kg of dU requires around 80 L, which is rounded up to 100 L when considering interconnection pipes and valves.
- For the SVS unit 15 m^3, a quarter of a standard glovebox, was considered.

2.1.3 Grouping of equipment

Gloveboxes

The determination of the required glovebox size and available space for equipment therein must also take into account some constraints. The maximum size of a glovebox is assumed to be 2 m x 10 m x 3 m; this is a commercially available size [13] that can be transported by truck. Each glovebox will be composed of four 2.5 m-long modules, since the modularity of the gloveboxes allows the complete removal and replacement of a module in order to reduce the time that the plant has to be offline.

Half a meter from the bottom and half a meter from the top of each glovebox is reserved for interconnecting piping, drains, vents, instruments, cables, and supporting structures. At least 10 cm on the lateral sides of each glovebox is reserved for gloves and free space for ease of manipulation. Maximum reach of a glove is considered to be 0.75 m. Tritiated water will flow by gravity to the tanks located in the basement. Doing so reduces the need of equipment, particularly pumps.

Individual equipment will not be removable from inside the glovebox. Instrumentation may be replaced if reachable. The limiting factor for mounting equipment inside gloveboxes is considered to be the required height, limited to 2.0 m.

Figure 2 presents the side views of the modularized standard glovebox, with indication of the circulation areas around it.

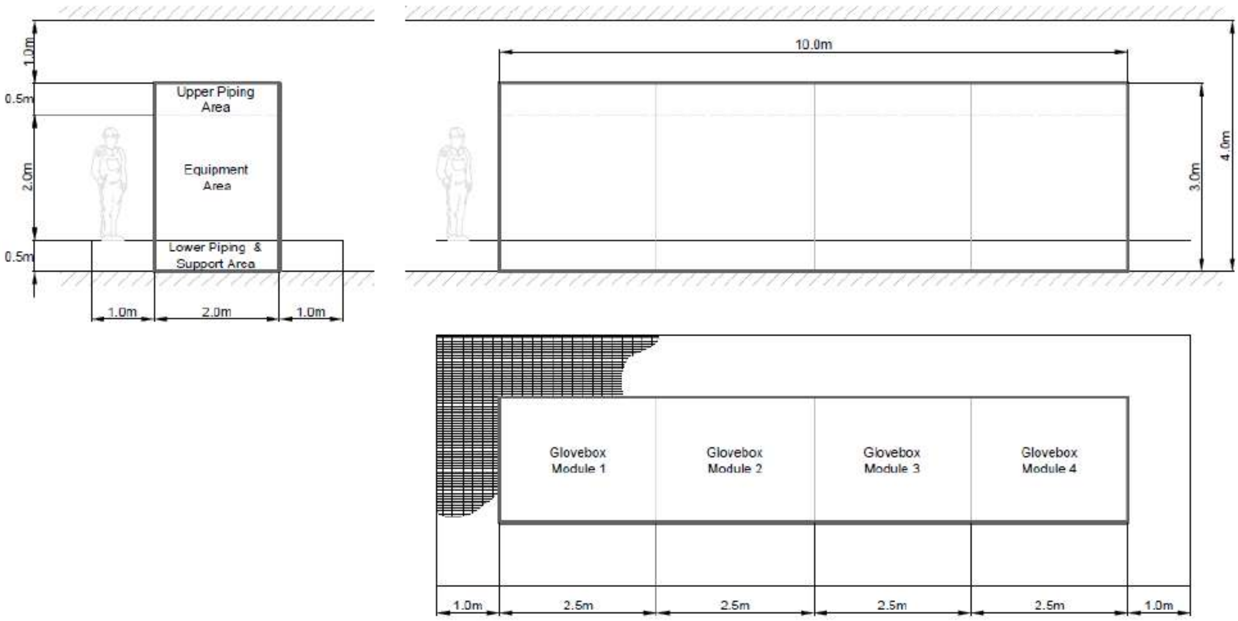

Figure 2 – Views and dimensions of a typical 60 m^3 glovebox.

These points are translated into the calculations by considering that medium and large equipment possess a fill factor of 70%, meaning that 30% of the volume they occupy when considered as a square box, is free space, and, that the net equipment volume is considered to represent a maximum of 40% of the required glovebox size. The remaining 60% corresponds mainly to free space but also to piping, supporting structures and room for equipment manipulation inside the box. The only exception to this are the electrolyzers employed in the WDS which are considered to fill 80% of their corresponding “box volume” inside the glovebox instead of 40%, since they are compact and do not require much supporting, piping and instrumentation.

All pipes coming in and out of gloveboxes are required to have valves to each side of the boxes wall with venting capability, to permit the isolation and removal of the glovebox without the need to shut down and evacuate all the plant. All vent lines are to be connected to the SVS. Piping transporting tritiated species between two different gloveboxes are encased by a secondary layer connected to the GB-DS of one of the gloveboxes. Figure 3 shows the mentioned valves arrangement.

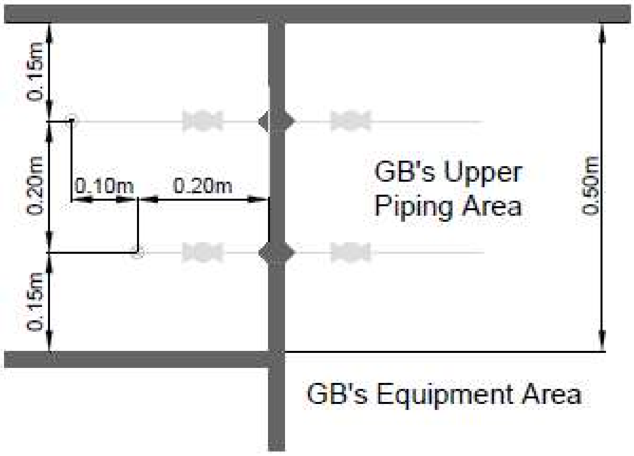

Figure 3 – Valves arrangement for pipes going through gloveboxes walls.

Metalboxes, coldboxes and tanks

Equipment unable to fit inside a glovebox requires special consideration. Cryogenic distillation columns, with their corresponding condenser, reboiler, and feed liquefiers, are consider to be located inside a coldbox which also provides the same confinement function as a regular glovebox. A separation between columns and between columns and the coldbox walls is adopted as 0.5 m. Coldboxes additionally require an external wall separated 0.5 m from the internal wall, to operate under vacuum pressure for thermal insulation. Regarding the height of these primary confinements, an additional 20% from the columns height is considered. A similar criterion has been assumed for big equipment without special temperature requirements, such as the liquid phase catalytic exchange column (LPCE) or the wet scrubber columns that will be confined inside simple-walled metalboxes. Lastly, process water, drain and emergency tanks are simply located inside rooms in which the air is continuously processed through the N-EDS-OT&R when in service. Examples of both kinds of this primary confinements boxes are shown in Figure 4.

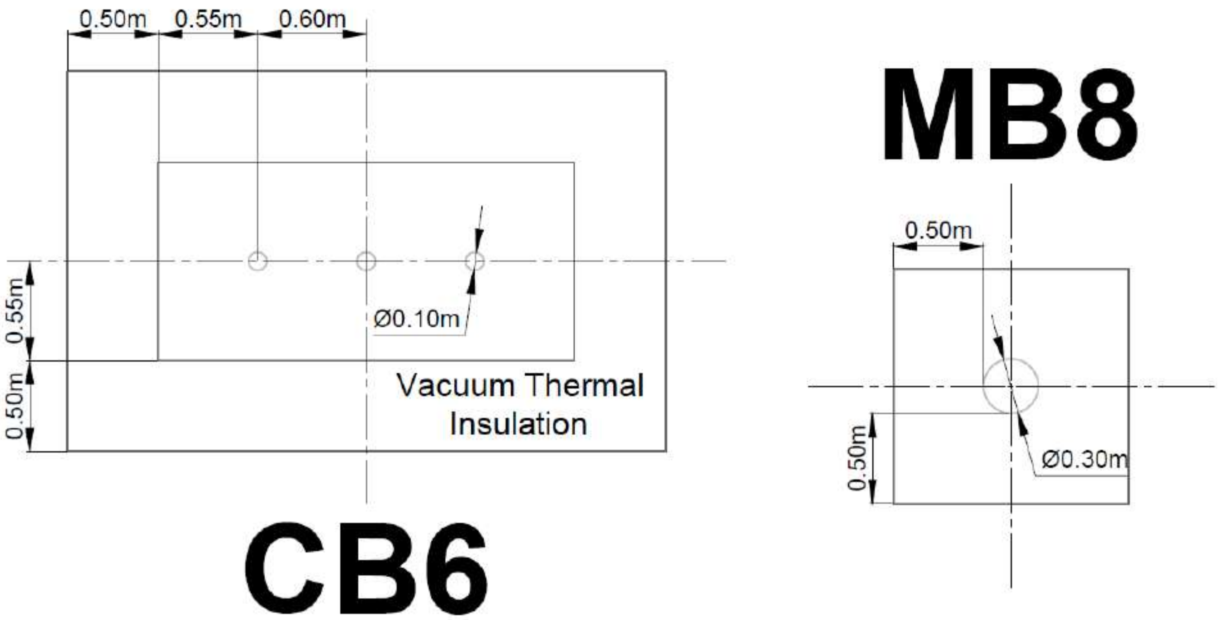

Figure 4 – Top view of a coldbox and a metalbox.

2.2 Piping dimensioning strategy

The determination of the tritium inventory in interconnection pipes is performed by calculating the required internal diameter of the piping, which is obtained based on the flowrate and allowable pressure drop criteria. All pipes must be designed for internal pressure according to DIN EN 13480-3 [23] and standard thickness and outer diameters are selected based on DIN EN ISO 1127 [24]. There is a lack of specific European standards that apply to tritium handling facilities, and since this work involves a first estimation of the tritium inventory found in the interconnecting pipes of the tritium plant, the use of the DIN standards is considered appropriate in this instance. A case could also be argued for the use of KTA standards such as 3201.2 [25] and 3211.2 [26]. However, they apply to “pressure and activity-retaining systems and components of light water reactors of fission power plants”, and both are meant for pipes bigger than DN50, which is mostly not the case.

All tritiated lines must also be verified to withstand vacuum conditions, corresponding to the evacuation required for shut down (decommissioning), so that any tritium trapped in the steel can be released. Taking into account a RAMI-friendly approach, the last line sizing iteration focuses on unifying pipe diameters and thicknesses in order to reduce the stock of different pipe types.

An important input information is the steady-state flowrates and composition of the process streams between the system blocks, which serve as input for the calculation of pipe diameters. All sizing calculations are based on a machine gas throughput of 430 Pa·m^3/s scenario [4], which is an upper limit for the flowrates on the EU-DEMO project. The process of identifying, grouping and arranging the blocks and units also split up theoretical streams between systems into actual pipe connections in which tritium flows continuously, which require sizing. The design flowrates, compositions, inlet pressure and temperatures used for the pipe sizing can be found in Table A-4 and Table A-5 in the annex.

2.2.1 Simplifying assumptions

The operational tritium inventory calculation will only consider the amount of tritium that is held up in the pipes connecting the process subsystems outside gloveboxes in continuous operation. The tritium absorbed and fixed in the steel lattice and the tritium inventory inside the equipment or the pipes inside the subsystems will not be estimated in this work.

All gaseous streams are modelled thermodynamically as “ideal gas” meaning that all the properties are only a function of the temperature and the composition. Ideal gases make ideal mixtures and thus, the properties of a gas mixture are obtained by weighting the properties of the pure species with the molar fraction. This simplification is done taking into consideration that the gas molecules present are non-polar and are found at near ambient conditions. The only streams working at higher pressure (around 80 bar) are the primary coolant in the case of the helium cooled blanket and, since it is a noble gas, it behaves as an ideal gas until around 100 bar.

All analyzed flows are modelled in continuum mechanics as incompressible, isothermal, Newtonian and in steady state. In order for the incompressible flow assumption to be true, density must remain (almost) constant along the pipe and this is achieved by keeping the pressure drop low and at constant temperature, which in combination with the Newtonian fluid assumption means that the viscosity is also constant.

2.2.2 Piping design criteria & constraints

The allowable pressure drop (Δp_{allow}), design pressure (DP) and design temperature (DT), are reference parameters to which the designed pipe needs to be contrasted. Pressure drop criteria are of concern to the proper operation of the plant, while DP and DT criteria are derived from process safety and integrity criteria of the pipes and equipment. This section specifies the criteria that needs to be fulfilled.

1. Pressure drop:

   a. Liquid streams:

In the case of liquids, the allowable pressure drop per pipe length depends on the service and the condition of the fluid, with the goal of obtaining reasonable sizes for pumping equipment. Table 2 presents the normal and maximum allowable pressure drop per pipe length for different situations:

Table 2 – Allowable pressure drop criteria for liquids.

Liquid lines		$\Delta \dot{p}$ (bar/100 m)	
		Normal	Maximum
Pump suction	Liquid at bubble point	0.0500	0.1000
	Non boiling liquid	0.1250	0.2500
Unit lines	p <= 50 bar	0.3500	0.5000
	p > 50 bar	0.7500	0.9500

   b. Gaseous streams:

Table 3 sets the normal and maximum allowable pressure drop per pipe length for certain operating pressures. The allowable pressure drop for other operating pressure values must be interpolated from the values in the table. These limits ensure that the pressure drop in 100 m is kept below 4%, so that vacuum pumps and compressors are not oversized.

Table 3 – Allowable pressure drop criteria for gases.

Operating pressure	$\Delta \dot{p}$ (bar/100 m)	
	Normal	Maximum
p = 0.75 bara	0.0200	0.0300
p = 20 barg	0.0700	0.1050
p = 50 barg	0.1250	0.1875
p = 80 barg	0.1950	0.2925
p = 138 barg	0.2780	0.4155

2. Design pressure

Sizing the piping required the determination of a design pressure (DP), which considers additional safety margins compared to the normal operational pressure (NOP).

   a. The maximum operational pressure (MOP) is determined based on the normal operational pressure (NOP).

      i. If the NOP is below 20 barg, MOP = NOP + 1 bar

      ii. If the NOP is equal to or higher than 20 barg, MOP = NOP x 1.05

b. The design pressure (DP) must be the highest of the following:

   i. 3.5 barg

   ii. MOP + 3.5 bar

   iii. MOP x 1.10

   Additionally, tritiated gas lines must be able to withstand at least 10 bar in the event of an upstream explosion. If the calculated MOP is lower than this value, then 10 bar should be the reference.

3. Design temperature

All the lines sized in this work operate at temperatures above 0 ºC. The design temperature (DT) shall be the greatest of the following, and indicated in multiples of 25 ºC:

a. 50 ºC

b. Normal operational temperature (NOT) plus 25 ºC

2.2.3 Correlations used for piping dimensioning

To obtain the required internal diameter of pipes, the pressure drop along it needs to be calculated and contrasted to the allowable pressure drop. The determination requires two calculations, one for the straight pipe and one for the fittings.

1. Pressure drop in straight pipes:

Pressure drop in pipelines (Δp_s) calculation require a way to estimate the Fanning's friction factor (λ). In this work, the generalized Churchill correlation [27] has been selected since it is valid for any Reynolds number (Re) and relative roughness (${}^{\varepsilon}/_{D}$). The equations, in terms of the λ, are as follows:

$$\lambda = 2 \cdot \left[\left(\frac{8}{Re} \right)^{12} + \frac{1}{(A+B)^{3/2}} \right]^{1/12} \quad \text{(2.2.3-EQ1)}$$

Where:

$$A = \left[2.457 \cdot \ln \frac{1}{\left({}^{7}/_{Re} \right)^{0.9} + 0.27 \cdot {}^{\varepsilon}/_{D}} \right]^{16} \quad \text{(2.2.3-EQ2)}$$

And

$$B = \left(\frac{37530}{Re} \right)^{16} \quad \text{(2.2.3-EQ3)}$$

Then, the pressure drop in a straight pipe is obtained from:

$$\Delta p_s = \frac{\lambda \cdot 2 \cdot L \cdot \rho \cdot \langle v \rangle^2}{D} \quad \text{(2.2.3-EQ4)}$$

Where:

- L is the pipe length,
- ρ is the fluid density,
- $\langle v \rangle$ is the mean velocity inside the pipe,
- D is the pipe internal diameter.

2. Pressure drop in fittings:

The pressure drop in fittings (Δp_f) can be estimated in different ways. One method assigns an equivalent length over internal diameter $\left(\frac{L}{D}\right)_{eq}$ to each kind of fitting and the pressure drop is then calculated in the same way as in a straight pipe.

$$\Delta p_f = \lambda \cdot 2 \cdot \rho \cdot \langle v \rangle^2 \cdot \sum \left(\frac{L}{D}\right)_{eq} \qquad (2.2.3\text{-EQ5})$$

The equivalent L/D method is good as a first approximation of the pressure drop. Nevertheless, better results can be obtained by applying Darby's 3K method [28], since it takes into account the Reynolds number and fitting diameter effects on the pressure drop of each fitting. The parameters K_1, K_i and K_d are obtained from a table based on experimental data, and used alongside Re and the nominal diameter in inches ($D_{n,in}$) to calculate a K_f, which in turn is used to calculate the pressure drop:

$$K_f = \frac{K_1}{Re} + K_i \cdot \left(1 + \frac{K_d}{D_{n,in}^{0.3}}\right) \qquad (2.2.3\text{-EQ6})$$

$$\Delta p_f = \frac{K_f \cdot \rho \cdot \langle v \rangle^2}{2} \qquad (2.2.3\text{-EQ7})$$

In this work, only 90º elbows and ball valves are considered for the pipe sizing. The parameters for these fittings are given in Table 4.

Table 4 – Constants for loss coefficient for valves and fittings [28].

Fitting		Description	(L/D)eq	K1	Ki	Kd
Elbows	90º	Threaded, standard (R/D=1)	30	800	0.140	4.0
Valves	Ball	Standard, beta=1	3	300	0.017	3.5

2.2.4 Property data

This section summarizes all the fluid and piping material properties required for the dimensioning.

1. Fluid species & properties

Properties such as molecular weight (Mr), viscosity (μ) and density (ρ) are required for the pressure drop calculations. Table 5 and Table 6 present the properties used for calculations of liquid and gaseous species, respectively.

a. Liquid streams:

All the analyzed liquid streams are water streams, with different degrees of tritiation. For liquid water, even if it is tritiated, the properties have been assumed to be those of regular water, since the concentration of tritiated species is not enough to have a significant impact in the properties such as density and viscosity of the bulk.

Table 5 – Water properties.

Species		Molecular weight	Viscosity [x10^{-3} Pa·s] @				Density [kg/m^3] @				Source
			300 K			500 K	300 K			500 K	
		kg/kmol	1 bar	1.2 bar	5 bar	120 bar	1 bar	1.2 bar	5 bar	120 bar	
Water	H_2O	18.0153	0.85374	0.85374	0.85371	0.12034	996.56	996.57	996.74	839.78	NIST [29]

b. Gaseous streams:

Table 6 – Properties of gaseous species.

Species		Molecular weight	Source	Viscosity [x10^{-7} Pa·s] @				Source
				1 bar		80 bar		
		kg/kmol		300K	500K	300K	500K	
Hydrogen	H_2	2.016	NIST [29]	89.39	127.38			NIST [29]
Deuterium	D_2	4.028	NIST [29]	126.41	180.15			NIST [29]
Tritium	T_2	6.032	NIST [29]	*154.82*	*220.63*			Estimated
Deuterium tritide	DT	5.030	NIST [29]	*141.33*	*201.41*			Estimated
Hydrogen tritide	HT	4.024	NIST [29]	*126.41*	*180.14*			Estimated
Helium	He	4.003	NIST [29]	199.30	283.63	201.92	285.24	NIST [29]
Argon	Ar	39.948	NIST [29]	227.41	340.77			NIST [29]
Xenon	Xe	131.293	NIST [29]	231.94	371.78			NIST [29]
Oxygen	O_2	31.999	NIST [29]	206.52	304.86			NIST [29]
Nitrogen	N_2	28.013	NIST [29]	178.90	260.63			NIST [29]

For tritiated species, the viscosity has been estimated by multiplying the H_2 viscosity by the squared rooted ratio of the nucleons of the species and the nucleons of hydrogen (A_i/A_{H2}), assuming that the temperatures are high enough to consider that the rotations of both molecules are classical, as done in references [30] and [31].

Thus:

$$\mu_i = \sqrt{A_i / A_{H2}} \cdot \mu_{H_2} \qquad (2.2.4\text{-EQ1})$$

2. Piping material

Due to tritium handling restrictions and in order to avoid corrosion in non-tritiated pipes, all the piping in the plant is defined as being made of low carbon stainless steel. In particular, DIN X2CrNiMo17-12-2 (EN 1.4404 – ASTM 316L) is the selected material.

For the internal and external pressure calculations, the following properties have been used:

- Austenitic steel.
- Corrosion allowance (c): 0 mm
  No extra thickness due to corrosion or tritium attack through diffusion has been considered for the materials. It has been assumed that helium and tritium embrittlement of the containment walls is not a significant issue at low pressures even after years of exposure [10].
- Roughness (ε): 0.002 mm [28].
- Poisson's ratio (υ): 0.28
- Welding factor (z): 1 [23].
- Elongation at break: 35% (material group 13E0 according to DIN EN 1092-1 [32])
- Wall thickness tolerance class: T3 (±10% with min. ±0.2mm) according to DIN EN ISO 1127 [24].

The elasticity module is obtained from DIN EN 10088-1 [33] and is shown in Table 7 for different temperatures.

Table 7 – Elasticity module for DIN X2CrNiMo17-12-2.

T	ºC	20	100	200	300	400	500
E_t	GPa	200	194	186	179	172	165
	MPa	200000	194000	186000	179000	172000	165000

The specified minimum values for the 0.2% and 1.0% yield strength at different temperatures were obtained from DIN EN 10088-3 [34] as shown in Table 8.

Table 8 – Minimum values for 0.2% and 1.0% yield strength for DIN X2CrNiMo17-12-2.

T	ºC	20	100	150	200	250	300	350	400	450	500	550
$R_{p0.2}$	MPa	200	165	150	137	127	119	113	108	103	100	98
$R_{p1.0}$	MPa	225	200	180	165	153	145	139	135	130	128	127

2.2.5 Pipe diameter sizing

The pipe diameter sizing is closely related to the layout optimization determining the pipe lengths. As no layout is available for the first iteration, a preliminary calculation is carried out to obtain the order of magnitude of the tritium inventory in pipes and to classify the streams accordingly. After the development of the plant 3D model, pipes can be drawn and the actual length, amount of elbows and valves be obtained, allowing a more precise calculation of the pipes diameters.

The first step in the calculation procedure is to determine the required internal diameter:

1. Set the flowrate ($\dot{V}$), composition (x_i), inlet pressure (p) and inlet temperature (T).
2. Using the pure substances properties from Table 5 and Table 6, determine the mixture molecular weight (Mr), density (ρ) and viscosity (μ) for each stream composition, pressure and temperature.

$$Mr = \sum_i x_i \cdot Mr_i \tag{2.2.5-EQ1}$$

$$\rho = \sum_i x_i \cdot \rho_i \quad @\, T, p \tag{2.2.5-EQ2}$$

$$\mu = \sum_i x_i \cdot \mu_i \quad @\, T, p \tag{2.2.5-EQ3}$$

3. Select the material. For all calculations DIN X2CrNiMo17-12-2 (EN 1.4404 – ASTM 316L) is used, and the properties from 2.2.4-2 apply.
4. **Iteration Loop 1:**
   a. Assume a starting internal diameter (ID).
   b. Calculate the flow cross section (S):

$$S = \pi \cdot \frac{ID^2}{4} \tag{2.2.5-EQ4}$$

   c. Calculate flow velocity ($\langle v \rangle$):

$$\langle v \rangle = \frac{\dot{V}}{S} \tag{2.2.5-EQ5}$$

d. Calculate Reynolds number (Re):

$$Re = \frac{\rho \cdot ID \cdot \langle v \rangle}{\mu} \qquad \text{(2.2.5-EQ6)}$$

e. Calculate relative roughness ($^{\varepsilon}/_{ID}$).

f. Calculate friction factor (λ) according to equation 2.2.3-EQ1.

g. Set the pipe length. For the first calculation, all pipes are considered to be 50m long (L) and have an additional 3m length to account for vertical correction (Δz). The subsequent calculations include the actual length obtained from the 3D model.

h. Calculate the normal allowable pressure drop according to 2.2.2-1, by using equation 2.2.5-EQ7:

$$\Delta p_{allow} = \Delta\dot{p}_{allow} \cdot (L + \Delta z) \qquad \text{(2.2.5-EQ7)}$$

i. Obtain the equivalent length $\left(\frac{L}{D}\right)_{eq}$ for fittings from Table 4. The first inventory estimation considers that each pipe has four 90º elbows and four ball valves. The subsequent estimations include the actual amounts obtained from the 3D model.

   The amount of valves is determined by the following criteria that permits the safe isolation of the plant inventory in case of a process safety event:

   i. Each line has a valve immediately before or after crossing the boundary of a box (outside the box).
   ii. When crossing internal walls or crossing between building levels, the lines have a valve on each side.
   iii. When crossing external walls (1.5 m walls), the lines have only one valve on the side of the tritium plant.
   iv. Connections to headers have an additional valve close to the header if the line is longer than 1 m.

   Figure 5 and Figure 6 show examples of each arrangement.

j. Calculate pipe pressure drop (Δp_s) with equation 2.2.3-EQ4.

k. Calculate fittings pressure drop (Δp_f) with the L/D method according to equation 2.2.3-EQ5.

l. Calculate total pressure drop (Δp_T):

$$\Delta p_T = \Delta p_s + \Delta p_f \qquad \text{(2.2.5-EQ8)}$$

5. Check that $\Delta p_T = \Delta p_{allow}$, if this is true, then the iteration for the ID is finished and its value is the ID_{req}. If not, modify the ID and return to 4.a.

Figure 7 (Decision diagram 1) represents this calculation procedure graphically.

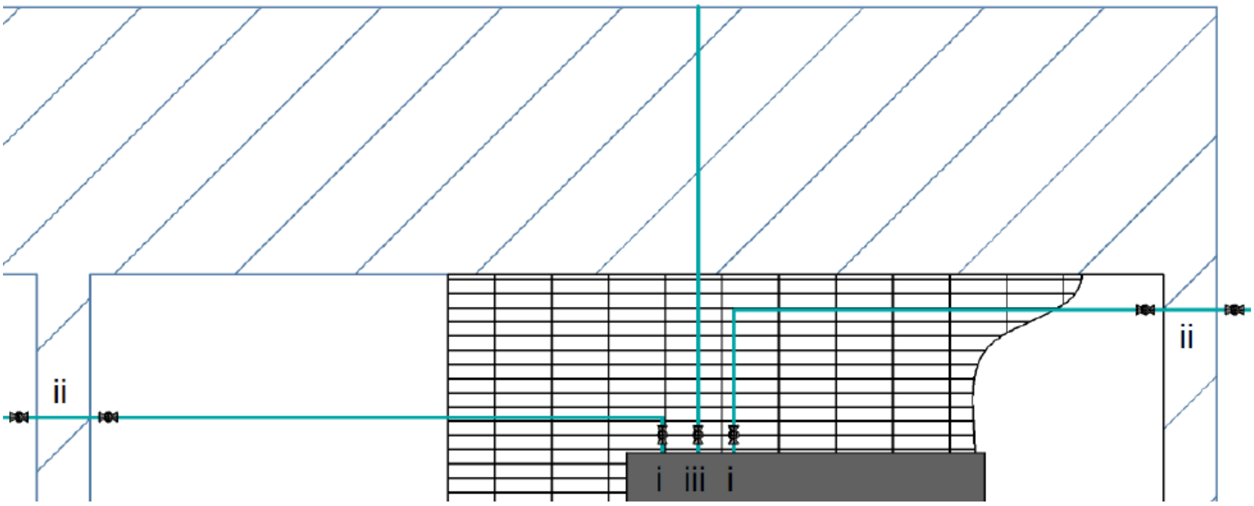

Figure 5 – Aid for the determination of the actual valves requirement in tritiated piping with the numbers indicating the different connection types as given in 2.2.5-4.i (I).

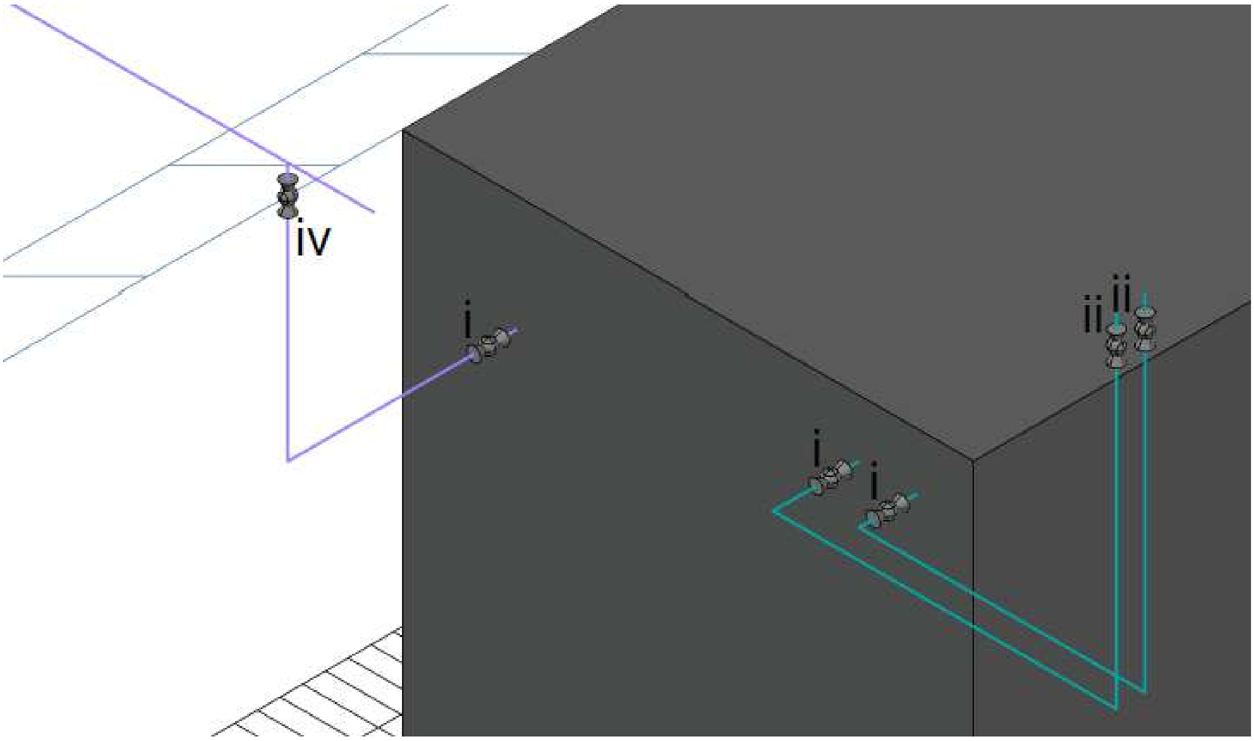

Figure 6 – Aid for the determination of the actual valves requirement in tritiated piping with the numbers indicating the different connection types as given in 2.2.5-4.i (II).

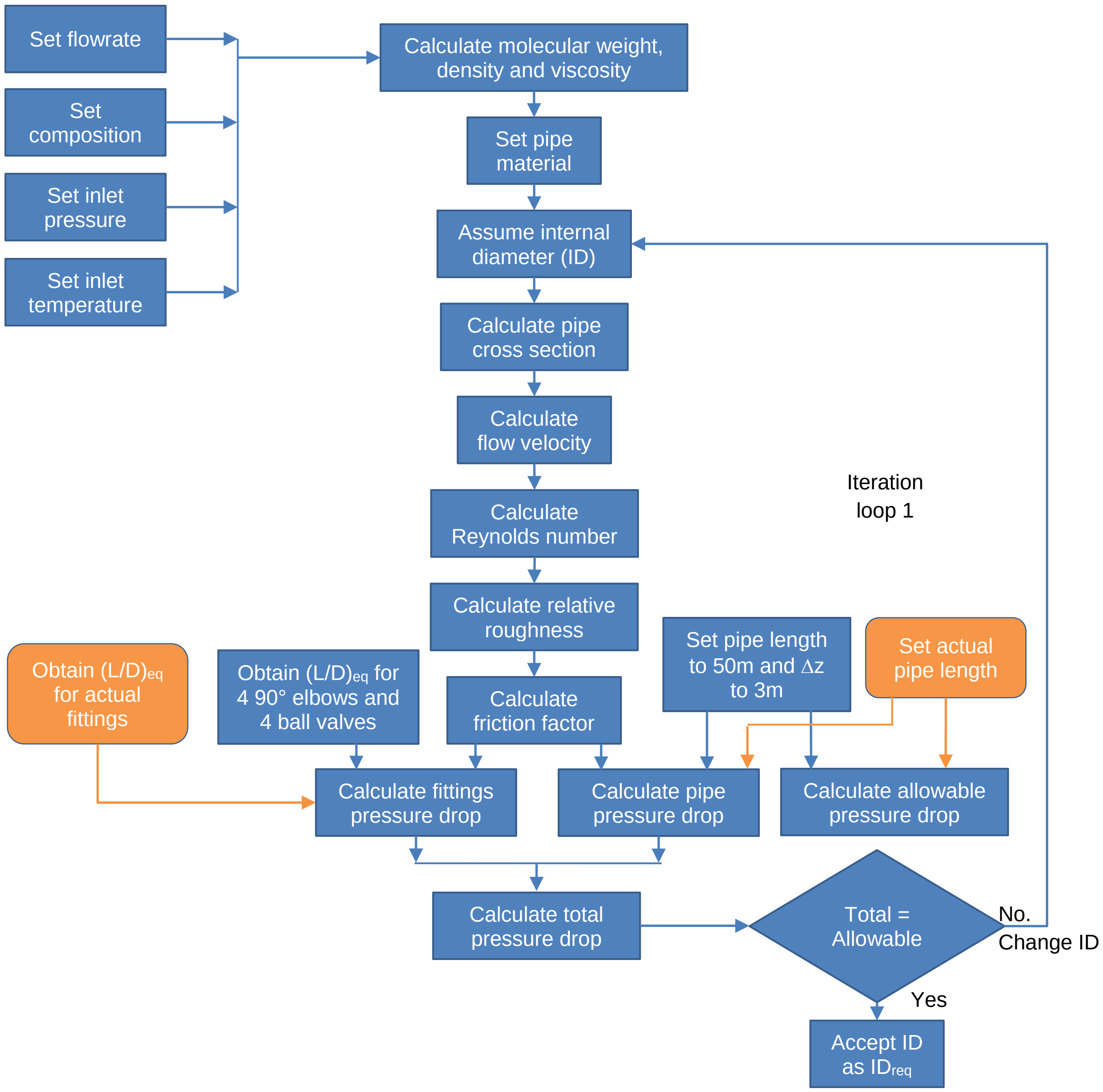

Figure 7 – Decision diagram 1 - Required internal diameter calculation. Orange boxes refer to the calculations taking into account the actual pipe routing.

Once the required internal diameter (ID_{req}) is obtained, the calculation procedure continues with the determination of the outer diameter and thickness of the pipe:

1. Determine the maximum operational pressure (MOP) and design pressure (DP) according to 2.2.2-2.
2. Determine the design temperature (DT) according to 2.2.2-3.
3. Determine the yield strength at 1.0% at the design temperature ($R_{p1.0\ t}$) with Table 8.
4. Calculate the design tension (f) according to DIN EN 13480-3 [23], section 5.2.2.1:

$$f = \frac{R_{p1.0\ t}}{1.5} \qquad (2.2.5\text{-EQ9})$$

5. Calculate the minimum required thickness (t_{min}) according to DIN EN 13480-3 [23], section 6.1, for $OD/ID \leq 1.7$ (welding factor: z=1, according to 2.2.4-2):

$$t_{min} = \frac{DP \cdot ID_{req}}{2 \cdot f \cdot z - DP} \quad \text{(2.2.5-EQ10)}$$

6. Calculate the nominal required thickness (t_{nom}) with T3 tolerance class, according to 2.2.4-2:

$$t_{nom} = \max\left\{\frac{t_{min} + c}{0.900} \;\; ; \;\; (t_{min} + c) + 0.2mm\right\} \quad \text{(2.2.5-EQ11)}$$

7. Find the next standard thickness ($t_{nom,std}$) available according to DIN EN ISO 1127 [24].
8. Calculate the required outer diameter (OD_{req}):

$$OD_{req} = ID_{req} + 2 \cdot t_{nom,std} \quad \text{(2.2.5-EQ12)}$$

9. Iteration Loop 2:

a. Find the next standard outer diameter (OD_{std}) available according to DIN EN ISO 1127 [24] and check that the selected standard thickness is available for said OD; if not, select the next one.

b. Calculate the standard inner diameter (ID_{std}):

$$ID_{std} = OD_{std} - 2 \cdot t_{nom,std} \quad \text{(2.2.5-EQ13)}$$

c. Calculate the flow cross section (S_{std}):

$$S_{std} = \pi \cdot \frac{ID_{std}^2}{4} \quad \text{(2.2.5-EQ14)}$$

d. Calculate flow velocity ($\langle v \rangle$):

$$\langle v \rangle = \frac{\dot{V}}{S_{std}} \quad \text{(2.2.5-EQ15)}$$

e. Calculate Reynolds number (Re):

$$Re = \frac{\rho \cdot ID_{std} \cdot \langle v \rangle}{\mu} \quad \text{(2.2.5-EQ16)}$$

f. Calculate relative roughness ($^{\varepsilon}/_{ID_{std}}$).

g. Calculate friction factor (λ) according to equation 2.2.3-EQ1.

h. Calculate pipe pressure drop (Δp_s) with equation 2.2.3-EQ4.

i. Obtain K_1, K_i and K_d values from Table 4 and calculate K_f for the fittings with equation 2.2.3-EQ6. For the first inventory estimation, consider four 90º elbows and four valves. The subsequent estimations include the actual amounts obtained from the 3D model.

j. Calculate fittings pressure drop (Δp_f) with the 3K method with equation 2.2.3-EQ7.

k. Calculate total pressure drop (Δp_T):

$$\Delta p_T = \Delta p_s + \Delta p_f \quad \text{(2.2.5-EQ17)}$$

10. Check $\Delta p_T \leq \Delta p_{allow}$, if this is true, then the iteration for the OD_{std} and t_{std} is finished. If not, modify the OD and return to 9.a.

Figure 8 (Decision diagram 2) represents this calculation procedure graphically.

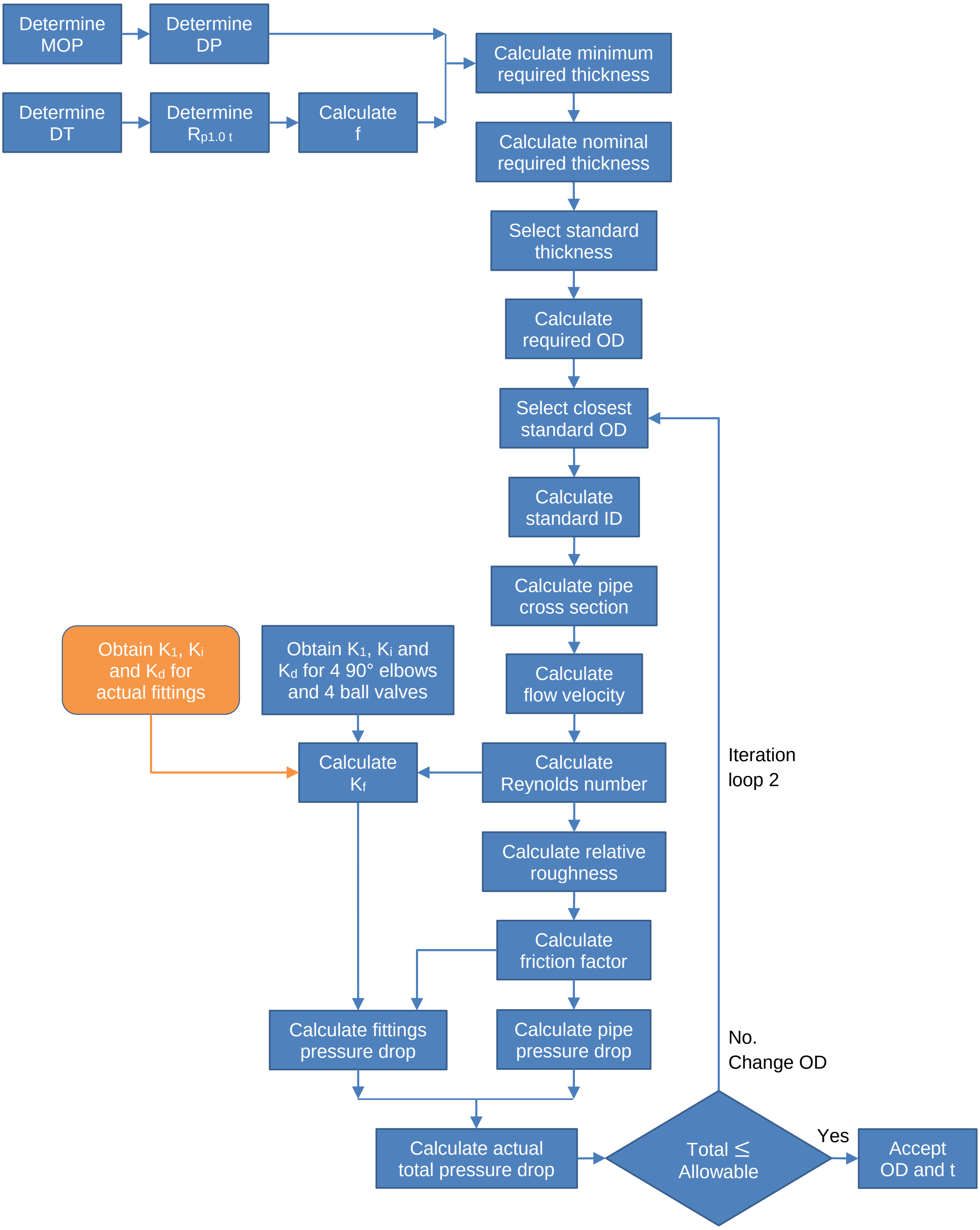

Figure 8 – Decision diagram 2 - Design for internal pressure according to DIN EN 13480-3 [23]. Orange boxes refer to the calculations taking into account the actual pipe routing.

The last step of the calculation procedure is to verify the selected pipe size (OD_{std} & t_{std}) for external pressure:

1. Calculate the analysis wall thickness (e_a) and the mean radius (R_m) of the pipe:

$$e_a = min\,\{(t_{std} - c) \cdot 0.90 \;\; ; \;\; (t_{std} - c) - 0.2mm\,\} \qquad (2.2.5\text{-EQ18})$$

$$R_m = \frac{OD_{std} - e_a}{2} \qquad (2.2.5\text{-EQ19})$$

2. Determine the yield strength at 0.2% at the design temperature ($R_{p0.2\,t}$) with Table 8.
3. Calculate the elasticity limit (S_l) according to DIN EN 13480-3 [23], section 9.2.2:

$$S_l = \frac{R_{p0.2\,t}}{1.25} \qquad (2.2.5\text{-EQ20})$$

4. Calculate the pressure at which the mean hoop stress of the cylindrical pipe at the midpoint between stiffeners reaches the yield point of the material (p_y) according to DIN EN 13480-3 [23], section 9.3.2-a:

$$p_y = \frac{S_l \cdot e_a}{R_m} \qquad (2.2.5\text{-EQ21})$$

5. For the first inventory calculation, adopt 6 m as the unstiffened pipe length (L_u). For the subsequent calculations L_u should be obtained from the 3D model; if a pipe section is longer than 6 m, then consider 6 m.
6. Calculate Z according to DIN EN 13480-3 [23], section 9.3.2-b.

$$Z = \frac{\pi \cdot R_m}{L_u} \qquad (2.2.5\text{-EQ22})$$

7. Adopt 2 as the number of complete circumferential waves forming at buckling (n_{cyl}). This value should be a round number equal or greater than 2, that minimizes the calculated value of the theoretical elastic buckling pressure at failure of an exactly cylindrical tube (p_m).
8. Calculate ϵ according to DIN EN 13480-3 [23], section 9.3.2-b.

$$\epsilon = \frac{1}{n_{cyl}^2 - 1 + \frac{Z^2}{2}} \cdot \left\{ \frac{1}{\left(\frac{n_{cyl}^2}{Z^2} + 1\right)^2} + \frac{e_a^2}{12 \cdot R_m^2 \cdot (1 - \nu^2)} \cdot \left(n_{cyl}^2 - 1 + Z^2\right) \right\} \qquad (2.2.5\text{-EQ23})$$

9. Determine the elasticity modulus at the design temperature (E_t) with Table 7.
10. Calculate the theoretical elastic buckling pressure at failure of an exactly cylindrical tube (p_m):

$$p_m = \frac{E_t \cdot e_a \cdot \epsilon}{R_m} \qquad (2.2.5\text{-EQ24})$$

11. Check that the selected n_{cyl} value minimizes p_m, if not iterate from step 7.
12. Calculate the relation p_m/p_y.
13. Obtain p_r/p_y from Table 9, interpolating as needed.

Table 9 – Table 9.3.2-1 from DIN EN 13480-3 [23].

p_m/p_y	0.0000	0.2500	0.5000	0.7500	1.0000	1.2500	1.5000	1.7500
p_r/p_y	0.0000	0.1245	0.2505	0.3750	0.4995	0.6045	0.6795	0.7200
p_m/p_y		2.0000	2.2500	2.5000	2.7500	3.0000	3.2500	3.5000
p_r/p_y		0.7545	0.7800	0.8025	0.8220	0.8355	0.8450	0.8610
p_m/p_y		3.7500	4.0000	4.2500	4.5000	4.7500	5.0000	5.2500
p_r/p_y		0.8700	0.8790	0.8865	0.8955	0.9045	0.9135	0.9165
p_m/p_y		5.5000	5.7500	6.0000	6.2500	6.5000	6.7500	7.0000 and over
p_r/p_y		0.9225	0.9285	0.9345	0.9405	0.9465	0.9525	0.9585

14. Calculate p_r with p_r/p_y and p_y.
15. Adopt k = 1.5 and the external pressure $p = p_0$ (101325 Pa).
16. Check that $p_r >= k \cdot p$. If this is true, then the selected OD_{std} and t_{std} can withstand full vacuum. If $p_r < k \cdot p$, either L_u should be reduced (by reducing the separation between stiffeners) or the e_a increased (by increasing the selected wall thickness).

Figure 9 (Decision diagram 3) represents this calculation procedure graphically.

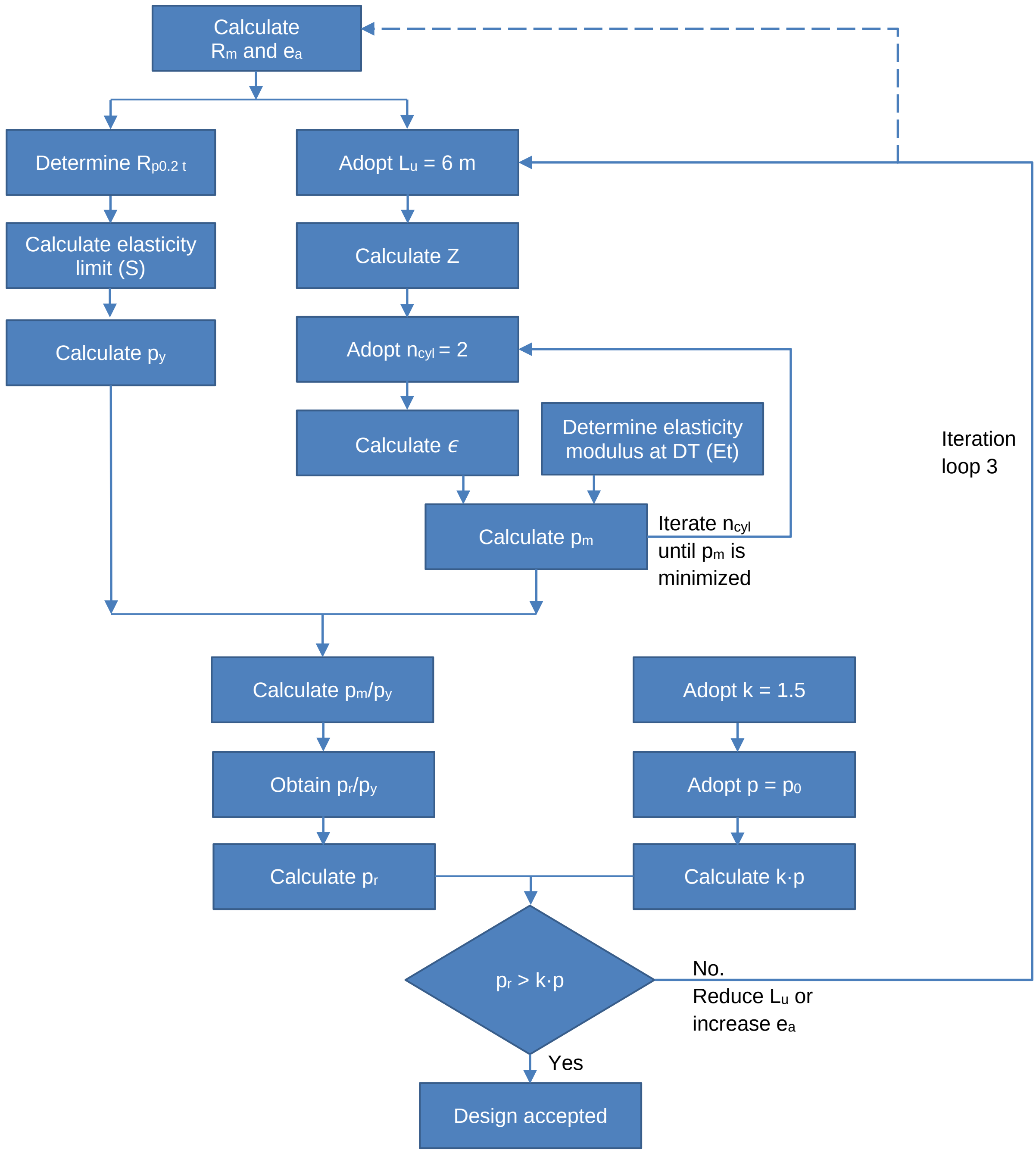

Figure 9 – Decision diagram 3 - External pressure verification according to DIN EN 13480-3 [23].

2.3 Building layout optimization

Once all the equipment is sized and organized into groups, and a first estimation of the tritium inventory in the pipes is accomplished, a footprint and volume can be assessed. Next to the process itself, there are some additional considerations that need to be tackled before defining and optimizing the building layout.

2.3.1 Safety considerations

In the TPB, as in any nuclear facility, people and process safety are major design factors. Tritium inventory inside the groups is the biggest contributor to the radioactive inventory in the plant and its presence must be addressed even though its minimization is not part of the scope of this work.

Firstly, the three layers of the tritium confinement strategy and leak control presented in section 1.4 are adopted for the plant design. Additionally, each group is separated into an individual room to prevent the spread of radioactive material in the event of a loss of the primary containment and primary confinement (first and second layer) and eventual fires. Each room can be isolated from the process by isolation valves which must be mounted to each side of pipes going through walls and floors, as previously stated in section 2.2.5. Furthermore, the SEDS is sized to treat the air of rooms in addition to the other process streams, and the groups segregation in various rooms allows the targeted treatment of a specific room instead of the whole building atmosphere. Lastly, space for the pipes of the fire suppression system in each room needs to be accounted for as well as dedicated non-tritiated rooms for the required equipment.

2.3.2 Building structure, relevant heights and piping routing

Regarding the building structure, the outer walls thickness is considered to be 1.5 m, internal walls have a thickness of at least 0.3 m, the floor thickness is 0.8 m (separation between levels) and each level will have 4.0 m of available height.

Table 10 shows certain heights for each level concerning circulation space and piping routing constrains.

Table 10 – Relevant heights for pipe routing inside the building.

	Height [mm]
Level floor	0
High concentration tritiated liquid headers (gravity flow)	200
High concentration tritiated liquids upper row (gravity flow)	400
Walkways around boxes	500
Low concentration tritiated water header	1500
Tritiated gas header (lateral room walls)	2200
Tritiated gas lines - Lower row (if needed)	2400
End of equipment area in gloveboxes	2500
Tritiated gas - Middle row	2600
Tritiated gas - Upper row	2800
Glovebox top	3000
Tritiated gas headers (over rooms doors)	3500
HVAC and rooms headers to EDS	3750
Level ceiling	4000

Piping routing inside rooms is accomplished along to the walls, to allow easy access to the boxes. If this piping transports tritiated fluids, enough space must be considered for encasing it in shafts connected to the GB-DS to provide a second layer of confinement.

The gloveboxes need to be located in a room big enough and in a suiting position to allow the complete replacement of a module, thus 3.0 m of free space for maintenance accessibility is considered in each room. In the case of metalboxes and coldboxes, this space is only 2.0 m since they cannot be removed from their rooms. Around the other sides of each box, 1.0 m corridors are required for the circulation of operators and work space.

As stated in the safety considerations, each box requires its own room, thus allowing for containment of both, leaks and eventual fires. An exception is made for EDS trains due to their low operational tritium inventory, although at least half of the trains for each EDS (NEDS, OEDS and SEDS) must be located in a different room as the other half.

The main corridors outside the rooms are required to have at least 4.0 m for maneuverability of machinery. Moreover, the main corridor of any given floor must not be located directly under/over the corridor of the floor above/below, so that, a corridor can be “crossed” by a tritiated pipe by taking that line either a level up or a level down through a room.

2.3.3 Additional space requirements

The focus is set on assessing the space required by process equipment of the fuel cycle. However, there will be additional systems that also require space in the building. The fire suppression system piping, HVAC system as well as lighting fixtures are considered to occupy 0.5 m of the height of each floor. The required space for the instrumentation & control (I&C) and electrical cable trays is accounted for in the space for corridors between gloveboxes or along the lateral walls of the rooms. Non-tritiated service pipelines such as the open cooling water loop, purified water supply, cryogenic cooling loops and gas reposition systems are not to be sized, although enough space for them will be available, assuming that they will be routed outside gloveboxes, either along the lateral walls of the rooms or over the gloveboxes tops. A room of 6 m by 12 m will be dedicated in each level to locate the programmable logic controller (PLC) and motor control center (MCC) panels/cabinets and another room with the same dimensions, for the compressed air supply and fire suppression system. The tritium export storage (tritium vault) is considered to be located on the basement of the TPB. No piping for tritium import and export is required, since this process is carried out by moving containers (e.g. dU-beds). Stairwells and elevators are located on the sides of the building, this accounts for a space of 5.7 m x 11.5 m, twice, in the plant view of each accessible level.

The control room of the plant is considered to be located in a separate building and no extra space is accounted for future expansions of the facilities.

2.3.4 Groups arrangement considerations

An analysis regarding the physical location of the groups inside the TPB must be carried out considering aspects of process flow, safety, operability and maintenance, as well as the required space of the rooms, in order to obtain an optimized layout that minimized the operational tritium inventory in pipes. The main points considered are:

- <u>Flow method</u>: The process units should be laid out *so that the material flow follows the process flow diagram. This arrangement minimizes the transfer of materials, which is* *desirable both for economics and safety* [35]. This means that closely related units should be located as close to each other as possible and not in opposite sides of the plant.

- Tritium inventory minimization: The length and diameter of pipes with high concentration of tritium have to be minimized as much as possible. This is achieved by locating the related groups close together, prioritizing connections with higher relative tritium linear density (λ_m [g $T_{2,eq}$ / m]).
- Size of the rooms: Due to their height, some boxes and equipment require to be located in rooms stretching more than one level. These rooms should be arranged so that the external building geometry is simple (i.e. box-like).
- Accessibility: Enough space needs to be accounted for in each room so that equipment can be accessed for construction, commissioning, operation and maintenance.
- Equipment inventory segregation: Different system blocks cannot share the same room in order to minimize the potential risks posed by a loss of containment or fire. Corridors are considered tritium free areas and as such, no tritiated streams should be routed through them.
- Gravity flow: In order to minimize the use of pumping equipment, tritiated water will flow by gravity through the headers to the WDFT, which then needs to be located in the basement.
- Symmetry: A symmetrical distribution of units operating in parallel helps reduce the power consumption of pumps and compressors.
- Building: The plant is located inside a multistory building, this presents the advantage that the arrangement can be assessed in 3D (different levels) and not just in 2D (one level), increasing the possibilities of connection for a box without necessarily increasing the distance between boxes.

Contemplating all these factors, it can be assumed that, since the INTL loop contains the highest tritium concentration and the OUTL the highest amount of equipment/boxes, the INTL boxes will need to be located in a central position, close to the TKB, and the OUTL can be placed around the INTL.

From this layout the full pipe routing can be drawn, allowing the determination of the actual length, amount of elbows and valves, which is used in the seconds pass of the piping diameter calculation.

3 Optimized tritium plant layout & piping

Based on the inherently safer design concept [36], the approach of this work is constructed around four major strategies:

- *"Minimize: Reduce quantities of hazardous substances."*, by grouping and arranging the subsystems in such a way that minimizes the piping.
- *"Substitute: Replace a material with a less hazardous substance."*, by specifying stainless steel as the piping material, by assuming tritium compatible equipment and by unifying the pipe types combinations.
- *"Moderate: Use less hazardous conditions, less hazardous material or energy."*, by operating at low pressure and temperature when possible and segregating the inventory into different rooms.
- *"Simplify: Design facilities which eliminate unnecessary complexity and make operating errors less likely and which are forgiving of errors that are made."*, by arranging the layout in a way that it follows the process and associated subsystems are close to each other, or by reducing the amount of pumps by using gravity flow to collect all the liquids in the basement.

3.1 Equipment identification, sizing and grouping

Starting from the original list of equipment provided as input data, the first step for obtaining the plant layout and tritium inventory consisted on properly identifying all the equipment and ancillary units. Applying the criteria detailed in section 2.1.1 the plant equipment amount was increased from 373 to 627. The reason for this is mainly the need to secure the operation by having spare equipment in case of failure of the main one. The decision of decentralizing the primary confinement detritiation systems also contributed to increasing the amount of equipment while achieving the in-situ treatment of the boxes atmospheres (even though each GB-DS and MB-DS is counted as one equipment).

The space requirement for permeators and the WDFT tanks was divided into two units in parallel instead of adding full size stand-by equipment since the operation (albeit with reduced capacity) will still be possible if one of the tanks or the permeator units is taken out of service. This decision also saves costs due to the expensive materials of the permeators.

All gloveboxes include a glovebox cooling system (GB-CS) composed by a water-water heat exchanger with its pumps for the internal cooling loop and a vacuum pump to aid the service vacuum system when a box or module needs to be decommissioned.

The identified equipment that had no previous reference for its size was classified into S, M and L as explained in section 2.1.2. The net volume of all the equipment reaches 1248.96 m^3, 911.36 m^3 of which must be contained inside primary confinement structures. All the equipment was then grouped by the fuel cycle subsystems and subsequently, the subsystems were grouped into boxes following the flow principle.

Finally, the plant subsystems have been grouped into 29 gloveboxes, 2 coldboxes and 19 metalboxes. Their space requirement is calculated following the guidelines from section 2.1.3, totaling a required primary confinement volume of 2256.31 m^3. Standardizing all the gloveboxes to a 60 m^3 one, and applying the sizing criteria for the columns inside coldboxes and metalboxes, the total confinement volume of 3203.80 m^3 is obtained, plus the volume of WDFT tanks, AWSS and non-tritiated gas storage cylinder bundles (337.60 m^3). Table 11 shows the subsystem distribution into groups as well as the amount of equipment inside each of the subsystems.

Table 11 – Subsystem grouping and equipment quantity of each subsystem.

Group	Subsystem	Equipment qty.
GB1	IRS	6
	IPS	16
	G-DS	16
	EPVS	2
	GB1-AUX	5
CB2	PRS	6
GB2	PSS	8
	GB2-AUX	7
GB3	IRPRS	13
	GB3-AUX	8
GB4A	WCPS	4
	GB4A-AUX	5
MB4A	WCPS	3
	MB4A-AUX	2
GB4B	HeCPS	27
	GB4B-AUX	5
GB5A	WTCS	18
	GB5A-AUX	5

Group	Subsystem	Equipment qty.
GB5B	HTCS	8
	GB5B-AUX	5
GB6	ISS	15
	GCBS	3
	DT+SS	1
	GB6-AUX	7
CB6	ISS	15
GB7	WDFT	8
	GB7-AUX	5
GB8	ODS	11
	WDS	14
	GB8-AUX	5
MB8	WDS	8
	MB8-AUX	2
GB9	DTSS	4
	He3ExS	1
	GB9-AUX	5
GB10	SVS	1
	GB10-AUX	5

Group	Subsystem	Equipment qty.
GB1x	N-EDS-OT-x	8
(x: 1 to 6)	GB1x-AUX	5
MB1x	N-EDS-OT-x	6
(x: 1 to 6)	GB1x-AUX	2
GB2x	N-EDS-OT&R-x	8
(x: 1 to 3)	GB2x-AUX	5
MB2x	N-EDS-OT&R-x	6
(x: 1 to 3)	GB2x-AUX	2
GB3x	S-EDS-OT-x	7
(x: 1 to 8)	GB3x-AUX	5
MB3x	S-EDS-OT-x	4
(x: 1 to 8)	GB3x-AUX	2
WDFT		4
H2SS		1
O2SS		1
D2SS		1
AWSS		8

It is worth highlighting that the three EDS are composed of various trains each. Each train requires a glovebox and a metalbox, and can process up to 5000 Nm^3/h of tritiated gases. As explained in section 1.2, the N-EDS-OT trains run continuously, processing 20000 Nm^3/h under normal operation. This system houses six trains, four of them in operation and two of them as stand-by. The N-EDS-OT&R trains serve to purify the rooms air when tritium is found outside the primary confinement. This system houses three trains and only one of them runs continuously to treat the WDFT and the tritium vault rooms air. During open box maintenance operation, another train is turned on and one remains as stand-by. The S-EDS-OT trains are only started in case of accidents in the plant. This system contains eight trains that can completely replace the other two EDS with six of them processing up to 30000 Nm^3/h, while two remain as stand-by units. All EDS trains are considered to be tritium free when stand-by.

The complete list of equipment with their tags, sizing and grouping can be found in Table A-1 in the annex.

3.2 Group footprint and volume

The definition of the equipment grouping and determination of their confinement, gives a footprint and volume for each of them. Another important information obtained, was the required height, and subsequently the required levels for each box, particularly, columns in cold- and metalboxes.

Table 12 presents the net equipment volume for each box, their required box volume calculated as explained in section 2.1.3 and the final dimensions of width, length and height of each box, alongside their footprint, volume and required levels. The final primary confinement volume is sufficiently larger than the required box volume in every case.

Table 12 – Volumes, primary confinement dimensions and levels requirement for groups.

Group name	Net equipment volume	Required box volume	Primary confinement dimensions					Levels required
			W	L	H	Footprint	Volume	
	m^3	m^3	m	m	m	m^2	m^3	
GB1	15.52	38.5	2.0	10.0	3.0	**20.0**	**60**	1
CB2	0.48	1.2	2.1	2.7	6.0	**5.7**	**34**	2
GB2	5.70	14.3	2.0	10.0	3.0	**20.0**	**60**	1
GB3	16.45	41.1	2.0	10.0	3.0	**20.0**	**60**	1
GB4A	10.10	25.3	2.0	10.0	3.0	**20.0**	**60**	1
MB4A	33.61	84.0	2.5	2.5	18.0	**6.3**	**113**	4
GB4B	23.10	57.8	2.0	10.0	3.0	**20.0**	**60**	1
GB5A	23.32	58.3	2.0	10.0	3.0	**20.0**	**60**	1
GB5B	11.77	29.4	2.0	10.0	3.0	**20.0**	**60**	1
GB6	9.10	22.8	2.0	10.0	3.0	**20.0**	**60**	1
CB6	1.32	3.3	2.1	3.3	6.0	**6.9**	**42**	2
GB7	19.50	48.8	2.0	10.0	3.0	**20.0**	**60**	1
GB8	30.55	54.3	2.0	10.0	3.0	**20.0**	**60**	1
MB8	6.57	16.4	1.3	1.3	30.0	**1.7**	**51**	7
GB9	13.90	34.8	2.0	10.0	3.0	**20.0**	**60**	1
GB10	18.10	45.3	2.0	10.0	3.0	**20.0**	**60**	1
GB11 to GB16	16.30	40.8	2.0	10.0	3.0	**20.0**	**60**	1
MB11 to MB16	25.88	64.7	2.0	2.0	18.0	**4.0**	**72**	4
GB21 to GB23	16.30	40.8	2.0	10.0	3.0	**20.0**	**60**	1
MB21 to MB23	25.88	64.7	2.0	2.0	18.0	**4.0**	**72**	4
GB31 to GB38	16.30	40.8	2.0	10.0	3.0	**20.0**	**60**	1
MB31 to MB38	20.28	50.7	2.0	2.0	18.0	**4.0**	**72**	4

As explained in section 2.3.1, these boxes must be located in rooms for safety reasons. Applying the methodology described in sections 2.3.2 and 2.3.3, the rooms dimensions have been obtained. The Table 13 shows the rooms dimensions for the primary confinement structures and the equipment to be located outside of gloveboxes.

Table 13 – Dimensions, footprint and volume of groups rooms.

Room name			GB1	CB2	GB2	GB3	GB4A	MB4A	GB4B	GB5A	GB5B	GB6	CB6
Room dimensions	W	m	6	6.7	6	6	6	6.5	6	6	6	6	7.3
	L	m	12	5.1	12	12	12	5.5	12.3	12.3	12	12	5.1
	H	m	4	8.8	4	4	4	18.4	4	4	4	4	8.8
	Footprint	m^2	72	34	72	72	72	36	74	74	72	72	37
	Volume	m^3	288	301	288	288	288	658	295	295	288	288	328

Room name			GB7	GB8	MB8	GB9	GB10	GB11+GB12+GB13	MB11+MB12+MB13	GB14+GB15+GB16	MB14+MB15+MB16	GB21+GB22	MB21+MB22
Room dimensions	W	m	6	6	5.3	6	6	14	14	5	5	10	10
	L	m	12	12	4.3	12.3	12	12	5	12	5	12	5
	H	m	4	4	31.1	4	4	4	18.4	4	18.4	4	18.4
	Footprint	m^2	72	72	23	74	72	168	70	168	70	120	50
	Volume	m^3	288	288	709	295	288	672	1288	672	1288	480	920

Room name			GB23	MB23	GB31+GB32+GB33+GB34	MB31+MB32+MB33+MB34	GB35+GB36+GB37+GB38	MB35+MB36+MB37+MB38	H2SS+O2SS+D2SS	WDFT	AWSS-1	AWSS-2
Room dimensions	W	m	6	6	18	18	18	18	6	14.8	13	7
	L	m	12	5	12	5	12	5	5	8.2	14	10
	H	m	4	18.4	4	18.4	4	18.4	4	8.8	8.8	8.8
	Footprint	m^2	72	30	216	90	216	90	30	121	182	70
	Volume	m^3	288	552	864	1656	864	1656	120	1068	1602	616

Table 14 shows the final dimensions of auxiliary rooms such as the tritium vault, the MCC & PLC rooms, the compressed air supply & fire suppression system rooms, the stairwells and elevators, and corridors, all of which have been obtained from the 3D model of the tritium plant.

Table 14 – Dimensions, footprint and volume of additional rooms and corridors.

Room name			T2 vault	B2 MCC & PLC	B1 MCC & PLC	B1+B2 Compressed air + Fire suppression	L1 MCC & PLC	L1 Compressed air + Fire suppression	L2 MCC & PLC	L2 Compressed air + Fire suppression	L3 MCC & PLC	L3 Compressed air + Fire suppression	Stairwells + Elevators	Corridors	Piping corridors
Room dimensions	W	m	7	6	6	6	6	6	6	6	6	6	5.7		
	L	m	63	12	12	12	12	12	12	12	12	12	11.2		
	H	m	4	4	4	4	4	4	4	4	4	4	4		
	Footprint	m^2	461	72	72	72	72	74	72	72	72	72	766*	2156*	124*
	Volume	m^3	1845	288	288	288	288	295	288	288	288	288	3064*	8625*	507*

(*) Cumulative dimensions for all levels.

3.3 Tritium plant block diagram

After grouping all the subsystems, a detailed block diagram has been drawn. The goal of this diagram is to indicate all physical piping connections between the systems, subsystems and groups as a visual aid for determining the best layout distribution achievable.

In Figure 10, five areas can be distinguished. Area A contains the INTL systems, grouped inside GB1, GB2, CB2 and GB3. This same area includes GB9 for tritium storage and GB10, which contains the SVS.

In area B, GB6 and CB6, which contain the OUTL-IS, are found. This area marks the center of the diagram since GB6 is heavily integrated with other gas processing units.

At the top right side, area C includes GB4A, GB4B, GB5A and GB5B for the OUTL-CP and OUTL-TC system blocks, which are auxiliary systems for the Tokamak Building and present little integration with the rest of the Tritium Plant.

Area D belongs to GB7, GB8 and MB8, which are the heart of the water detritiation system of the plant, as well as the AWSS, WDFT, and O2SS and H2SS.

Lastly, at the bottom of the diagram in area E, a condensed version of the OUTL-ED shows the interconnections for the N-EDS-OT, N-EDS-OT&R and S-EDS-OT.

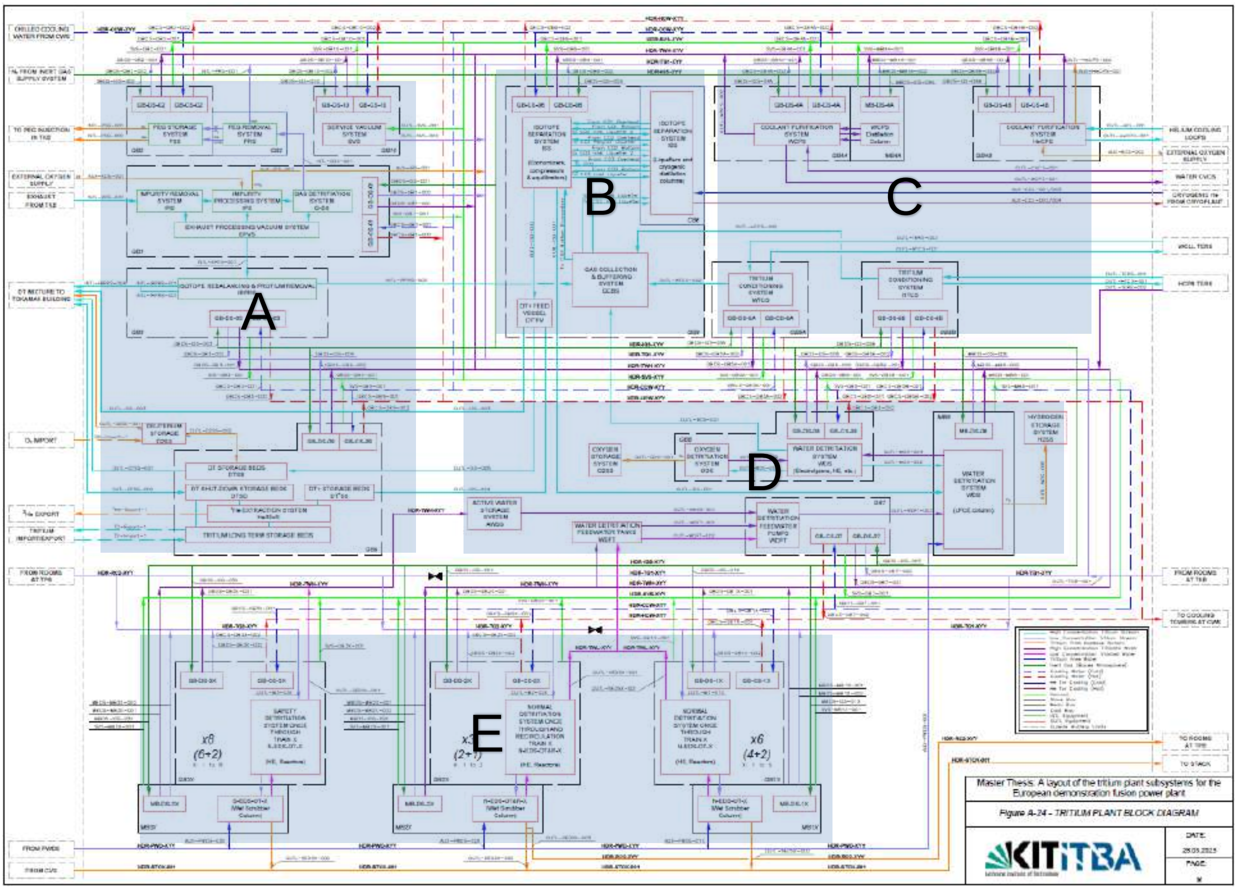

Figure 10 – Tritium plant block diagram marked for reference to its explanation.

The full size version of the block diagram can be found in the annex as Figure A-24.

3.4 Optimized layout

The application of the considerations from section 2.3.4 to all the results obtained up to this point pave the way to the development of an optimized building layout that minimizes the tritium inventory while not overlooking crucial safety, operability and maintainability factors.

From the plant block diagram and relative tritium inventory in each connection (see section 3.5), it can be derived that:

- The TKB presents connections to GB1, GB2, GB3, GB4A, GB4B, GB5A, GB5B, GB6, GB7, GS and the NEDS header.
- GB1 needs to be close to the TKB, CB2 and GB3.
- CB2 needs to be close to GB1 and GB2.
- GB2 needs to be close to the TKB and CB2.
- GB3 needs to be close to the TKB, GB1 and GB6.
- GB4A needs to be close to the TKB and MB4A.
- MB4A needs to be close to GB4A.
- GB4B only needs to be close to the TKB, since all other connections are to headers.
- GB5A needs to be close to the TKB and GB6.
- GB5B needs to be close to the TKB and GB6.
- GB6 handles tritiated gas process streams, and presents connections to the TKB, GB3, GB5A, GB5B, CB6, GB9, GB8 and MB8.
- CB6 is part of the GB6 subsystems so it needs to be as close as possible to it.
- GB7 needs to be close to the WDFT for the pumps suction and close to the MB8 for the discharge.
- GB8 needs to be close to GB6, MB8 and GS (O2SS).
- MB8 needs to be close to GB6, GB7, GB8 and GS (H2SS).
- GB9 needs to be close to TKB, GB6 and GS (D2SS).
- GB10 contains the SVS which is an auxiliary system connected to headers.
- GS contains the non-tritiated gas storage. Ideally it should be close to GB8, MB8 and GB9, to reduce power consumption.
- WDFT receives water from the tritiated water headers mostly by gravity, so it needs to be located at the lowest possible point in the building and to be close to GB7 for the pumps suction.
- AWSS receives water from the SEDS by gravity, so it needs to be located at the lowest possible point in the building.
- NEDS (GB11 to GB16 and MB11 to MB16) are all the N-EDS-OT trains, which are connected to all gloveboxes and metalboxes of the plant and the rooms of the TKB by headers, and discharge to the stack and WDFT. For each train, the glovebox must be as close as possible to its respective metalbox.
- OEDS (GB21 to GB23 and MB21 to MB23) are all the N-EDS-OT&R trains, which are connected to the plant rooms and could be used as additional backup for the NEDS. They

discharge water to the WDFT and air back to the rooms or to the stack. For each train, the glovebox must be as close as possible to its respective metalbox.

- SEDS (GB31 to GB38 and MB31 to MB38) are all the S-EDS-OT trains, which are only used in a loss of contention event, discharging treated air to the Stack and water to the AWSS. For each train, the glovebox must be as close as possible to its respective metalbox.

All this can be summarized as shown in Table 15, which indicates the interconnections between groups and helps to identify a strategy for the arrangement of them in the building.

For each group, the table shows the connections to other groups while indicating the direction of flow (F: from, T: to, FT/TF: from and to). It is worth noting that the WDFT, GB10 and NEDS groups show connections to almost all other groups since they receive fluids from headers, and thus they are not a conditioning factor for the design, while GB6 and MB8 are the two main groups of the plant in terms of interconnections since they contain the ISS and WDS, respectively.

Table 15 – Relationships between groups of the fuel cycle.

	TKB	MB4A	GB4A	GB4B	GB2	CB2	GB1	GB3	GB6	CB6	GB5A	GB5B	GB9	GB8	MB8	GS	GB7	AWSS	WDFT	GB10	NEDS	OEDS	SEDS	STACK
TKB			FT	FT	F		T	F	F		FT	FT	F			F			T		T	T	T	
MB4A			TF																T	T	T			
GB4A	TF	FT																	T	T	T			
GB4B	TF																		T	T	T			
GB2	T					F													T	T	T			
CB2					T		F														T			
GB1	F					T		T											T	T	T			
GB3	T						F		T										T	T	T			
GB6	T							F		FT	F	F	T	F	T				T	T	T			
CB6									TF															
GB5A	TF								T										T	T	T			
GB5B	TF								T										T	T	T			
GB9	T								F							F			T	T	T			
GB8									T						FT	T			T	T	T			
MB8									F					TF		T	F		T	T	T			
GS	T												T	F	F									
GB7															T			F	FT	T	T			
AWSS																	T						F	
WDFT	F	F	F	F	F		F	F	F		F	F	F	F	F		TF			F	F			
GB10		F	F	F	F		F	F	F		F	F	F	F	F		F		T		T			
NEDS	F	F	F	F	F	F	F	F	F		F	F	F	F	F		F		T	F	T			T
OEDS	F																					T		T
SEDS	F																	T					T	T
STACK																					F	F	F	

Tritium inventory inside equipment and arrangement of rooms

In addition to arranging the rooms in a way that the pipes lengths are optimized, care must be taken in considering the tritium inventory inside the units. As explained in section 2.3.1, each group has its own room for safety reasons so that if the primary containment and primary confinement are breached, tritiated species are retained in the volume of their room and do not spread across the plant. Particularly, gloveboxes and metalboxes from the EDS trains are in separate rooms and half of the trains from each EDS are in different rooms than the other half, to guarantee continuous operation of this last layer between the plant and the environment.

The tritium inventory contained inside the units of each room has been obtained by adapting the information from [7]. Table 16 presents the tritium inventories for normal operation under mode A (WCLL breeding blankets) alongside the maximum expected mobilized tritium in each room. Table 17 does the same for normal operation under mode B (HCPB breeding blankets). From the total mobilized tritium inventory in the equipment of the fuel cycle, 589 g are found inside the TKB. Under mode A, 1359 g are found in the TPB, and 1271 g under mode B.

Table 16 – Tritium inventory under operational mode A (WCLL) and maximum tritium inventory expected in rooms.

Room	Subsystem	N.O. g $T_{2,eq}$	Max. g $T_{2,eq}$
GB1	IRS	6	6
	IPS		
	G-DS		
	EPVS		
CB2	PRS	<1	<1
GB2	PSS	<1	<1
GB3	IRPRS	556	556
GB4A	WCPS	<1	<1
MB4A	WCPS	4	4
GB4B	HeCPS	Offline	3
GB5A	WTCS	67	67
GB5B	HTCS	Offline	1
GB6	ISS	85	85
	GCBS		
	DT+SS		
CB6	ISS	613	613
GB7	WDFT	<1	<1
GB8	ODS	<1	<1
	WDS	<1	<1
MB8	WDS	6	6

Room	Subsystem	N.O. g $T_{2,eq}$	Max. g $T_{2,eq}$
GB9	DTSS	100, immobilized	2000*
	He3ExS	<1	<1
GB10	SVS	Offline	<1
GB11 to GB13	NEDS	<1	<1
MB11 to MB13	NEDS	9	14
GB14 to GB16	NEDS	<1	<1
MB14 to MB16	NEDS	9	14
GB21 & GB22	OEDS	<1	<1
MB21 & MB22	OEDS	5	11
GB23	OEDS	Offline	<1
MB23	OEDS	Offline	5
GB31 to GB34	SEDS	Offline	<1
MB31 to MB34	SEDS	Offline	18
GB35 to GB38	SEDS	Offline	<1
MB35 to MB38	SEDS	Offline	18
WDFT		<1	<1
H2SS, O2SS, D2SS		-	<1
AWSS-1		Offline	<1
AWSS-2		Offline	<1
Tritium Vault		Variable stock, immobilized **	

* In the event of a fire inside the room while the plant is out of service and all the operational tritium inventory is stored in the DTSS.

** To be defined by regulator.

Table 17 – Tritium inventory under operational mode B (HCPB) and maximum tritium inventory expected in rooms.

Room	Subsystem	N.O. g $T_{2,eq}$	Max. g $T_{2,eq}$
GB1	IRS	6	6
	IPS		
	G-DS		
	EPVS		
CB2	PRS	<1	<1
GB2	PSS	<1	<1
GB3	IRPRS	556	556
GB4A	WCPS	Offline	<1
MB4A	WCPS	Offline	4
GB4B	HeCPS	3	3
GB5A	WTCS	Offline	67
GB5B	HTCS	1	1
GB6	ISS	85	85
	GCBS		
	DT+SS		
CB6	ISS	592	613
GB7	WDFT	<1	<1
GB8	ODS	<1	<1
	WDS	<1	<1
MB8	WDS	5	6

Room	Subsystem	N.O. g $T_{2,eq}$	Max. g $T_{2,eq}$
GB9	DTSS	100, immobilized	2000*
	He3ExS	<1	<1
GB10	SVS	Offline	<1
GB11 to GB13	NEDS	<1	<1
MB11 to MB13	NEDS	9	14
GB14 to GB16	NEDS	<1	<1
MB14 to MB16	NEDS	9	14
GB21 & GB22	OEDS	<1	<1
MB21 & MB22	OEDS	5	9
GB23	OEDS	Offline	<1
MB23	OEDS	Offline	5
GB31 to GB34	SEDS	Offline	<1
MB31 to MB34	SEDS	Offline	18
GB35 to GB38	SEDS	Offline	<1
MB35 to MB38	SEDS	Offline	18
WDFT		<1	<1
H2SS, O2SS, D2SS		-	<1
AWSS-1		Offline	<1
AWSS-2		Offline	<1
Tritium Vault		Variable Stock, Immobilized **	

* In the event of a fire inside the room while the plant is out of service and all the operational tritium inventory is stored in the DTSS.

** To be defined by regulator.

Taking advantage of the plant being located inside a building with multiple levels and that metalboxes, which contain columns, require rooms that take up more than one level, a layout is proposed that fulfils all the requirements described in the previous sections.

The final building requires seven levels, two underground basements (B2 and B1) and five aboveground levels (L1 to L5). Each level has a total height of 4.8 m (4.0 m + 0.8 m, see section 2.3.2).

- <u>Level B2</u> accommodates GB7; the first floor of MB8 (which requires 7 levels), the WDFT and the AWSS (which require 2 levels), as well as a room for the MCC & PLCs of this level.
- <u>Level B1</u> accommodates the Tritium Vault, a room for the MCC & PLCs of this level, a room for the fire suppression and compressed air for levels B1 and B2, and the second floor of WDFT, AWSS and MB8.
- <u>Level L1</u> accommodates the GB4B, GB5A, GB9, GB23, GB31 to GB38 and GS rooms, a room for the MCC & PLCs of this level, a room for the fire suppression and compressed air for this level, the first floor of CB2, CB6, MB4A, MB23 and MB31 to MB38, and the third floor of MB8.
- <u>Level L2</u> accommodates the GB1, GB2, GB3, GB4A, GB5B, GB6 and GB10 rooms, a room for the MCC & PLCs of this level, a room for the fire suppression and compressed air for this level, the first floor of MB11 to MB16, MB21 and MB22, the second floor of CB2, CB6, MB4A, MB23 and MB31 to MB38, and the fourth floor of MB8.

- Level L3 accommodates the GB8 and GB11 to GB16 rooms, a room for the MCC & PLCs of this level, a room for the fire suppression and compressed air for this level, the second floor of MB11 to MB16, MB21 and MB22, the third floor of MB4A, MB23 and MB31 to MB38, and the fifth floor of MB8.
- Level L4 accommodates the third floor of MB11 to MB16, MB21 and MB22, the fourth and last floor of MB4A, MB23 and MB31 to MB38, and the sixth floor of MB8.
- Level L5 accommodates the fourth and last floor of MB11 to MB16, MB21 and MB22, and the seventh and last floor of MB8.

Levels B2 to L4 are accessible by stairwells and elevators, and they all have wide corridors for maintenance; except for L4, which together with L5 are only required to accommodate the heights of columns inside metalboxes. The building roof is accessible through L4 and accommodates the HVAC and depression system, as well as the motors of the elevators.

The coordinate list for all boxes and equipment located outside the gloveboxes is presented in the annex in Table A-6. The zero-point reference is located at floor of the B2 level, as shown in Figure 11. The position of the floor of level B2 matches the position of the same floor in the tokamak building.

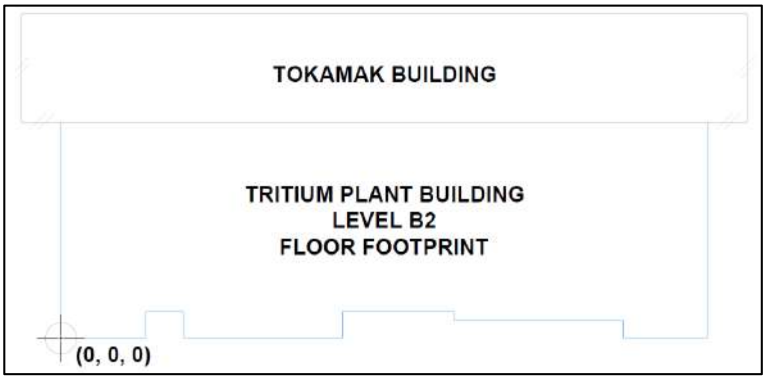

Figure 11 – Reference point for the given coordinates of boxes and equipment located outside the gloveboxes.

Figure 12 to Figure 15 (duplicated in larger size as Figure A-1 to Figure A-4 in annex) present a side-by-side comparison of the operational tritium inventory in the plant groups for modes A and B, and Table 18 gives the reference for the color scale employed.

Table 18 – Color scale for tritium inventory in groups.

Color	Tritium inventory g $T_{2,eq}$
ACI 10	> 100
ACI 30	up to 100
ACI 50	up to 10
ACI 92	< 1
ACI 254	0, offline

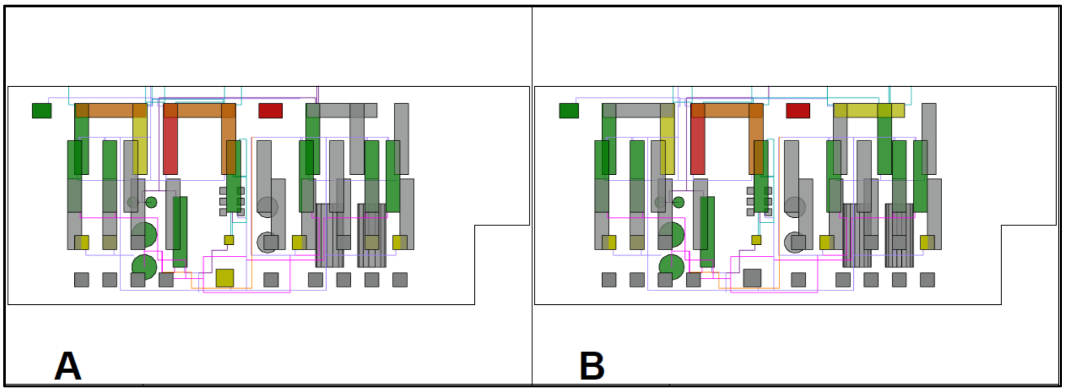

Figure 12 – Top view of the tritium plant groups and their inventory distribution under operational mode A and B.

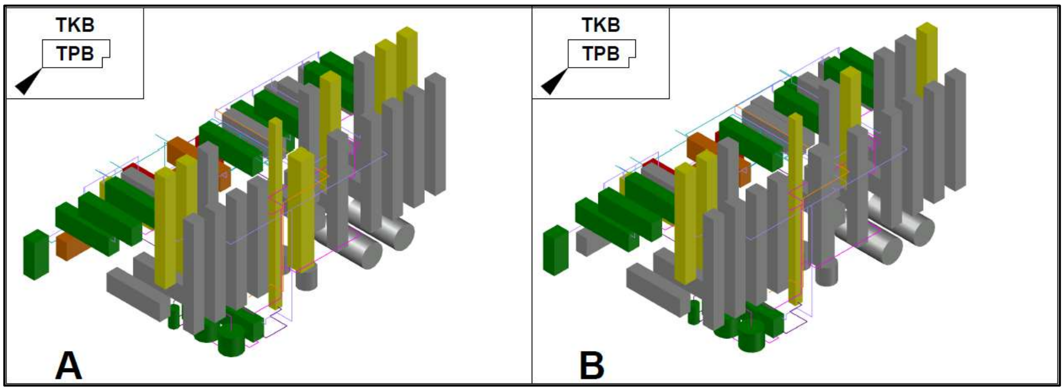

Figure 13 – SW view of the tritium plant groups and their inventory distribution under operational mode A and B.

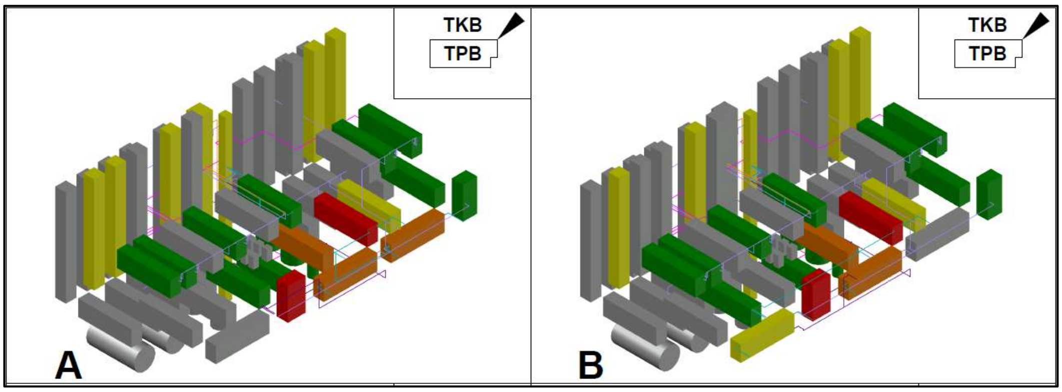

Figure 14 – NE view of the tritium plant groups and their inventory distribution under operational mode A and B.

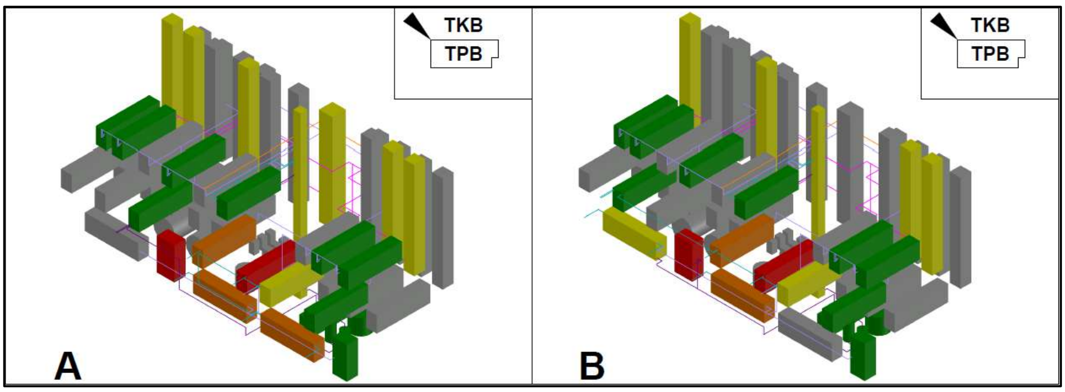

Figure 15 – NW view of the tritium plant groups and their inventory distribution under operational mode A and B.

This rooms and groups distribution fulfils all the layout related criteria outlined in section 2.3. Groups with high tritium content and closely related are located close together as well as close to the tokamak building. Moreover, they are centered vertically and horizontally, improving the possibility of retaining any unexpected tritium release inside the building. Rooms containing columns in metalboxes are clustered so they do not disrupt the layout of gloveboxes. Enough space for circulation, operation and maintenance has been accounted for within rooms and corridors. Atmospheric tanks are located in the basement, helping the drain of tritiated water by gravity flow and the EDS trains are positioned symmetrically to reduce the headers diameters by dividing the flowrate before reaching the units. Corridors outside the rooms of levels B1, L1, L2 and L3 are intentionally misaligned, allowing the tritiated pipes to "cross" them by changing levels to a room so that the corridors can be considered tritium free areas. In level B1 there is a room that acts as a corridor to enable the crossing from the tritium vault to the WDFT of a tritiated water header while keeping three layers of confinement.

Final building design

Figure 16 to Figure 19 (duplicated in larger size as Figure A-17 to Figure A-20 in the annex) present 3D views of the arrangement of rooms and groups in each level of the tritium plant.

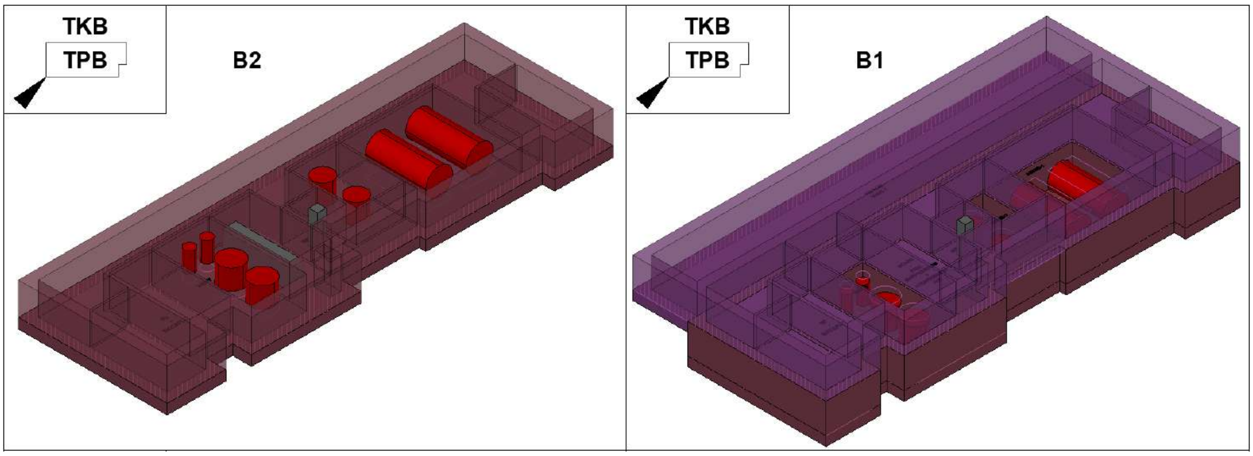

Figure 16 – 3D view of levels B2 and B1 of the tritium plant building.

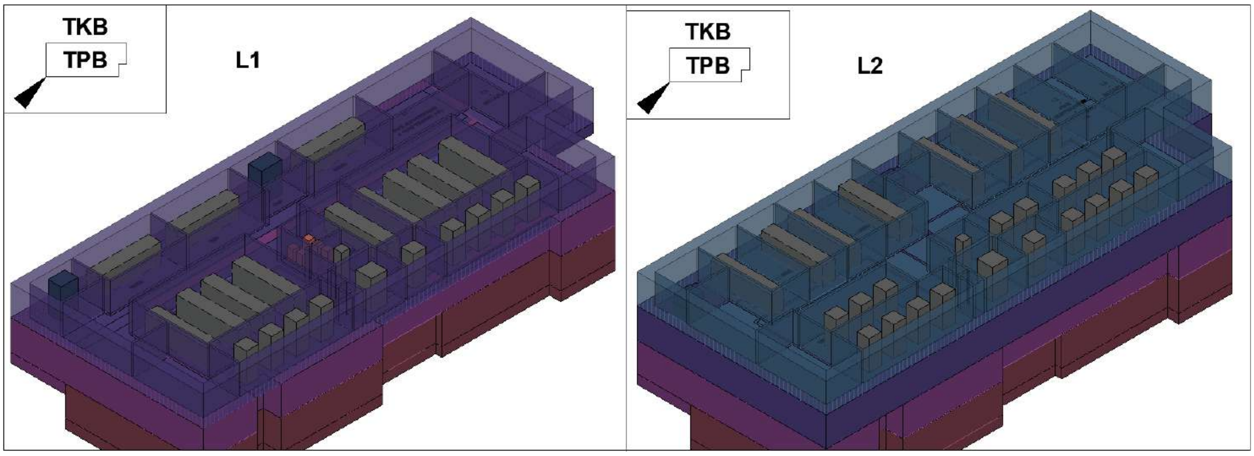

Figure 17 – 3D view of levels L1 and L2 of the tritium plant building.

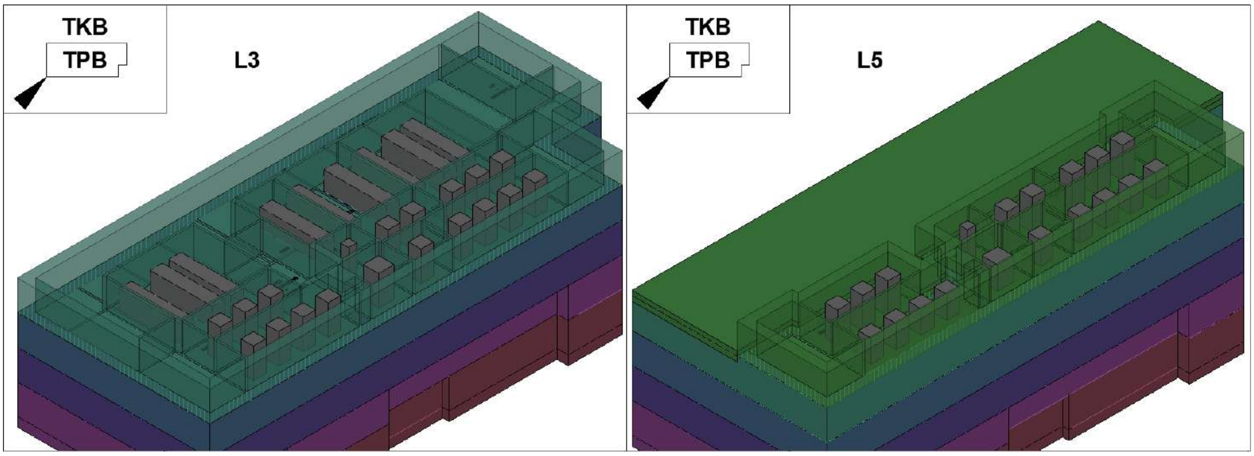

Figure 18 – 3D view of levels L3 and L4 of the tritium plant building.

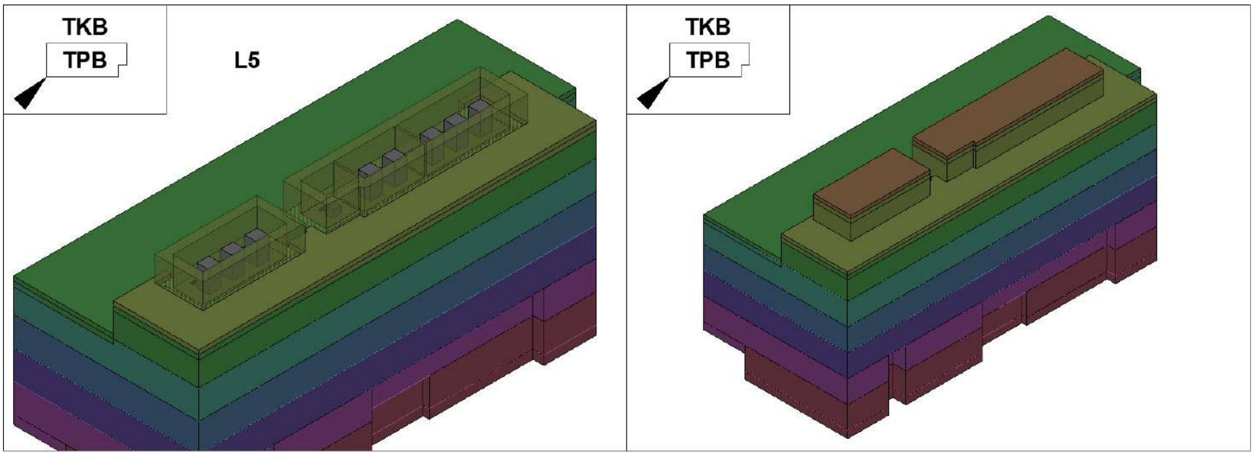

Figure 19 – 3D view of level L5 and external view of the tritium plant building.

The layouts for each of the levels, as well as sectional views at different cut distances from the tokamak building can be found in Figure A-5 to Figure A-16 in the annex.

The resulting external building dimensions are:

- Height (H): 35.8 m
- Length (L): 74.0 m
- Width (W): 30.9 m

The projected footprint is around 2200 m^2 and the cumulative footprint of all levels is around 11240 m^2, while the external volume of the building is around 57030 m^3. Figure A-21 in the annex shows external views of the tritium plant building from different angles.

Comparison to ITER tritium plant building

To evaluate the effectivity of the design criteria applied to the development of the optimized layout for the EU-DEMO TPB, a comparison to the tritium plant building from ITER can be drawn. In reference [37] it is indicated that the ITER tritium plant building has a width of 20 m, a length of 79 m and it comprises two floors below grade with the bottom at about -11 m and five floors above grade with the roof at an elevation of about 34 m. Figure 2 of that paper shows a 3D representation of the layout which demonstrates that the dimensions given are fully occupied in a box-like building.

The total external volume is 71100 m^3 (20 m x 79 m x 45 m), and its projected footprint 1580 m^2. On the other hand, the optimized EU-DEMO TBP presented in the previous section, resulted in the same amount of levels although with lower overall height and with a projected footprint 39% higher than the ITER building. However, the volume is 20% smaller than that of the ITER project.

It is imperative to highlight that the EU-DEMO power plant is designed for a fusion power output of four times the fusion power of ITER, and these results are a direct consequence of the implementation of the direct internal recycle concept which significantly reduces the size of the equipment and building.

3.5 Piping dimensioning and tritium inventory

In total three inventory calculations have been carried out.

The first one, before the creation of the 3D model, considering a length of 50 m, a height difference of 3 m, four 90º elbows, four ball valves and a stiffener separation of 6 m for each pipe. This first estimation served as an indication of the relative tritium inventory per meter (linear mass density) in interconnection pipes, and also as a reference for a poor layout distribution. Once the pipes have been designed, the operational tritium inventory inside them can be determined. This calculation only considers the pipes containing tritiated fluids under continuous operation with their “normal operation” conditions, and does not include a pressure nor a temperature profile along the pipes. Since there are two operational modes, A and B, both alternatives have been assessed. The operational tritium inventory in pipes obtained in this calculation was 3.610 g for mode A and 3.658 g for mode B, the total tritiated pipes length added up to 3498 m, and the amount of different pipe types was 18.

The second calculation was carried out after the elaboration of the 3D model of the plant. This time, the pipes lengths, amount of elbows and valves, and the separation between stiffeners were obtained from the optimized 3D layout. Particularly, the headers have been sized by considering the distance between the furthest continuous contribution being collected and the discharge of the header, with the cumulative flowrate of all the continuous contribution so as to guarantee the capacity for the flowrate in all cases. This pass also features significantly reduced pipe lengths for pipes with high linear mass density of tritium and as such the tritium inventory reduction is a direct consequence of the layout optimization. This pipe length reduction is not trivial, since it not only affects directly the inventory and diameter size of the pipes, but also mitigates the possibility of tritium leaks and improves the reliability of the facility. Table 19 presents the lengths of tritiated pipes under operational modes A and B obtained from the 3D model.

Table 19 – Resulting tritiated pipe lengths for modes A and B.

		Mode A	Mode B
Total tritiated pipes length	**m**	688.60	693.20
Average length *	**m**	3.88	3.99
Shortest pipe *	**m**	0.65	0.80
Longest pipe *	**m**	24.70	24.70

* without considering headers

Once all the diameters have been determined, a third calculation was done. In this iteration pass, the aim was set on reducing the amount of pipe diameter options to be found across the plant in order to reduce the stock needs while at the same time, reducing the tritium inventory even further.

This was realized by slightly relaxing the defined pressure drop criteria, as long as it remained below the maximum allowable. Additionally, an extra 10% flowrate was considered as margin for eventual flow fluctuations. The unification was also focused on avoiding having a pipe option solely for one stream of less than 10 m, in these cases, pipes diameters were increased if needed to match an option with more streams and greater overall lengths.

After a first pass of these unification criteria, streams that contributed to the tritium inventory with less than $1\cdot10^{-4}$ g, were further unified (to higher diameters if needed) due to their marginal contribution. Further optimization was achieved by increasing the wall thickness (and thus effectively reducing the internal diameter) as long as the maximum allowable pressure drop is not reached, when the external pressure verification failed, instead of reducing the spacing between stiffeners. The process of unifying the pipes diameters and wall thicknesses has reached a reduction from initially 22 different pipe types to 10. The product of this final calculation is designated as “optimized base case” (OBC).

In Table 20, significant results obtained for operational modes A and B are shown together with a comparison of the volume and inventory reduction between the calculations.

The inventory reduction between calculations one and two is significant, led by the reduction of the pipes lengths. Even though the total pipe volume is increased between the second and third calculations, the inventory reduction reaches up to 6% in the OBC. This is because the gas headers represent around 99,2% of the volume while only contributing with $2.42\cdot10^{-5}$ g $T_{2,eq}$, and the optimization is achieved mainly by reducing the volume of pipes under 25 mm of outer diameter.

Table 20 – Operational tritium inventory in pipes and pipes volume for modes A and B.

			Mode A		Mode B	
Total pipes volume	**1º calculation**	**m^3**	86.01		85.83	
	2º calculation	**m^3**	41.95	-51.2%	41.94	-51.1%
	3º calculation	**m^3**	50.22	+19.7%	50.23	+19.8%
Pipes volume (OD < 25 mm)	**1º calculation**	**m^3**	0.3217		0.3224	
	2º calculation	**m^3**	0.0387	-88.0%	0.0413	-87.2%
	3º calculation	**m^3**	0.0366	-5.5%	0.0390	-5.4%
Operational tritium inventory	**1º calculation**	**g $T_{2,eq}$**	3.610		3.658	
	2º calculation	**g $T_{2,eq}$**	0.224	-93.8%	0.227	-93.8%
	3º calculation	**g $T_{2,eq}$**	**0.210**	-6.3%	**0.215**	-5.2%

Table 21 shows the options in terms of outer diameter and wall thickness resulting from the second and third calculations, alongside the cumulative length and amount of steams for each of them for modes A and B respectively, to demonstrate the effect of the unification in the pipe types options for the obtainment of the OBC.

Table 21 – Cumulative length and amount of each pipe type (outer diameter, thickness combination) for modes A and B in the second and third calculations.

Operational Mode A								Operational Mode B							
2° Calculation				3° Calculation				2° Calculation				3° Calculation			
OD	t	L	Qty.	OD	t	L	Qty.	OD	t	L	Qty.	OD	t	L	Qty.
mm	mm	m	-	mm	mm	m	-	mm	mm	m	-	mm	mm	m	-
6	1	63.20	4	6	1	63.20	4	6	1	64.75	5	6	1	64.75	5
8	1	13.25	3	8	1	29.05	4	8	1	13.25	3	8	1	29.05	4
10	1	24.80	8					10	1	19.80	6				
				12	1	55.30	8					12	1	50.30	6
12.7	1	46.30	1					12.7	1	46.30	1				
14	1	61.80	2	14	1	64.30	3	14	1	61.80	2	14	1	64.30	3
16	1	87.35	25	16	1	85.75	25	16	1	74.30	25	16	1	71.80	24
17.2	1	0.90	1	17.2	1	31.90	2	17.2	1	0.00	0	17.2	1	31.90	2
18	1	31.90	2					18	1	31.90	2				
19	1	3.30	1					19	1	3.30	1				
20	1	0.00	0	20	1	17.30	3	20	1	19.40	1	20	1	36.70	4
22	1	14.00	2					22	1	14.00	2				
25	1	0.00	0					25	1	2.50	1				
48.3	1.6	123.30	2	48.3	1.6	153.60	4	48.3	1.6	123.30	2	48.3	1.6	156.10	5
51	1.6	17.30	1					51	1.6	17.30	1				
51	1	13.00	1					51	1	13.00	1				
82.5	2	3.30	1					82.5	2	3.30	1				
139.7	7.1	0.00	0	139.7	7.1	10.50	3	139.7	7.1	7.30	2	139.7	7.1	10.60	3
139.7	1.6	7.20	2					139.7	1.6	0.00	0				
406.4	2.6	8.90	1					406.4	2.6	8.90	1				
457	3.2	60.25	6					457	3.2	60.25	6				
508	3.2	2.90	1					508	3.2	2.90	1				
				610	6.3	177.70	10					610	6.3	177.70	10
610	3.2	105.65	2					610	3.2	105.65	2				
Total		**688.60**	**66**	**Total**		**688.60**	**66**	**Total**		**693.20**	**66**	**Total**		**693.20**	**66**

Table 22 presents the top ten contributors to the tritium inventory in interconnecting pipes of the plant under normal operation, as found after the third calculation. These streams contribute to 98% and 95% of the tritium inventory from the optimized base case of modes A and B respectively.

Table 22 – Top 10 contributors to operational tritium inventory in pipes.

No.	Tag	Phase	$T_{2,eq}$ Inventory		Length	Linear density	Volume
			mol	g	m	g $T_{2,eq}$ / m	m^3
1	INTL-EPVS-001	Gas	$9.47 \cdot 10^{-3}$	**$5.71 \cdot 10^{-2}$**	3.1	$1.84 \cdot 10^{-2}$	0.00048
2	INTL-RPS-001	Gas	$7.35 \cdot 10^{-3}$	**$4.43 \cdot 10^{-2}$**	2.5	$1.77 \cdot 10^{-2}$	0.00038
3	INTL-IRPRS-004	Gas	$5.65 \cdot 10^{-3}$	**$3.41 \cdot 10^{-2}$**	2.5	$1.36 \cdot 10^{-2}$	0.00028
4	INTL-IRPRS-003	Gas	$2.66 \cdot 10^{-3}$	**$1.60 \cdot 10^{-2}$**	7.1	$2.26 \cdot 10^{-3}$	0.00020
5	HDR-TWL-XYY	Liquid	$2.45 \cdot 10^{-3}$	**$1.48 \cdot 10^{-2}$**	138.7	$1.07 \cdot 10^{-4}$	0.01591
6	OUTL-DTSS-001	Gas	$2.05 \cdot 10^{-3}$	**$1.24 \cdot 10^{-2}$**	3.65	$3.38 \cdot 10^{-3}$	0.00010
7	OUTL-ISS-003	Gas	$1.98 \cdot 10^{-3}$	**$1.20 \cdot 10^{-2}$**	2.5	$4.79 \cdot 10^{-3}$	0.00007
8A	HDR-TWH-100-A	Liquid	$1.06 \cdot 10^{-3}$	**$6.41 \cdot 10^{-3}$**	51.2	$1.25 \cdot 10^{-4}$	0.00064
8B	HDR-TWH-100-B	Liquid	$1.03 \cdot 10^{-3}$	**$6.22 \cdot 10^{-3}$**	49.7	$1.25 \cdot 10^{-4}$	0.00062
9	OUTL-HTCS-002	Gas	$7.02 \cdot 10^{-4}$	**$4.24 \cdot 10^{-3}$**	19.4	$2.18 \cdot 10^{-4}$	0.00494
10A	OUTL-TERS-001	Gas	$5.40 \cdot 10^{-4}$	**$3.26 \cdot 10^{-3}$**	2.5	$1.30 \cdot 10^{-3}$	0.00399
10B	OUTL-WTCS-002	Gas	$4.37 \cdot 10^{-4}$	**$2.64 \cdot 10^{-3}$**	16.95	$1.56 \cdot 10^{-4}$	0.00261
Subtotal mode A				**0.205**			0.027
Subtotal mode B				**0.204**			0.026

As it is to be expected, the highest contributors to the tritium inventory are gaseous streams from INTL. INTL-EPVS-001, with a length of 3.1 m, contains the highest tritium inventory and accounts for more than 25% of the total. If also adding the INTL-RPS-001 and INTL-IRPRS-004, these pipes account for more than 60% of the total inventory and as such have the highest sensitivity for optimization. The top ten streams added volume is equal to 0.027-0.026 m^3, that is, only 0.05% of the tritiated pipes volume.

The complete list of the tritiated pipes sized for normal operation under modes A and B can be found in Table A-7 in the annex.

Figure 20 (duplicated in larger size as Figure A-22 in the annex) shows the pipes isometrics for the tritium plant building that continuously contain tritiated species under normal operation for modes A and B.

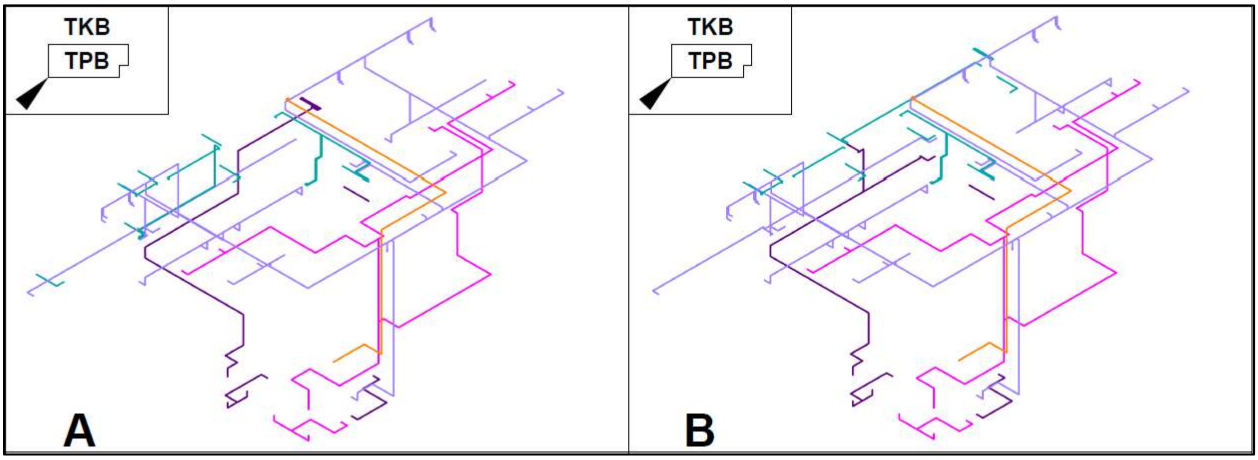

Figure 20 – Tritium plant piping routing for operational modes A and B. The colors reflect the same scheme as the block diagram.

In Figure 21 (duplicated in larger size as Figure A-23 in the annex), a logarithmic color scale shows the linear tritium density of the same isometrics. Incidentally, the pipes with highest linear density are located in the same areas of the building as the equipment groups with the highest tritium inventories as shown in Figure 12 to Figure 15.

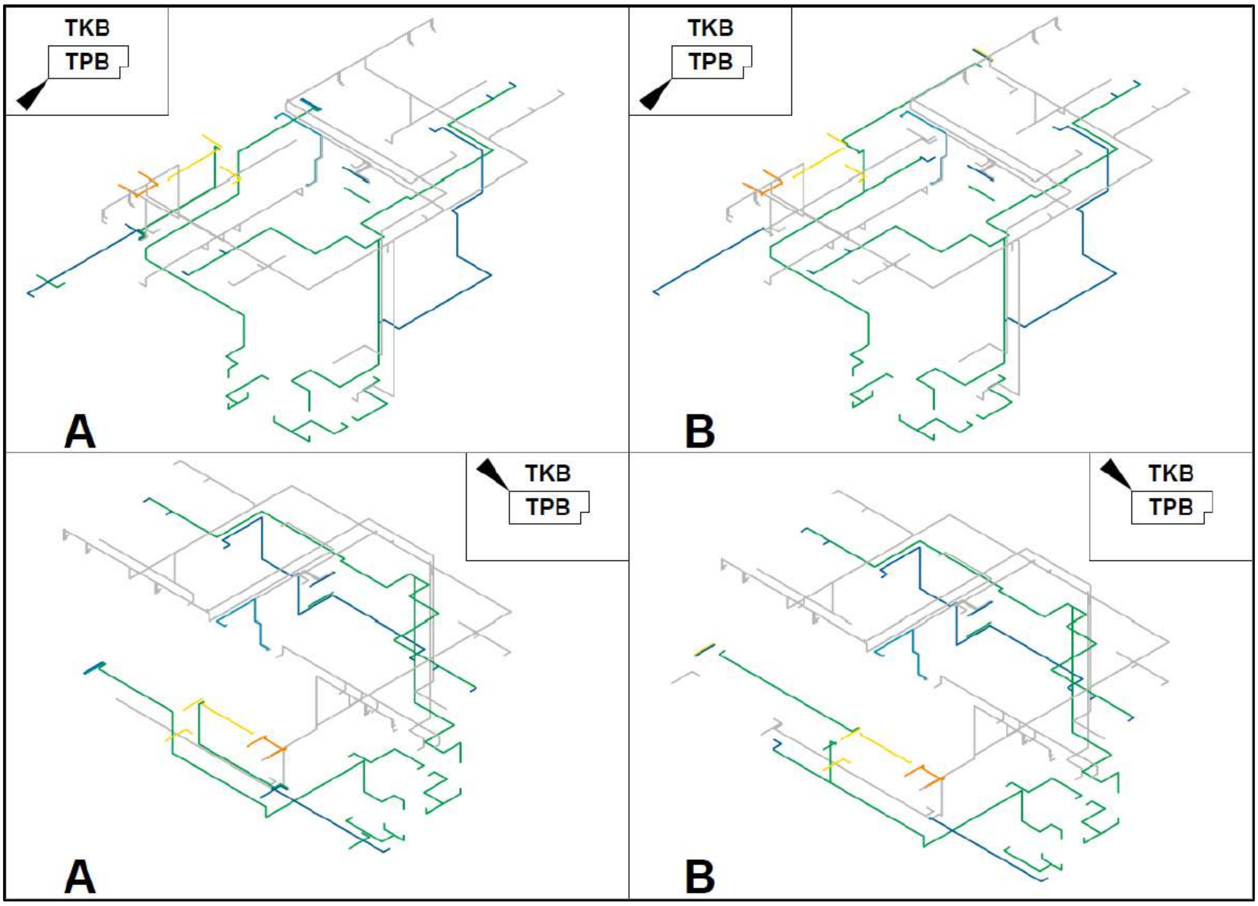

Figure 21 – Tritium plant piping routing for operational modes A and B. The colors show the linear tritium density.

Table 23 presents the linear density ranges for each color shown in Figure 21. Values below $1{\cdot}10^{-6}$ g / m have been consolidated since they are negligible compared to the others.

Table 23 – Color scale for linear tritium density in pipes.

	Linear density g $T_{2,eq}$ / m	
Color	**From**	**To**
DIC 636	$1{\cdot}10^{-2}$	$1{\cdot}10^{-1}$
DIC 637	$1{\cdot}10^{-3}$	$1{\cdot}10^{-2}$
DIC 638	$1{\cdot}10^{-4}$	$1{\cdot}10^{-3}$
DIC 641	$1{\cdot}10^{-5}$	$1{\cdot}10^{-4}$
DIC 639	$1{\cdot}10^{-6}$	$1{\cdot}10^{-5}$
DIC 650	$1{\cdot}10^{-11}$	$1{\cdot}10^{-6}$
(*) Logarithmic scale		

3.6 Sensitivity analysis

A sensitivity analysis has been performed to assess the influence of variations in relevant parameters. These parameters can be divided into two groups, one regarding the operational conditions and the other regarding the design criteria. Moreover, changes of the operational conditions have different effects if they are introduced in the design stage or the operation stage. The results presented in this section are based on the operational mode A, since no significant differences have been found compared to operational mode B.

The studied operational parameters are flowrate, inlet pressure and inlet temperature. Since the base case has been sized for the highest expected flowrate of the fuel cycle associated with 430 Pa·m^3/s of gas exhausted from the torus [4] and verified for an extra 10% flowrate as explained in section 3.5, only the impact of flowrate reduction during the design stage has been analyzed. Particularly, the selected scenarios were: 10% reduction of all flowrates and 38.4% reduction which is the minimum expected flowrate of the fuel cycle associated with 265 Pa·m^3/s of gas exhausted from the torus [4]. Sizing the piping for reduced flowrates leads to smaller volumes and inventory compared to the OBC presented in section 3.5. Nevertheless, this reduction is not directly proportional to the flowrate because of the discrete steps between pipe diameters and the existence of a minimum pipe size of 6 mm. Figure 22 shows the effect on the tritium inventory of these reductions in the flowrate introduced during the design stage. The impact on the inventory of changes in the flowrate during operation stage of the OBC design have not been investigated since the inventory is independent from this variable in this situation.

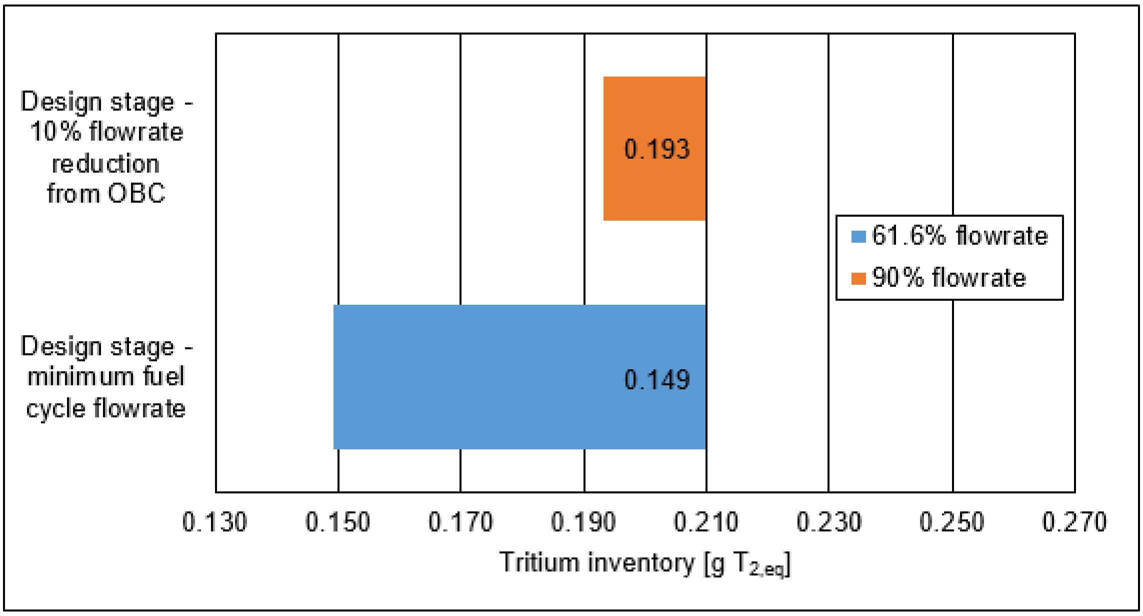

Figure 22 – Graphical representation of the effect on the tritium inventory of the reduction of flowrate in the design stage (Base case: 0.210 g $T_{2,eq}$).

Changes in the inlet pressure affect the fluids properties, particularly in gases, and the pipe thickness requirements. Higher normal operating pressures lead to higher gas density, which increases the inventory and also reduces the pressure drop in the pipe by reducing the flow velocity for the same internal diameter. Higher pressure translates into smaller volumetric flows permitting a reduction of diameters. On the other hand, increased design pressures also restrict the unification possibilities due to the required thickness for withstanding higher pressures. The opposite is true for a decrease in the NOP. In the end, the density changes overcompensate the effect of the change in pipes diameter with a slight reduction of the tritium inventory at lower pressures even with an increase of the volume of the pipes or a slight increase of the tritium inventory at higher pressures even with a reduction of the volume.

The effect of inlet temperature on the design has been tested by analyzing a 25 K increase or decrease from the normal operating temperatures. This variable affects both, density and viscosity of the fluids. Particularly, in gases this effect is inverse, more temperature reduces the density but increases the viscosity. This inverse effect means that at higher temperatures, the pressure drop in gas pipes will increase, forcing in some situations an increase of the internal diameter although the inventory would still be reduced because of the density decrease. The liquid water viscosity is much more sensitive to variations in temperature being multiplied or divided almost by a factor of 2 with a 25 K temperature decrease or increase respectively. Changes in the temperature conditions in the design phase end up forcing a slight volume increase in both analyzed scenarios although the changes in density still govern the tritium inventory, reducing it compared to the OBC when the temperature is increased (the density is decreased) and increasing it compared to the OBC when the temperature is reduced.

The second sensitivity analysis is performed by evaluating the effects of changes in pressure and temperature condition during the operation stage, using the pipes designed for the OBC. This analysis assesses the operational flexibility of the facility. A 10% increase or decrease in the operating pressure leads to around 8.6% increase or decrease, respectively, in the operational tritium inventory. A 25 K increase or decrease in the operating temperature decreases or increases, respectively the tritium inventory. The percentage change in the operating conditions does not translate directly to the same percentage change in the inventory because of the existence of liquid streams for which the density is almost not modified. Figure 23 and Figure 24 show the effect of variations in pressure and temperature to the tritium inventory if they are introduced either during the design stage or during the operation stage, taking the base case (with 0.210 g $T_{2,eq}$) as reference.

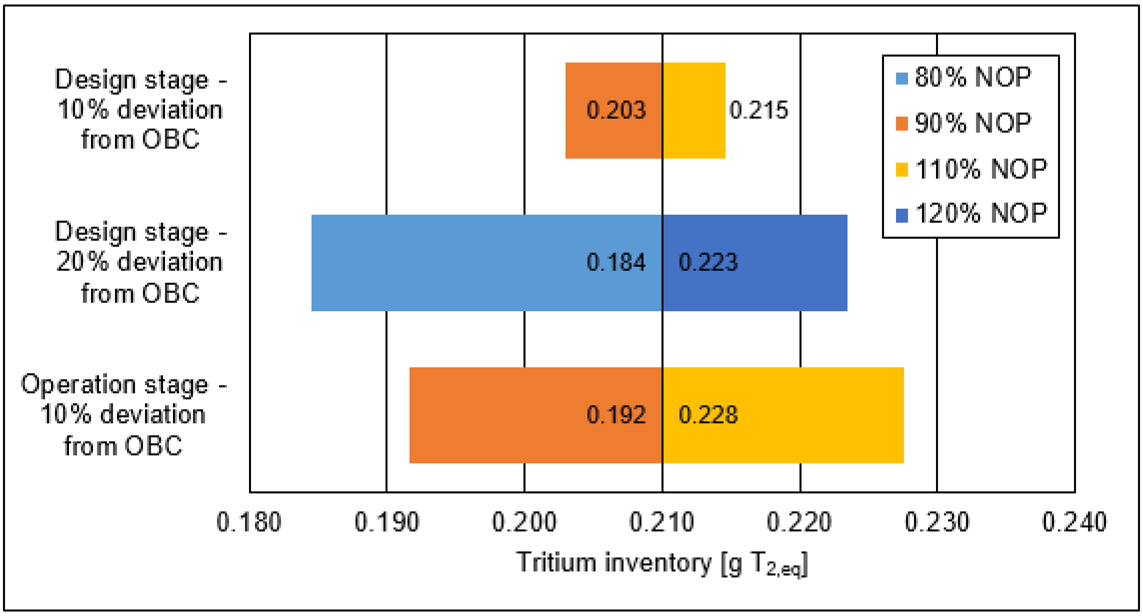

Figure 23 – Graphical representation of the effect of variations in pressure in the design and operation stages.

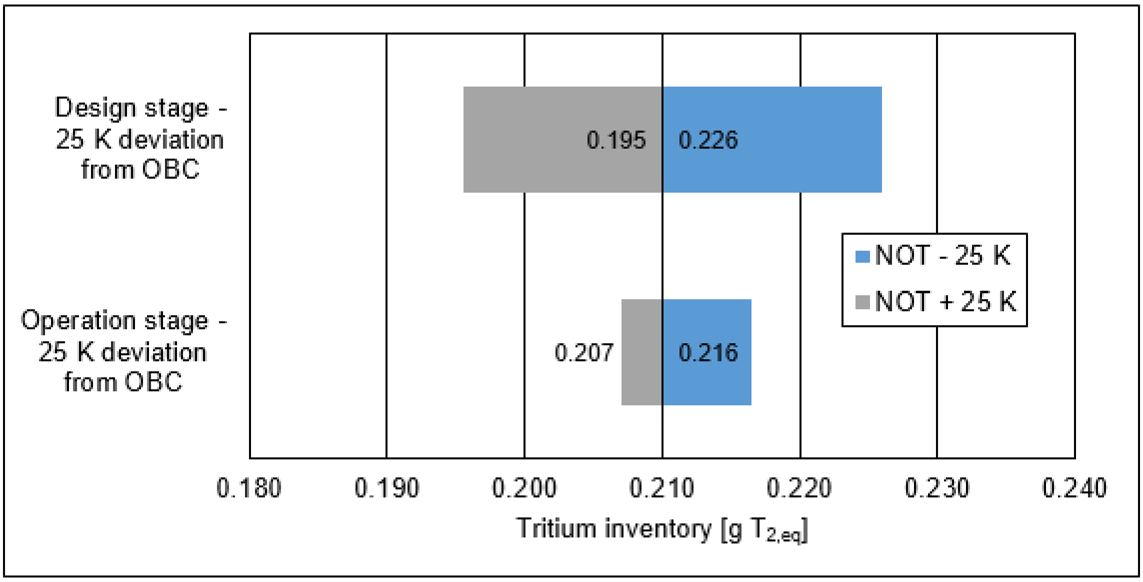

Figure 24 – Graphical representation of the effect of variations in temperature in the design and operation stages.

Concerning the sensitivity to changes in the design criteria, as stated in section 3.5, the first calculation of pipes diameters can be taken as a "poor layout distribution" scenario, since it considers 53 m of pipe length for every stream. This calculation gives an upper limit for the tritium inventory in pipes with 3.610 g $T_{2,eq}$, which is 17.2 times the optimized tritium inventory (0.210 g $T_{2,eq}$).

Another studied design parameter was the level of unification in pipe types options (OD-t combinations). Excessive unification leads to an increase in the tritium inventory by assigning larger diameters than needed to streams with high tritium content. On the other side of the spectrum, an excessive reduction in pipes diameters for each stream while searching for the minimum inventory possible for certain operating conditions, leads to an increase in the pipe types options (from 10 to 28) while achieving only a 12% reduction in the inventory compared to the OBC. The presented optimized base case is a compromise solution between reducing the inventory and the pipes stock in the plant. The presented unification alternatives are:

- 3, 4 and 6 pipe types, showing the effect of excessive unification on the inventory.
- 10, which is the optimized base case.
- 12, whose inventory is practically the same as the OBC.
- 22, which is obtained from the second calculation for the base case prior to the unification.
- 28, which seeks the minimization of the inventory in pipes regardless of the number of pipe types.

Figure 25 presents the tritium inventory for different degrees of pipe types unification.

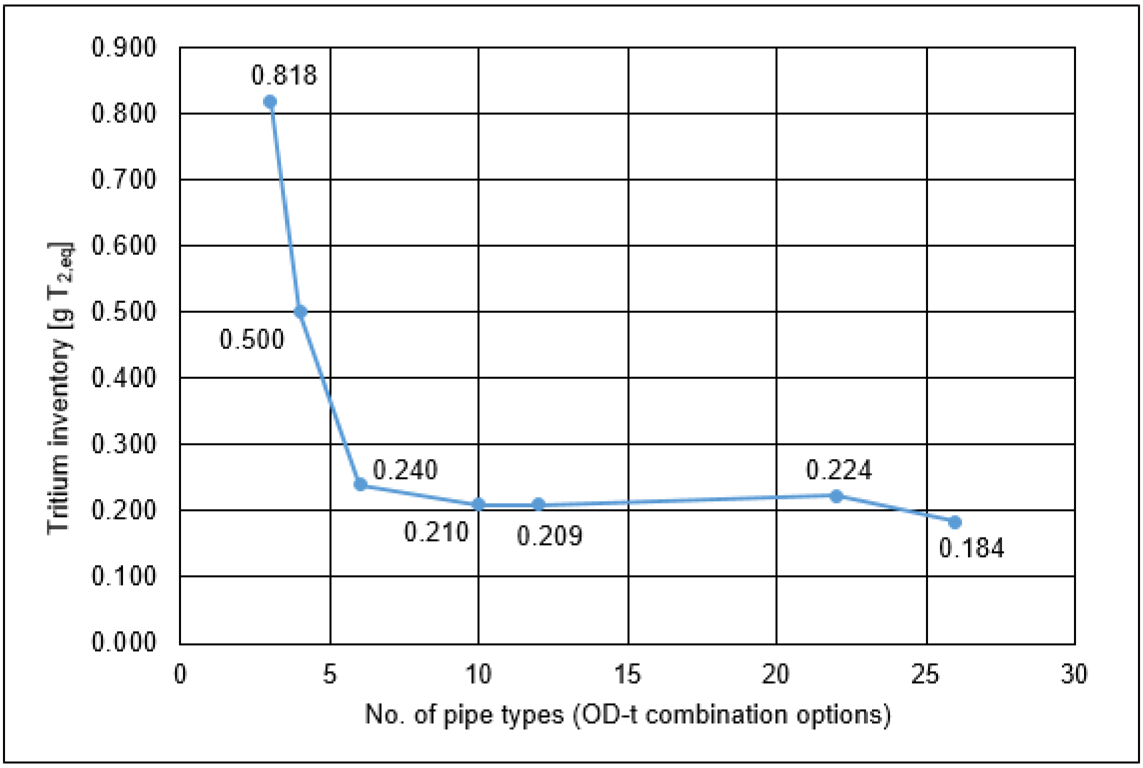

Figure 25 – Graphical representation of the effect on the tritium inventory of different pipe types unification strategies.

A comparison of all the sensitivity analyses can be found in Table A-8, in the annex.

4 Summary & conclusions

The application of the developed methodologies resulted in the identification of 627 process equipment most of which have been grouped into 29 gloveboxes, 2 coldboxes and 19 metalboxes. It has been found that these confinement structures can be housed inside a compact seven-story-building design, with a projected footprint of 2200 m^2, a cumulative footprint of 11240 m^2, an external volume of 57030 m^3 and external dimensions of 35.8 m of height, 74.0 m of length and 30.9 m of width. Lastly, the resulting tritium inventory inside interconnecting pipes under normal operation has been effectively minimized to be in the order of 0.2 g with only 10 pipe types (outer diameter and thickness combinations) for the optimized base case design, in contrast to the expected 3.6 g in an un-optimized case.

The proposed building fulfils the developed design basis as it considers personnel and process safety, operational flexibility, sufficient space for maintainability and inspectability, as well as the requirements and relationships between process units. The building is compact balancing safety and operability of the process with the minimization of tritiated piping and separating tritium inventory into different rooms which also facilitates the containment of accidents. Also considered is the limitation of the exposure of personnel to hazardous substances and sufficient space for efficient and safe construction, operation and maintenance, as well as firefighting facilities and auxiliary services [35]. Even with all these conservative design considerations, the EU-DEMO tritium plant building still is projected to be 20% smaller in volume than that of ITER.

Thanks to the application of the direct internal recycling concept, the processing systems housed in the EU-DEMO tritium plant have been significantly reduced compared to a direct scale-up from the ITER tritium plant. This is evident in the dimensions of the pre-sized components that oriented the equipment identification and dimensions estimation through a classification into small, medium and large sizes, based on typical reference equipment. 73% of the identified fuel cycle equipment could be grouped inside 29 gloveboxes of standard size.

The majority of the plant volume, totaling 20079 m^3 for the process rooms, is dedicated to the outer tritium plant loop, requiring 18626 m^3 or 93%. About 60% of that volume is taken up by rooms dedicated to the exhaust detritiation system trains, although under normal operation they contribute with less than 2% to the total process tritium inventory. 97 % of the process tritium inventory of the plant is distributed across four rooms located centrally in the building, with other rooms providing additional layers of protection towards the environment.

The piping of the facility has been successfully optimized to offer a low operational tritium inventory and at the same time a low stock of different pipe types, simplifying the design and aiding the economics of the project in the construction and operation stages. Sensitivity analyses have been carried out showing that the expected normal operation inventory in pipes can be found at around 0.2 g, at any operational mode with a wide range of process conditions. Regarding the final piping design, 98% of the volume that is continuously tritiated under normal operation corresponds to the exhaust detritiation system gathering network although it contributes merely $3 \cdot 10^{-4}$ g to the piping tritium inventory. Five gaseous streams concentrate 76% of the tritium inventory in pipes and thanks to the layout and piping optimization their total length has been minimized to 17.70 m with a total volume of $1.4 \cdot 10^{-3}$ m^3 while in total 50.22 m^3 of piping volume is required.

Finally, it must be noted that, even though the process flow design and operational conditions will likely change as the project engineering evolves and all the systems are properly sized, this work can be easily adapted to those changes since it establishes a design methodology and criteria that will serve as a guideline for engineers during the undertaking of the final plant design.

4.1 Next steps

The methodology presented in this thesis should be applied to the next stages of the project design to further improve the inventory estimation and layout definition. The final sizing of the identified equipment will lead to changes in the required footprint and volume of the plant, expected to be smaller than the one presented here since the uncertainties will be reduced and the conservative margins can be narrowed. Once the pressure levels between systems are defined, the allowable pressure drop criteria can be adapted to a pipe-by-pipe hydraulic calculation and a new inventory estimation can be performed. Lastly, thermal integration between systems might be analyzed later on, which can have an impact on the layout and the inventory, although it carries the risk of tritium migration along the additional pathways resulting from integration.

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5.1 List of tables

5.2 List of figures

6 Annex

6.1 List of tables

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Table A-1 – Equipment list of the tritium plant with sizing and grouping

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
Exhaust Processing INTL-EP	Impurity Removal IRS	GB1	**Compressor**	FM	IRS-C-001	M	2.00	0.7
			Compressor (spare)	FM	IRS-C-002	M	2.00	0.7
			Permeator Stage 1 (30+10)	SEP	IRS-S-001	(L=0.5m D=0.1m)x4	0.02	1.0
			Permeator Stage 1 (30+10)	SEP	IRS-S-002	(L=0.5m D=0.1m)x4	0.02	1.0
			Spiral/Baffle Water Cooler (DT)	HE	IRS-E-001	M	2.00	0.7
			Jacket Water Cooler (He)	HE	IRS-E-002	S	0.10	1.0
	Impurity Processing IPS	GB1	**Low temperature converter**	RE	IPS-R-001	0.1m^3	0.10	1.0
			Low temperature converter (spare)	RE	IPS-R-002	0.1m^3	0.10	1.0
			Circulator (HTC regeneration w/O_2)	FM	IPS-C-001	S	0.10	1.0
			Cooler (HTC regeneration w/O_2)	HE	IPS-E-001	S	0.10	1.0
			High Temperature Converter 1	RE	IPS-R-003	0.1m^3	0.10	1.0
			High Temperature Converter 2 (spare)	RE	IPS-R-004	0.1m^3	0.10	1.0
			HTC 1 Filter	FT	IPS-U-001	S	0.10	1.0
			HTC 2 Filter	FT	IPS-U-002	S	0.10	1.0
			Jacket Water Cooler (after HTC)	HE	IPS-E-002	S	0.10	1.0
			Compressor	FM	IPS-C-003	S	0.10	1.0
			Compressor (Spare)	FM	IPS-C-004	S	0.10	1.0
			Vacuum Pump (HTC regeneration)	FM	IPS-C-002	S	0.10	1.0
			Permeator Stage 2 (5+5)	SEP	IPS-S-001	(L=0.5m D=0.1m)x2	0.01	1.0
			Permeator Stage 2 (5+5)	SEP	IPS-S-002	(L=0.5m D=0.1m)x2	0.01	1.0
			Spiral/Baffle Water Cooler (DT)	HE	IPS-E-003	S	0.10	1.0
			Jacket Water Cooler (He)	HE	IPS-E-004	S	0.10	1.0
	Gas Detritiation G-DS	GB1	**Pre-Filter**	FT	GDS-U-003	S	0.10	1.0
			Pre-Filter	FT	GDS-U-004	S	0.10	1.0
			Getter Bed 1	SEP	GDS-S-001	L=0.6m, D=0.2m	0.02	1.0
			Getter Bed 2 (spare)	SEP	GDS-S-002	L=0.6m, D=0.2m	0.02	1.0
			Getter Bed 1 Filter	FT	GDS-U-001	S	0.10	1.0
			Getter Bed 2 Filter	FT	GDS-U-002	S	0.10	1.0
			Q_2 Filter	FT	GDS-U-005	S	0.10	1.0
			Q_2 Filter (spare)	FT	GDS-U-006	S	0.10	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
			Spiral/Baffle Water Cooler (Q_2)	HE	GDS-E-001	S	0.10	1.0
			Vacuum Pump (4 stages)	FM	GDS-C-001	M	2.00	0.7
			Vacuum Pump (4 stages) (spare)	FM	GDS-C-002	M	2.00	0.7
			Permeator (5+5)	SEP	GDS-S-003	(L=0.5m D=0.1m)x2	0.01	1.0
			Permeator (5+5)	SEP	GDS-S-004	(L=0.5m D=0.1m)x2	0.01	1.0
			Spiral/Baffle Water Cooler (DT)	HE	GDS-E-002	S	0.10	1.0
			Jacket Water Cooler (He)	HE	GDS-E-003	S	0.10	1.0
			Buffer Vessel (Temperature Controlled)	VS	GDS-V-001	0.1m^3	0.10	1.0
	Exhaust Processing Vacuum EPVS	GB1	**Vacuum Pump (4 stages)**	FM	EPVS-C-001	M	2.00	0.7
			Vacuum Pump (4 stages) (spare)	FM	EPVS-C-002	M	2.00	0.7
	Glovebox 1 Auxiliary GB1-AUX	GB1	Water-Water Heat Exchanger	HE	GB1-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB1-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB1-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-1	M	2.00	0.7
			SVS Vacuum Pump	FM	GB1-C-101	S	0.10	1.0
	PEG Removal PRS	CB2	**PRS Column 1**	CD	PRS-T-001	H=5m, D=0.1m	0.04	1.0
			PRS Column 2	CD	PRS-T-002	H=5m, D=0.1m	0.04	1.0
			Column 1 Reboiler Electrical	HE	PRS-E-002	S	0.10	1.0
			Column 1 Condenser Cryocooler	HE	PRS-E-003	S	0.10	1.0
			Column 2 Reboiler Electrical	HE	PRS-E-004	S	0.10	1.0
			Column 2 Condenser Cryocooler	HE	PRS-E-005	S	0.10	1.0
	PEG Storage PSS	GB2	**PEG storage (Ar) 1**	VS	PSS-V-001	0.5m^3	0.50	1.0
			PEG storage (Ar) 2	VS	PSS-V-002	0.5m^3	0.50	1.0
			PEG storage (Xe) 1	VS	PSS-V-003	0.5m^3	0.50	1.0
			PEG storage (Xe) 2	VS	PSS-V-004	0.5m^3	0.50	1.0
			O_2 capture column 1	SEP	PSS-S-001	S	0.10	1.0
			O_2 capture column 2	SEP	PSS-S-002	S	0.10	1.0
			CO_2 removal column 1	SEP	PSS-S-003	S	0.10	1.0
			CO_2 removal column 2	SEP	PSS-S-004	S	0.10	1.0
	Glovebox 2 Auxiliary GB2-AUX	GB2	Water-Water Heat Exchanger	HE	GB2-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB2-P-101	S	0.10	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
			Cooling Loop Pump (spare)	FM	GB2-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-2	M	2.00	0.7
			SVS Vacuum Pump	FM	GB2-C-101	S	0.10	1.0
			Coldbox Vacuum Pump	FM	GB2-C-102	S	0.10	1.0
			Coldbox Vacuum Pump (spare)	FM	GB2-C-103	S	0.10	1.0
Isotope Rebalancing & Protium Removal INTL-IRPR	**Isotope Rebalancing & Protium Removal IRPRS**	GB3	**Compressor**	FM	IRPRS-C-001	M	2.00	0.7
			Compressor (spare)	FM	IRPRS-C-002	M	2.00	0.7
			Membrane	SEP	IRPRS-S-001	S	0.10	1.0
			Membrane (spare)	SEP	IRPRS-S-002	S	0.10	1.0
			Vacuum Pump	FM	IRPRS-C-003	S	0.10	1.0
			Vacuum Pump (spare)	FM	IRPRS-C-004	S	0.10	1.0
			Feed Tank	VS	IRPRS-V-001	0.15m^3	0.15	1.0
			TSA Column 1A (2+1)	SEP	IRPRS-S-003	M	2.00	0.7
			TSA Column 1B (2+1)	SEP	IRPRS-S-004	M	2.00	0.7
			TSA Column 1C (2+1) (spare)	SEP	IRPRS-S-005	M	2.00	0.7
			TSA Column 2A (2+1)	SEP	IRPRS-S-006	M	2.00	0.7
			TSA Column 2B (2+1)	SEP	IRPRS-S-007	M	2.00	0.7
			TSA Column 2C (2+1) (spare)	SEP	IRPRS-S-008	M	2.00	0.7
	Glovebox 3 Auxiliary GB3-AUX	GB3	Water-Water Heat Exchanger	HE	GB3-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB3-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB3-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-3	M	2.00	0.7
			SVS Vacuum Pump	FM	GB3-C-101	S	0.10	1.0
			Heating Oil Electrical Heater/Accumulator	HE	GB3-E-201	M	2.00	0.7
			Heating Oil System Pump	FM	GB3-P-201	S	0.10	1.0
			Heating Oil System Pump (spare)	FM	GB3-E-202	S	0.10	1.0
Water Detritiation OUTL-WD	**Feed Water Tanks FT**	WDFT	**WDS Feed water Tank (high T conc.)**	TK	WDFT-V-001	2x5m^3	5.00	1.0
			WDS Feed water Tank (high T conc.)	TK	WDFT-V-002	2x5m^3	5.00	1.0
			WDS Feed water Tank (low T conc.)	TK	WDFT-V-003	2x25m^3	25.00	1.0
			WDS Feed water Tank (low T conc.)	TK	WDFT-V-004	2x25m^3	25.00	1.0
		GB7	**Purifier Skid (Ion Exchange + Pumps)**	FT	WDFT-U-001	L	4.00	0.7
			Purifier Skid (Ion Exchange + Pumps) (spare)	FT	WDFT-U-002	L	4.00	0.7

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
			Purifier Skid (Ion Exchange + Pumps)	FT	WDFT-U-003	L	4.00	0.7
			Purifier Skid (Ion Exchange + Pumps) (spare)	FT	WDFT-U-004	L	4.00	0.7
			WDS Feed water Tank (for mixing)	TK	WDFT-V-005	1x1m^3	1.00	1.0
			Pump	FM	WDFT-P-001	M	2.00	0.7
			Pump (Spare)	FM	WDFT-P-002	M	2.00	0.7
			Water Heater	HE	WDFT-E-001	M	2.00	0.7
	Glovebox 7 Auxiliary GB7-AUX	GB7	Water-Water Heat Exchanger	HE	GB7-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB7-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB7-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-7	M	2.00	0.7
			SVS Vacuum Pump	FM	GB7-C-101	S	0.10	1.0
	Tritiated Water Storage & Drain Tanks Active Water Storage AWSS	AWSS	**Emergency Tank 1**	TK	AWSS-V-001	100 m^3	100.00	1.0
			Emergency Tank 2	TK	AWSS-V-002	100 m^3	100.00	1.0
			Drain Tank 1	TK	AWSS-V-003	30 m^3	30.00	1.0
			Drain Tank 2	TK	AWSS-V-004	30 m^3	30.00	1.0
			Pump 1	FM	AWSS-P-001	M	2.00	0.7
			Pump 2	FM	AWSS-P-002	M	2.00	0.7
			Pump 3	FM	AWSS-P-003	M	2.00	0.7
			Pump 4	FM	AWSS-P-004	M	2.00	0.7
	Water Detritiation WDS	GB8	**Electrolyzer 1 (200 Nm^3/h Q_2)**	RE	WDS-R-001	D=1.5m; L=2.5m	4.42	1.0
			Electrolyzer 2 (200 Nm^3/h Q_2)	RE	WDS-R-002	D=1.5m; L=2.5m	4.42	1.0
			Electrolyzer 3 (200 Nm^3/h Q_2)	RE	WDS-R-003	D=1.5m; L=2.5m	4.42	1.0
			Electrolyzer 4 (200 Nm^3/h Q_2) (spare)	RE	WDS-R-004	D=1.5m; L=2.5m	4.42	1.0
			Electrolyzer Condenser (300 Nm^3/h O_2)	HE	WDS-E-001	M	2.00	0.7
			Electrolyzer Condenser (300 Nm^3/h O_2) (spare)	HE	WDS-E-002	M	2.00	0.7
			Pump	FM	WDS-P-001	S	0.10	1.0
			Pump (spare)	FM	WDS-P-002	S	0.10	1.0
			Permeator	SEP	WDS-S-001	S	0.10	1.0
			Permeator	SEP	WDS-S-002	S	0.10	1.0
			Spiral/Baffle Water Cooler (DT)	HE	WDS-E-003	S	0.10	1.0
			Jacket Water Cooler (H_2)	HE	WDS-E-004	S	0.10	1.0
			Vacuum Pump (4 stages)	FM	WDS-C-001	L	4.00	0.7

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m³]	Fill Factor
			Vacuum Pump (4 stages) (spare)	FM	WDS-C-002	L	4.00	0.7
		MB8	**LPCE Column**	RE	WDS-T-001	H=25m, D=0.3m	1.77	1.0
			Overhead Condenser (H_2)	HE	WDS-E-004	S	0.10	1.0
			Overhead Compressor (H_2)	FM	WDS-C-003	S	0.10	1.0
			Overhead Compressor (H_2) (spare)	FM	WDS-C-004	S	0.10	1.0
			Pump	FM	WDS-P-003	M	2.00	0.7
			Pump (Spare)	FM	WDS-P-004	M	2.00	0.7
			Purified Water Heat Exchanger	HE	WDS-E-005	S	0.10	1.0
			Overhead Reflux Heat Exchanger	HE	WDS-E-006	S	0.10	1.0
	Oxygen Detritiation ODS	GB8	**ZMS Bed 1**	SEP	ODS-S-001	D=0.2m, L=0.6m	0.02	1.0
			ZMS Bed 2	SEP	ODS-S-002	D=0.2m, L=0.6m	0.02	1.0
			ZMS Bed 3 (spare)	SEP	ODS-S-003	D=0.2m, L=0.6m	0.02	1.0
			ZMS Bed 4 (spare)	SEP	ODS-S-004	D=0.2m, L=0.6m	0.02	1.0
			Vacuum Pump	FM	ODS-C-001	S	0.10	1.0
			Vacuum Pump (spare)	FM	ODS-C-002	S	0.10	1.0
			Circulator	FM	ODS-C-003	S	0.10	1.0
			Circulator (spare)	FM	ODS-C-004	S	0.10	1.0
			Heater	HE	ODS-E-001	S	0.10	1.0
			Economizer	HE	ODS-E-002	S	0.10	1.0
			Condenser	HE	ODS-E-003	S	0.10	1.0
	Glovebox 8 Auxiliary GB8-AUX	GB8	Water-Water Heat Exchanger	HE	GB8-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB8-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB8-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-8	M	2.00	0.7
			SVS Vacuum Pump	FM	GB8-C-101	S	0.10	1.0
	Metalbox 8 Auxiliary MB8-AUX	MB8	Metal box Detritiation System	PKG	MB-DS-8	M	2.00	0.7
			SVS Vacuum Pump	FM	MB8-C-101	S	0.10	1.0
Coolant Purification OUTL-CP	**SEL A: Water Coolant Purification WCPS**	GB4A	**Economizer**	HE	WCPS-E-001	L	4.00	0.7
			Overhead Pump	FM	WCPS-P-001	M	2.00	0.7
			Bottom Cooler	HE	WCPS-E-004	M	2.00	0.7
			Bottom Pump	FM	WCPS-P-002	M	2.00	0.7
		MB4A	**Distillation Column**	DC	WCPS-T-001	H=15m, D=1.5m	26.51	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m³]	Fill Factor
			Reboiler + Electrical Water Heater	HE	WCPS-E-002	L	4.00	0.7
			Condenser	HE	WCPS-E-003	L	4.00	0.7
	Glovebox 4A Auxiliary GB4A-AUX	GB4A	Water-Water Heat Exchanger	HE	GB4A-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB4A-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB4A-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-4A	M	2.00	0.7
			SVS Vacuum Pump	FM	GB4A-C-101	S	0.10	1.0
	Metalbox 4A Auxiliary MB4A-AUX	MB4A	Metalbox Detritiation System	PKG	MB-DS-4A	M	2.00	0.7
			SVS Vacuum Pump	FM	MB4A-C-101	S	0.10	1.0
	SEL B: Helium Coolant Purification HeCPS	GB4B	**Circulator (O_2 - CuO bed regeneration)**	FM	HeCPS-C-001	S	0.10	1.0
			Cooler (O_2 - CuO bed regeneration)	HE	HeCPS-E-001	S	0.10	1.0
			CuO Bed 1	SEP	HeCPS-S-001	D=0.9m, L=1.4m	0.89	1.0
			CuO Bed 2	SEP	HeCPS-S-002	D=0.9m, L=1.4m	0.89	1.0
			CuO Bed 3 (spare)	SEP	HeCPS-S-003	D=0.9m, L=1.4m	0.89	1.0
			CuO Bed 4 (spare)	SEP	HeCPS-S-004	D=0.9m, L=1.4m	0.89	1.0
			CuO Bed 1 Filter	FT	HeCPS-U-001	+ 0.5m	0.41	1.0
			CuO Bed 2 Filter	FT	HeCPS-U-002	+ 0.5m	0.41	1.0
			CuO Bed 3 Filter	FT	HeCPS-U-003	+ 0.5m	0.41	1.0
			CuO Bed 4 Filter	FT	HeCPS-U-004	+ 0.5m	0.41	1.0
			Compressor (O_2 - CuO bed regeneration)	FM	HeCPS-C-002	M	2.00	0.7
			Economizer	HE	HeCPS-E-002	L	4.00	0.7
			Chiller	HE	HeCPS-E-003	L	4.00	0.7
			ZMS Bed 1	SEP	HeCPS-S-005	d=0.75, l=1.13	0.50	1.0
			ZMS Bed 2	SEP	HeCPS-S-006	d=0.75, l=1.13	0.50	1.0
			ZMS Bed 3 (spare)	SEP	HeCPS-S-007	d=0.75, l=1.13	0.50	1.0
			ZMS Bed 4 (spare)	SEP	HeCPS-S-008	d=0.75, l=1.13	0.50	1.0
			ZMS Bed 1 Filter	FT	HeCPS-U-005	+ 0.5m	0.28	1.0
			ZMS Bed 2 Filter	FT	HeCPS-U-006	+ 0.5m	0.28	1.0
			ZMS Bed 3 Filter	FT	HeCPS-U-007	+ 0.5m	0.28	1.0
			ZMS Bed 4 Filter	FT	HeCPS-U-008	+ 0.5m	0.28	1.0
			Heater	HE	HeCPS-E-004	M	2.00	0.7
			Economizer	HE	HeCPS-E-005	S	0.10	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
			Circulator	FM	HeCPS-C-003	S	0.10	1.0
			Condenser	HE	HeCPS-E-006	M	2.00	0.7
			Condenser Pump	FM	HeCPS-P-001	S	0.10	1.0
			Compressor (He ambient to 80bar)	FM	HeCPS-C-004	M	2.00	0.7
	Glovebox 4B Auxiliary GB4B-AUX	GB4B	Water-Water Heat Exchanger	HE	GB4B-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB4B-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB4B-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-4B	M	2.00	0.7
			SVS Vacuum Pump	FM	GB4B-C-101	S	0.10	1.0
Isotope Separation OUTL-IS	Isotope Separation ISS	CB6	**Liquefier (Inlet CD1)**	HE	ISS-E-001	S	0.10	1.0
			Cryo Distillation Column 1 (CD1)	CD	ISS-T-001	H=5m, D=0.1m	0.04	1.0
			CD1 Reboiler	HE	ISS-E-002	S	0.10	1.0
			CD1 Condenser	HE	ISS-E-003	S	0.10	1.0
			Equilibrator 1 Liquefier	HE	ISS-E-004	S	0.10	1.0
			Liquefier (Inlet CD2)	HE	ISS-E-005	S	0.10	1.0
			Cryo Distillation Column 2 (CD2)	CD	ISS-T-002	H=5m, D=0.1m	0.04	1.0
			CD2 Reboiler	HE	ISS-E-006	S	0.10	1.0
			CD2 Condenser	HE	ISS-E-007	S	0.10	1.0
			Equilibrator 2 Liquefier	HE	ISS-E-008	S	0.10	1.0
			Liquefier (Inlet CD3)	HE	ISS-E-009	S	0.10	1.0
			Cryo Distillation Column 3 (CD3)	CD	ISS-T-012	H=5m, D=0.1m	0.04	1.0
			CD3 Reboiler	HE	ISS-E-010	S	0.10	1.0
			CD3 Condenser	HE	ISS-E-011	S	0.10	1.0
			Equilibrator 3 Liquefier	HE	ISS-E-012	S	0.10	1.0
		GB6	**Overhead CD1 Heater**	HE	ISS-E-013	S	0.10	1.0
			Overhead CD1 Compressor	FM	ISS-C-001	S	0.10	1.0
			Overhead CD1 Compressor (spare)	FM	ISS-C-002	S	0.10	1.0
			Equilibrator 1 (Heated Reactor)	RE	ISS-R-001	$V=0.5m^3$	0.50	1.0
			Overhead CD2 Compressor	FM	ISS-C-003	S	0.10	1.0
			Overhead CD2 Compressor (spare)	FM	ISS-C-004	S	0.10	1.0
			Equilibrator 1 Economizer	HE	ISS-E-014	S	0.10	1.0
			Equilibrator 2 (Heated Reactor)	RE	ISS-R-002	$V=0.5m^3$	0.50	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
			Equilibrator 2 Economizer	HE	ISS-E-015	S	0.10	1.0
			Equilibrator 3 (Heated Reactor)	RE	ISS-R-003	V=0.5m^3	0.50	1.0
			Overhead CD3 Compressor	FM	ISS-C-005	S	0.10	1.0
			Overhead CD3 Compressor (spare)	FM	ISS-C-006	S	0.10	1.0
			Equilibrator 3 Economizer	HE	ISS-E-016	S	0.10	1.0
			Economizer (Bottom CD3)	HE	ISS-E-017	S	0.10	1.0
			Heater (Bottom CD3)	HE	ISS-E-018	S	0.10	1.0
	Gas Collection and Buffering GCBS	GB6	**Buffer Vessel CD1**	VS	GCBS-V-001	V=1m^3	1.00	1.0
			Buffer Vessel CD2	VS	GCBS-V-002	V=1m^3	1.00	1.0
			Buffer Vessel CD3	VS	GCBS-V-003	V=1m^3	1.00	1.0
	Glovebox 6 Auxiliary GB6-AUX	GB6	Water-Water Heat Exchanger	HE	GB6-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB6-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB6-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-06	M	2.00	0.7
			SVS Vacuum Pump	FM	GB6-C-101	S	0.10	1.0
			Coldbox Vacuum Pump	FM	GB6-C-102	S	0.10	1.0
			Coldbox Vacuum Pump (spare)	FM	GB6-C-103	S	0.10	1.0
Gas Storage OUTL-GS	DT Storage DTSS	GB6	**DT+ Feed Vessel**	VS	ISS-V-001	S	0.10	1.0
		GB9	**DT+ Storage Beds**	SS	DTSS-V-001/020	20 x 0.1m^3	2.00	1.0
			DT shut-down storage beds	SS	DTSS-V-021/040	20 x 0.1m^3	2.00	1.0
			DT Storage Beds - (Fuel Make-Up)	SS	DTSS-V-041/060	20 x 0.1m^3	2.00	1.0
			T long-term storage beds	SS	DTSS-V-061/080	20 x 0.1m^3	2.00	1.0
	^{3}He Extraction He3ExS	GB9	**^{3}He Extraction Unit**	PKG	He3ExS	L	4.00	0.7
	Glovebox 6 Auxiliary GB9-AUX	GB9	Water-Water Heat Exchanger	HE	GB9-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB9-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB9-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-9	M	2.00	0.7
			SVS Vacuum Pump	FM	GB9-C-101	S	0.10	1.0
	Protium Storage H2SS	H2SS	**H_2 Tanks**	VS	H2SS-V-001/020	2 x gas bundles	4.00	1.0
	Oxygen Storage	O2SS	**O_2 Tanks**	VS	O2SS-V-001/020	2 x gas bundles	4.00	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
	O2SS							
	D2 Supply D2SS	D2SS	**D_2 Tanks**	VS	D2SS-V-001/020	2 x gas bundles	4.00	1.0
Tritium Conditioning OUTL-TC	SEL A: WCLL Tritium Conditioning WTCS	GB5A	**Pre-Filter**	FT	WTCS-U-005	S	0.10	1.0
			Pre-Filter (spare)	FT	WTCS-U-006	S	0.10	1.0
			Getter Bed 1	SEP	WTCS-S-001	D=1m, L=3m	2.36	1.0
			Getter Bed 2	SEP	WTCS-S-002	D=1m, L=3m	2.36	1.0
			Getter Bed 3 (spare)	SEP	WTCS-S-003	D=1m, L=3m	2.36	1.0
			Getter Bed 4 (spare)	SEP	WTCS-S-004	D=1m, L=3m	2.36	1.0
			Getter Bed 1 Filter	FT	WTCS-U-001	+ 0.5m	0.50	1.0
			Getter Bed 2 Filter	FT	WTCS-U-002	+ 0.5m	0.50	1.0
			Getter Bed 3 Filter	FT	WTCS-U-003	+ 0.5m	0.50	1.0
			Getter Bed 4 Filter	FT	WTCS-U-004	+ 0.5m	0.50	1.0
			Q_2 Filter	FT	WTCS-U-007	S	0.10	1.0
			Q_2 Filter (spare)	FT	WTCS-U-008	S	0.10	1.0
			Q_2 Chiller	HE	WTCS-E-001	M	2.00	0.7
			Q_2 Vacuum Pump	FM	WTCS-C-001	M	2.00	0.7
			Q_2 Vacuum Pump (spare)	FM	WTCS-C-002	M	2.00	0.7
			He Chiller	HE	WTCS-E-002	M	2.00	0.7
			He Vacuum Pump	FM	WTCS-C-003	M	2.00	0.7
			He Vacuum Pump (spare)	FM	WTCS-C-004	M	2.00	0.7
	Glovebox 5A Auxiliary GB5A-AUX	GB5A	Water-Water Heat Exchanger	HE	GB5A-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB5A-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB5A-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-5A	M	2.00	0.7
			SVS Vacuum Pump	FM	GB5A-C-101	S	0.10	1.0
	SEL B: HCPB Tritium Conditioning HTCS	GB5B	**Compressor**	FM	HTCS-C-001	M	2.00	0.7
			Compressor (spare)	FM	HTCS-C-002	M	2.00	0.7
			Permeator (60+10)	SEP	HTCS-S-001	(L=0.5m D=0.1m) x7	0.04	1.0
			Permeator (60+10)	SEP	HTCS-S-002	(L=0.5m D=0.1m) x7	0.04	1.0
			Spiral/Baffle Water Cooler (DT)	HE	HTCS-E-001	S	0.10	1.0
			Jacket Water Cooler (He)	HE	HTCS-E-002	S	0.10	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m³]	Fill Factor
			Vacuum Pump (4 stages)	FM	HTCS-C-003	L	4.00	0.7
			Vacuum Pump (4 stages) (spare)	FM	HTCS-C-004	L	4.00	0.7
	Glovebox 5B Auxiliary GB5B-AUX	GB5B	Water-Water Heat Exchanger	HE	GB5B-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB5B-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB5B-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-5B	M	2.00	0.7
			SVS Vacuum Pump	FM	GB5B-C-101	S	0.10	1.0
Exhaust Detritiation OUTL-ED	**Normal Exhaust Detritiation System Once Trough Train 1 N-EDS-OT-1**	GB11	**Pre-Filter**	FT	NEDS-U-011	M	2.00	0.7
			Condenser	HE	NEDS-E-011	L	4.00	0.7
			LT Economizer	HE	NEDS-E-012	M	2.00	0.7
			Low Temperature Recombiner	RE	NEDS-R-011	$1m^3$	1.00	1.0
			HT Economizer	HE	NEDS-E-013	L	4.00	0.7
			High Temperature Recombiner	RE	NEDS-R-012	$1m^3$	1.00	1.0
			Pump	FM	NEDS-P-011	M	2.00	0.7
			Pump (Spare)	FM	NEDS-P-012	M	2.00	0.7
		MB11	**Saturator**	HE	NEDS-E-014	L	4.00	0.7
			Wet Scrubber Column	ABS	NEDS-T-011	H=15m, D=1m	11.78	1.0
			Condenser	HE	NEDS-E-015	L	4.00	0.7
			Electrical Water Heater	HE	NEDS-E-016	M	2.00	0.7
			Overhead Compressor	FM	NEDS-C-011	L	4.00	0.7
			Overhead Compressor (spare)	FM	NEDS-C-012	L	4.00	0.7
	Glovebox 11 Auxiliary GB11-AUX	GB11	Water-Water Heat Exchanger	HE	GB11-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB11-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB11-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-11	M	2.00	0.7
			SVS Vacuum Pump	FM	GB11-C-101	S	0.10	1.0
	Metalbox 11 Auxiliary MB11-AUX	MB11	Metalbox Detritiation System	PKG	MB-DS-11	M	2.00	0.7
			SVS Vacuum Pump	FM	MB11-C-101	S	0.10	1.0
	Normal Exhaust Detritiation System Once Trough Train 2	GB12	**Pre-Filter**	FT	NEDS-U-021	M	2.00	0.7
			Condenser	HE	NEDS-E-021	L	4.00	0.7
			LT Economizer	HE	NEDS-E-022	M	2.00	0.7
			Low Temperature Recombiner	RE	NEDS-R-021	$1m^3$	1.00	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m³]	Fill Factor
	N-EDS-OT-2		**HT Economizer**	HE	NEDS-E-023	L	4.00	0.7
			High Temperature Recombiner	RE	NEDS-R-022	$1m^3$	1.00	1.0
			Pump	FM	NEDS-P-021	M	2.00	0.7
			Pump (Spare)	FM	NEDS-P-022	M	2.00	0.7
		MB12	**Saturator**	HE	NEDS-E-024	L	4.00	0.7
			Wet Scrubber Column	ABS	NEDS-T-021	H=15m, D=1m	11.78	1.0
			Condenser	HE	NEDS-E-025	L	4.00	0.7
			Electrical Water Heater	HE	NEDS-E-026	M	2.00	0.7
			Overhead Compressor	FM	NEDS-C-021	L	4.00	0.7
			Overhead Compressor (spare)	FM	NEDS-C-022	L	4.00	0.7
	Glovebox 12 Auxiliary GB12-AUX	GB12	Water-Water Heat Exchanger	HE	GB12-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB12-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB12-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-12	M	2.00	0.7
			SVS Vacuum Pump	FM	GB12-C-101	S	0.10	1.0
	Metalbox 12 Auxiliary MB12-AUX	MB12	Metalbox Detritiation System	PKG	MB-DS-12	M	2.00	0.7
			SVS Vacuum Pump	FM	MB12-C-101	S	0.10	1.0
	Normal Exhaust Detritiation System Once Trough Train 3 N-EDS-OT-3	GB13	**Pre-Filter**	FT	NEDS-U-031	M	2.00	0.7
			Condenser	HE	NEDS-E-031	L	4.00	0.7
			LT Economizer	HE	NEDS-E-032	M	2.00	0.7
			Low Temperature Recombiner	RE	NEDS-R-031	$1m^3$	1.00	1.0
			HT Economizer	HE	NEDS-E-033	L	4.00	0.7
			High Temperature Recombiner	RE	NEDS-R-032	$1m^3$	1.00	1.0
			Pump	FM	NEDS-P-031	M	2.00	0.7
			Pump (Spare)	FM	NEDS-P-032	M	2.00	0.7
		MB13	**Saturator**	HE	NEDS-E-034	L	4.00	0.7
			Wet Scrubber Column	ABS	NEDS-T-031	H=15m, D=1m	11.78	1.0
			Condenser	HE	NEDS-E-035	L	4.00	0.7
			Electrical Water Heater	HE	NEDS-E-036	M	2.00	0.7
			Overhead Compressor	FM	NEDS-C-031	L	4.00	0.7
			Overhead Compressor (spare)	FM	NEDS-C-032	L	4.00	0.7
	Glovebox 13 Auxiliary	GB13	Water-Water Heat Exchanger	HE	GB13-E-101	M	2.00	0.7

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m³]	Fill Factor
	GB13-AUX		Cooling Loop Pump	FM	GB13-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB13-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-13	M	2.00	0.7
			SVS Vacuum Pump	FM	GB13-C-101	S	0.10	1.0
	Metalbox 13 Auxiliary MB13-AUX	MB13	Metalbox Detritiation System	PKG	MB-DS-13	M	2.00	0.7
			SVS Vacuum Pump	FM	MB13-C-101	S	0.10	1.0
	Normal Exhaust Detritiation System Once Trough Train 4 N-EDS-OT-4	GB14	**Pre-Filter**	FT	NEDS-U-041	M	2.00	0.7
			Condenser	HE	NEDS-E-041	L	4.00	0.7
			LT Economizer	HE	NEDS-E-042	M	2.00	0.7
			Low Temperature Recombiner	RE	NEDS-R-041	$1m^3$	1.00	1.0
			HT Economizer	HE	NEDS-E-043	L	4.00	0.7
			High Temperature Recombiner	RE	NEDS-R-042	$1m^3$	1.00	1.0
			Pump	FM	NEDS-P-041	M	2.00	0.7
			Pump (Spare)	FM	NEDS-P-042	M	2.00	0.7
		MB14	**Saturator**	HE	NEDS-E-044	L	4.00	0.7
			Wet Scrubber Column	ABS	NEDS-T-041	H=15m, D=1m	11.78	1.0
			Condenser	HE	NEDS-E-045	L	4.00	0.7
			Electrical Water Heater	HE	NEDS-E-046	M	2.00	0.7
			Overhead Compressor	FM	NEDS-C-041	L	4.00	0.7
			Overhead Compressor (spare)	FM	NEDS-C-042	L	4.00	0.7
	Glovebox 14 Auxiliary GB14-AUX	GB14	Water-Water Heat Exchanger	HE	GB14-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB14-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB14-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-14	M	2.00	0.7
			SVS Vacuum Pump	FM	GB14-C-101	S	0.10	1.0
	Metalbox 14 Auxiliary MB14-AUX	MB14	Metalbox Detritiation System	PKG	MB-DS-14	M	2.00	0.7
			SVS Vacuum Pump	FM	MB14-C-101	S	0.10	1.0
	Normal Exhaust Detritiation System Once Trough Train 5 N-EDS-OT-5	GB15	**Pre-Filter**	FT	NEDS-U-051	M	2.00	0.7
			Condenser	HE	NEDS-E-051	L	4.00	0.7
			LT Economizer	HE	NEDS-E-052	M	2.00	0.7
			Low Temperature Recombiner	RE	NEDS-R-051	$1m^3$	1.00	1.0
			HT Economizer	HE	NEDS-E-053	L	4.00	0.7

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m³]	Fill Factor
			High Temperature Recombiner	RE	NEDS-R-052	1m³	1.00	1.0
			Pump	FM	NEDS-P-051	M	2.00	0.7
			Pump (Spare)	FM	NEDS-P-052	M	2.00	0.7
		MB15	**Saturator**	HE	NEDS-E-054	L	4.00	0.7
			Wet Scrubber Column	ABS	NEDS-T-051	H=15m, D=1m	11.78	1.0
			Condenser	HE	NEDS-E-055	L	4.00	0.7
			Electrical Water Heater	HE	NEDS-E-056	M	2.00	0.7
			Overhead Compressor	FM	NEDS-C-051	L	4.00	0.7
			Overhead Compressor (spare)	FM	NEDS-C-052	L	4.00	0.7
	Glovebox 15 Auxiliary GB15-AUX	GB15	Water-Water Heat Exchanger	HE	GB15-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB15-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB15-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-15	M	2.00	0.7
			SVS Vacuum Pump	FM	GB15-C-101	S	0.10	1.0
	Metalbox 15 Auxiliary MB15-AUX	MB15	Metalbox Detritiation System	PKG	MB-DS-15	M	2.00	0.7
			SVS Vacuum Pump	FM	MB15-C-101	S	0.10	1.0
	Normal Exhaust Detritiation System Once Trough Train 6 N-EDS-OT-6	GB16	**Pre-Filter**	FT	NEDS-U-061	M	2.00	0.7
			Condenser	HE	NEDS-E-061	L	4.00	0.7
			LT Economizer	HE	NEDS-E-062	M	2.00	0.7
			Low Temperature Recombiner	RE	NEDS-R-061	1m³	1.00	1.0
			HT Economizer	HE	NEDS-E-063	L	4.00	0.7
			High Temperature Recombiner	RE	NEDS-R-062	1m³	1.00	1.0
			Pump	FM	NEDS-P-061	M	2.00	0.7
			Pump (Spare)	FM	NEDS-P-062	M	2.00	0.7
		MB16	**Saturator**	HE	NEDS-E-064	L	4.00	0.7
			Wet Scrubber Column	ABS	NEDS-T-061	H=15m, D=1m	11.78	1.0
			Condenser	HE	NEDS-E-065	L	4.00	0.7
			Electrical Water Heater	HE	NEDS-E-066	M	2.00	0.7
			Overhead Compressor	FM	NEDS-C-061	L	4.00	0.7
			Overhead Compressor (spare)	FM	NEDS-C-062	L	4.00	0.7
	Glovebox 16 Auxiliary GB16-AUX	GB16	Water-Water Heat Exchanger	HE	GB16-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB16-P-101	S	0.10	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
			Cooling Loop Pump (spare)	FM	GB16-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-16	M	2.00	0.7
			SVS Vacuum Pump	FM	GB16-C-101	S	0.10	1.0
	Metalbox 16 Auxiliary MB16-AUX	MB16	Metalbox Detritiation System	PKG	MB-DS-16	M	2.00	0.7
			SVS Vacuum Pump	FM	MB16-C-101	S	0.10	1.0
	Normal Exhaust Detritiation System Once Trough and Recirculation Train 1 N-EDS-OT&R-1	GB21	**Pre-Filter**	FT	OEDS-U-011	M	2.00	0.7
			Condenser	HE	OEDS-E-011	L	4.00	0.7
			LT Economizer	HE	OEDS-E-012	M	2.00	0.7
			Low Temperature Recombiner	RE	OEDS-R-011	1m^3	1.00	1.0
			HT Economizer	HE	OEDS-E-013	L	4.00	0.7
			High Temperature Recombiner	RE	OEDS-R-012	1m^3	1.00	1.0
			Pump	FM	OEDS-P-011	M	2.00	0.7
			Pump (Spare)	FM	OEDS-P-012	M	2.00	0.7
		MB21	**Saturator**	HE	OEDS-E-014	L	4.00	0.7
			Wet Scrubber Column	ABS	OEDS-T-011	H=15m, D=1m	11.78	1.0
			Condenser	HE	OEDS-E-015	L	4.00	0.7
			Electrical Water Heater	HE	OEDS-E-016	M	2.00	0.7
			Overhead Compressor	FM	OEDS-C-011	L	4.00	0.7
			Overhead Compressor (spare)	FM	OEDS-C-012	L	4.00	0.7
	Glovebox 21 Auxiliary GB21-AUX	GB21	Water-Water Heat Exchanger	HE	GB21-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB21-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB21-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-21	M	2.00	0.7
			SVS Vacuum Pump	FM	GB21-C-101	S	0.10	1.0
	Metalbox 21 Auxiliary MB21-AUX	MB21	Metalbox Detritiation System	PKG	MB-DS-21	M	2.00	0.7
			SVS Vacuum Pump	FM	MB21-C-101	S	0.10	1.0
	Normal Exhaust Detritiation System Once Trough and Recirculation Train 2 N-EDS-OT&R-2	GB22	**Pre-Filter**	FT	OEDS-U-021	M	2.00	0.7
			Condenser	HE	OEDS-E-021	L	4.00	0.7
			LT Economizer	HE	OEDS-E-022	M	2.00	0.7
			Low Temperature Recombiner	RE	OEDS-R-021	1m^3	1.00	1.0
			HT Economizer	HE	OEDS-E-023	L	4.00	0.7
			High Temperature Recombiner	RE	OEDS-R-022	1m^3	1.00	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
			Pump	FM	OEDS-P-021	M	2.00	0.7
			Pump (Spare)	FM	OEDS-P-022	M	2.00	0.7
		MB22	**Saturator**	HE	OEDS-E-024	L	4.00	0.7
			Wet Scrubber Column	ABS	OEDS-T-021	H=15m, D=1m	11.78	1.0
			Condenser	HE	OEDS-E-025	L	4.00	0.7
			Electrical Water Heater	HE	OEDS-E-026	M	2.00	0.7
			Overhead Compressor	FM	OEDS-C-021	L	4.00	0.7
			Overhead Compressor (spare)	FM	OEDS-C-022	L	4.00	0.7
	Glovebox 22 Auxiliary GB22-AUX	GB22	Water-Water Heat Exchanger	HE	GB22-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB22-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB22-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-22	M	2.00	0.7
			SVS Vacuum Pump	FM	GB22-C-101	S	0.10	1.0
	Metalbox 22 Auxiliary MB22-AUX	MB22	Metalbox Detritiation System	PKG	MB-DS-22	M	2.00	0.7
			SVS Vacuum Pump	FM	MB22-C-101	S	0.10	1.0
	Normal Exhaust Detritiation System Once Trough and Recirculation Train 3 N-EDS-OT&R-3	GB23	**Pre-Filter**	FT	OEDS-U-031	M	2.00	0.7
			Condenser	HE	OEDS-E-031	L	4.00	0.7
			LT Economizer	HE	OEDS-E-032	M	2.00	0.7
			Low Temperature Recombiner	RE	OEDS-R-031	1m^3	1.00	1.0
			HT Economizer	HE	OEDS-E-033	L	4.00	0.7
			High Temperature Recombiner	RE	OEDS-R-032	1m^3	1.00	1.0
			Pump	FM	OEDS-P-031	M	2.00	0.7
			Pump (Spare)	FM	OEDS-P-032	M	2.00	0.7
		MB23	**Saturator**	HE	OEDS-E-034	L	4.00	0.7
			Wet Scrubber Column	ABS	OEDS-T-031	H=15m, D=1m	11.78	1.0
			Condenser	HE	OEDS-E-035	L	4.00	0.7
			Electrical Water Heater	HE	OEDS-E-036	M	2.00	0.7
			Overhead Compressor	FM	OEDS-C-031	L	4.00	0.7
			Overhead Compressor (spare)	FM	OEDS-C-032	L	4.00	0.7
	Glovebox 23 Auxiliary GB23-AUX	GB23	Water-Water Heat Exchanger	HE	GB23-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB23-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB23-P-102	S	0.10	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m³]	Fill Factor
			Glovebox Detritiation System	PKG	GB-DS-23	M	2.00	0.7
			SVS Vacuum Pump	FM	GB23-C-101	S	0.10	1.0
	Metalbox 23 Auxiliary MB23-AUX	MB23	Metalbox Detritiation System	PKG	MB-DS-23	M	2.00	0.7
			SVS Vacuum Pump	FM	MB23-C-101	S	0.10	1.0
	Safety Exhaust Detritiation System Once Trough Train 1 S-EDS-OT-1	GB31	**Pre-Filter**	FT	SEDS-U-011	M	2.00	0.7
			Chiller	HE	SEDS-E-011	M	2.00	0.7
			Condenser	HE	SEDS-E-012	L	4.00	0.7
			Room Temperature Recombiner	RE	SEDS-R-011	1m³	1.00	1.0
			Low Temperature Recombiner	RE	SEDS-R-012	1m³	1.00	1.0
			Compressor	FM	SEDS-C-011	L	4.00	0.7
			Compressor (spare)	FM	SEDS-C-012	L	4.00	0.7
		MB31	**Saturator**	HE	SEDS-E-013	L	4.00	0.7
			Wet Scrubber Column	ABS	SEDS-T-011	H=15m, D=1m	11.78	1.0
			Condenser	HE	SEDS-E-014	L	4.00	0.7
			Electrical Water Heater	HE	SEDS-E-015	M	2.00	0.7
	Glovebox 31 Auxiliary GB31-AUX	GB31	Water-Water Heat Exchanger	HE	GB31-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB31-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB31-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-31	M	2.00	0.7
			SVS Vacuum Pump	FM	GB31-C-101	S	0.10	1.0
	Metalbox 31 Auxiliary MB31-AUX	MB31	Metalbox Detritiation System	PKG	MB-DS-31	M	2.00	0.7
			SVS Vacuum Pump	FM	MB31-C-101	S	0.10	1.0
	Safety Exhaust Detritiation System Once Trough Train 2 S-EDS-OT-2	GB32	**Pre-Filter**	FT	SEDS-U-021	M	2.00	0.7
			Chiller	HE	SEDS-E-021	M	2.00	0.7
			Condenser	HE	SEDS-E-022	L	4.00	0.7
			Room Temperature Recombiner	RE	SEDS-R-021	1m³	1.00	1.0
			Low Temperature Recombiner	RE	SEDS-R-022	1m³	1.00	1.0
			Compressor	FM	SEDS-C-021	L	4.00	0.7
			Compressor (spare)	FM	SEDS-C-022	L	4.00	0.7
		MB32	**Saturator**	HE	SEDS-E-023	L	4.00	0.7
			Wet Scrubber Column	ABS	SEDS-T-021	H=15m, D=1m	11.78	1.0
			Condenser	HE	SEDS-E-024	L	4.00	0.7

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
			Electrical Water Heater	HE	SEDS-E-025	M	2.00	0.7
	Glovebox 32 Auxiliary GB32-AUX	GB32	Water-Water Heat Exchanger	HE	GB32-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB32-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB32-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-32	M	2.00	0.7
			SVS Vacuum Pump	FM	GB32-C-101	S	0.10	1.0
	Metalbox 32 Auxiliary MB32-AUX	MB32	Metalbox Detritiation System	PKG	MB-DS-32	M	2.00	0.7
			SVS Vacuum Pump	FM	MB32-C-101	S	0.10	1.0
	Safety Exhaust Detritiation System Once Trough Train 3 S-EDS-OT-3	GB33	**Pre-Filter**	FT	SEDS-U-031	M	2.00	0.7
			Chiller	HE	SEDS-E-031	M	2.00	0.7
			Condenser	HE	SEDS-E-032	L	4.00	0.7
			Room Temperature Recombiner	RE	SEDS-R-031	1m^3	1.00	1.0
			Low Temperature Recombiner	RE	SEDS-R-032	1m^3	1.00	1.0
			Compressor	FM	SEDS-C-031	L	4.00	0.7
			Compressor (spare)	FM	SEDS-C-032	L	4.00	0.7
		MB33	**Saturator**	HE	SEDS-E-033	L	4.00	0.7
			Wet Scrubber Column	ABS	SEDS-T-031	h=15m, d=1m	11.78	1.0
			Condenser	HE	SEDS-E-034	L	4.00	0.7
			Electrical Water Heater	HE	SEDS-E-035	M	2.00	0.7
	Glovebox 33 Auxiliary GB33-AUX	GB33	Water-Water Heat Exchanger	HE	GB33-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB33-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB33-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-33	M	2.00	0.7
			SVS Vacuum Pump	FM	GB33-C-101	S	0.10	1.0
	Metalbox 33 Auxiliary MB33-AUX	MB33	Metalbox Detritiation System	PKG	MB-DS-33	M	2.00	0.7
			SVS Vacuum Pump	FM	MB33-C-101	S	0.10	1.0
	Safety Exhaust Detritiation System Once Trough Train 4 S-EDS-OT-4	GB34	**Pre-Filter**	FT	SEDS-U-041	M	2.00	0.7
			Chiller	HE	SEDS-E-041	M	2.00	0.7
			Condenser	HE	SEDS-E-042	L	4.00	0.7
			Room Temperature Recombiner	RE	SEDS-R-041	1m^3	1.00	1.0
			Low Temperature Recombiner	RE	SEDS-R-042	1m^3	1.00	1.0
			Compressor	FM	SEDS-C-041	L	4.00	0.7

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume $[m^3]$	Fill Factor
			Compressor (spare)	FM	SEDS-C-042	L	4.00	0.7
		MB34	**Saturator**	HE	SEDS-E-043	L	4.00	0.7
			Wet Scrubber Column	ABS	SEDS-T-041	H=15m, D=1m	11.78	1.0
			Condenser	HE	SEDS-E-044	L	4.00	0.7
			Electrical Water Heater	HE	SEDS-E-045	M	2.00	0.7
	Glovebox 34 Auxiliary GB34-AUX	GB34	Water-Water Heat Exchanger	HE	GB34-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB34-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB34-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-34	M	2.00	0.7
			SVS Vacuum Pump	FM	GB34-C-101	S	0.10	1.0
	Metalbox 34 Auxiliary MB34-AUX	MB34	Metalbox Detritiation System	PKG	MB-DS-34	M	2.00	0.7
			SVS Vacuum Pump	FM	MB34-C-101	S	0.10	1.0
	Safety Exhaust Detritiation System Once Trough Train 5 S-EDS-OT-5	GB35	**Pre-Filter**	FT	SEDS-U-051	M	2.00	0.7
			Chiller	HE	SEDS-E-051	M	2.00	0.7
			Condenser	HE	SEDS-E-052	L	4.00	0.7
			Room Temperature Recombiner	RE	SEDS-R-051	$1m^3$	1.00	1.0
			Low Temperature Recombiner	RE	SEDS-R-052	$1m^3$	1.00	1.0
			Compressor	FM	SEDS-C-051	L	4.00	0.7
			Compressor (spare)	FM	SEDS-C-052	L	4.00	0.7
		MB35	**Saturator**	HE	SEDS-E-053	L	4.00	0.7
			Wet Scrubber Column	ABS	SEDS-T-051	H=15m, D=1m	11.78	1.0
			Condenser	HE	SEDS-E-054	L	4.00	0.7
			Electrical Water Heater	HE	SEDS-E-055	M	2.00	0.7
	Glovebox 35 Auxiliary GB35-AUX	GB35	Water-Water Heat Exchanger	HE	GB35-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB35-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB35-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-35	M	2.00	0.7
			SVS Vacuum Pump	FM	GB35-C-101	S	0.10	1.0
	Metalbox 35 Auxiliary MB35-AUX	MB35	Metalbox Detritiation System	PKG	MB-DS-35	M	2.00	0.7
			SVS Vacuum Pump	FM	MB35-C-101	S	0.10	1.0
	Safety Exhaust Detritiation	GB36	**Pre-Filter**	FT	SEDS-U-061	M	2.00	0.7
			Chiller	HE	SEDS-E-061	M	2.00	0.7

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
	System Once Trough		**Condenser**	HE	SEDS-E-062	L	4.00	0.7
	Train 6		**Room Temperature Recombiner**	RE	SEDS-R-061	$1m^3$	1.00	1.0
	S-EDS-OT-6		**Low Temperature Recombiner**	RE	SEDS-R-062	$1m^3$	1.00	1.0
			Compressor	FM	SEDS-C-061	L	4.00	0.7
			Compressor (spare)	FM	SEDS-C-062	L	4.00	0.7
		MB36	**Saturator**	HE	SEDS-E-063	L	4.00	0.7
			Wet Scrubber Column	ABS	SEDS-T-061	H=15m, D=1m	11.78	1.0
			Condenser	HE	SEDS-E-064	L	4.00	0.7
			Electrical Water Heater	HE	SEDS-E-065	M	2.00	0.7
	Glovebox 36 Auxiliary	GB36	Water-Water Heat Exchanger	HE	GB36-E-101	M	2.00	0.7
	GB36-AUX		Cooling Loop Pump	FM	GB36-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB36-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-36	M	2.00	0.7
			SVS Vacuum Pump	FM	GB36-C-101	S	0.10	1.0
	Metalbox 36 Auxiliary	MB36	Metalbox Detritiation System	PKG	MB-DS-36	M	2.00	0.7
	MB36-AUX		SVS Vacuum Pump	FM	MB36-C-101	S	0.10	1.0
	Safety Exhaust	GB37	**Pre-Filter**	FT	SEDS-U-071	M	2.00	0.7
	Detritiation		**Chiller**	HE	SEDS-E-071	M	2.00	0.7
	System Once Trough		**Condenser**	HE	SEDS-E-072	L	4.00	0.7
	Train 7		**Room Temperature Recombiner**	RE	SEDS-R-071	$1m^3$	1.00	1.0
	S-EDS-OT-7		**Low Temperature Recombiner**	RE	SEDS-R-072	$1m^3$	1.00	1.0
			Compressor	FM	SEDS-C-071	L	4.00	0.7
			Compressor (spare)	FM	SEDS-C-072	L	4.00	0.7
		MB37	**Saturator**	HE	SEDS-E-073	L	4.00	0.7
			Wet Scrubber Column	ABS	SEDS-T-071	H=15m, D=1m	11.78	1.0
			Condenser	HE	SEDS-E-074	L	4.00	0.7
			Electrical Water Heater	HE	SEDS-E-075	M	2.00	0.7
	Glovebox 37 Auxiliary	GB37	Water-Water Heat Exchanger	HE	GB37-E-101	M	2.00	0.7
	GB37-AUX		Cooling Loop Pump	FM	GB37-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB37-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-36	M	2.00	0.7
			SVS Vacuum Pump	FM	GB37-C-101	S	0.10	1.0

System Block	Subsystems	Group	Equipment	Type	TAG	Dimensions	Volume [m^3]	Fill Factor
	Metalbox 37 Auxiliary MB37-AUX	MB37	Metalbox Detritiation System	PKG	MB-DS-37	M	2.00	0.7
			SVS Vacuum Pump	FM	MB37-C-101	S	0.10	1.0
	Safety Exhaust Detritiation System Once Trough Train 8 S-EDS-OT-8	GB38	**Pre-Filter**	FT	SEDS-U-081	M	2.00	0.7
			Chiller	HE	SEDS-E-081	M	2.00	0.7
			Condenser	HE	SEDS-E-082	L	4.00	0.7
			Room Temperature Recombiner	RE	SEDS-R-081	1m^3	1.00	1.0
			Low Temperature Recombiner	RE	SEDS-R-082	1m^3	1.00	1.0
			Compressor	FM	SEDS-C-081	L	4.00	0.7
			Compressor (spare)	FM	SEDS-C-082	L	4.00	0.7
		MB38	**Saturator**	HE	SEDS-E-083	L	4.00	0.7
			Wet Scrubber Column	ABS	SEDS-T-081	H=15m, D=1m	11.78	1.0
			Condenser	HE	SEDS-E-084	L	4.00	0.7
			Electrical Water Heater	HE	SEDS-E-085	M	2.00	0.7
	Glovebox 38 Auxiliary GB38-AUX	GB38	Water-Water Heat Exchanger	HE	GB38-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB38-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB38-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-38	M	2.00	0.7
			SVS Vacuum Pump	FM	GB38-C-101	S	0.10	1.0
	Metalbox 38 Auxiliary MB38-AUX	MB38	Metalbox Detritiation System	PKG	MB-DS-38	M	2.00	0.7
			SVS Vacuum Pump	FM	MB38-C-101	S	0.10	1.0
Service Vacuum SV	**Service Vacuum SVS**	GB10	**Vacuum Generation Package**	PKG	SVS	15m^3	15.00	1.0
	Glovebox 10 Auxiliary GB10-AUX	GB10	Water-Water Heat Exchanger	HE	GB10-E-101	M	2.00	0.7
			Cooling Loop Pump	FM	GB10-P-101	S	0.10	1.0
			Cooling Loop Pump (spare)	FM	GB10-P-102	S	0.10	1.0
			Glovebox Detritiation System	PKG	GB-DS-10	M	2.00	0.7
			SVS Vacuum Pump	FM	GB10-C-101	S	0.10	1.0

Type:

ABS: Absorption, CD: Cryogenic distillation, DC: Distillation column, FM: Fluid machine, FT: Filter, HE: Heat exchanger, PKG: Package, RE: Reactor, SEP: Separator, SS: Solid storage, TK: Tank, VS: Vessel.

TAG:

C: Compressor / vacuum pump, DS: Detritiation system, E: Heat exchanger, P: Pump, R: Reactor, S: Separator, T: Column, U: Filter, V: Vessel.

Table A-2 – Equipment list for glovebox detritiation packages

Subsystems	Group	Equipment	Type	TAG
Glovebox Detritiation System	GBXX	**Filter**	FT	GBDSXX-U-001
GB-DS-XX		Filter (spare)	FT	GBDSXX-U-002
One per Glovebox		**CuO Bed**	SEP	GBDSXX-S-001
(Mounted inside Packaged Skids)		**ZMS Bed 1**	SEP	GBDSXX-S-002
		ZMS Bed 2	SEP	GBDSXX-S-003
		Heater	HE	GBDSXX-E-001
		Vacuum Pump	FM	GBDSXX-C-001
		Heater	HE	GBDSXX-E-002
		Economizer	HE	GBDSXX-E-003
		Circulator	FM	GBDSXX-C-002
		Condenser	HE	GBDSXX-E-004
		Water Pump	FM	GBDSXX-P-001

Table A-3 – Equipment list for metalbox detritiation packages

Subsystems	Group	Equipment	Type	TAG
Metalbox Detritiation System	MBXX	**Filter**	FT	MBDSXX-U-001
MB-DS-XX		Filter (spare)	FT	MBDSXX-U-002
One per Metalbox		**CuO Bed**	SEP	MBDSXX-S-001
(Mounted inside Packaged Skids)		**ZMS Bed 1**	SEP	MBDSXX-S-002
		ZMS Bed 2	SEP	MBDSXX-S-003
		Heater	HE	MBDSXX-E-001
		Vacuum Pump	FM	MBDSXX-C-001
		Heater	HE	MBDSXX-E-002
		Economizer	HE	MBDSXX-E-003
		Circulator	FM	MBDSXX-C-002
		Condenser	HE	MBDSXX-E-004
		Water Pump	FM	MBDSXX-P-001

Table A-4 – Composition, inlet pressure, inlet temperature and design flowrate for sized liquid streams.

No.	Tag	Composition (mole fraction)		Pressure	Temperature	Flowrate
		H2O	HTO	bar-abs	K	mol/h
1	OUTL-HeCPS-002	1.00E+00	4.00E-05	5.00	300	146.26
2	OUTL-CVCS-001	1.00E+00	1.24E-06	120.00	500	6111.11
3	OUTL-WCPS-001	1.00E+00	1.26E-07	120.00	500	6001.11
4	OUTL-WCPS-002	1.00E+00	6.19E-05	5.00	300	110.00
5	OUTL-TERS-002	1.00E+00	3.09E-04	5.00	300	11.11
6	OUTL-WDFT-001	1.00E+00	5.99E-05	1.00	300	169.37
7	OUTL-WDFT-002	1.00E+00	5.57E-06	1.00	300	21087.75
8	OUTL-WDFT-003	1.00E+00	6.00E-06	1.20	300	21257.12
9	OUTL-WDS-004	1.00E+00	1.30E-05	1.20	300	26770.51
10	OUTL-NEDSX-001	1.00E+00	5.57E-06	5.00	300	3514.63
11	OUTL-OEDSX-001	1.00E+00	5.57E-06	5.00	300	3514.63
12	HDR-TWH-100	1.00E+00	5.97E-05	1.00	300	167.37
13	HDR-TWL-100	1.00E+00	5.57E-06	1.00	300	10543.88
14	HDR-TWL-101	1.00E+00	5.57E-06	1.00	300	14058.50
15	HDR-TWL-200	1.00E+00	5.57E-06	1.00	300	7029.25
16	HDR-TWL-300	1.00E+00	5.57E-06	1.00	300	21087.75

Table A-5 – Composition, inlet pressure, inlet temperature and design flowrate for sized gaseous streams.

No.	Tag	Composition (mole fraction)										Pressure	Temperature	Flowrate
		H_2	D_2	T_2	HT	DT	He	Ar	Xe	O_2	N_2	bar-abs	K	mol/h
1	INTL-RPS-001					9.53E-01	4.71E-02					1.00	300	140.75
2	INTL-GDS-001						8.56E-01	3.97E-02	1.04E-01			1.00	300	6.15
3	INTL-EPVS-001	1.03E-02				9.90E-01						1.00	300	135.48
4	GBDS-GB1-002				4.98E-09						1.00E+00	1.00	300	66.93
5	INTL-PRS-001					6.37E-03	9.94E-01					1.00	300	5.27
6	GBDS-GB2-002				4.98E-09						1.00E+00	1.00	300	66.93
7	INTL-IRPRS-004	9.19E-03	5.19E-02	5.71E-02		8.82E-01						1.00	300	132.92
8	INTL-IRPRS-003		6.70E-01	3.30E-01								1.00	300	2.56
9	GBDS-GB3-002				4.98E-09						1.00E+00	1.00	300	66.93
10	OUTL-HCL-001				5.00E-09		1.00E+00					80.00	500	1170000.00
11	OUTL-HeCPS-001				5.00E-10		1.00E+00					80.00	500	1170000.00
12	GBDS-GB4B-002				4.98E-09						1.00E+00	1.00	300	66.93
13	GBDS-GB4A-002				4.98E-09						1.00E+00	1.00	300	66.93
14	MBDS-MB4A-002				4.98E-09						1.00E+00	1.00	300	66.93
15	OUTL-TERS-001				6.74E-03		9.93E-01					1.00	300	644.44
16	OUTL-HTCS-001				4.65E-03		9.95E-01					1.00	300	93.44
17	OUTL-HTCS-002	9.93E-01			7.10E-03							1.00	300	551.00
18	GBDS-GB5B-002				4.98E-09						1.00E+00	1.00	300	66.93
19	OUTL-TERS-003				8.35E-05		1.00E+00					1.00	300	52050.87
20	OUTL-WTCS-001				8.39E-06		1.00E+00					1.00	300	51816.64
21	OUTL-WTCS-002	9.92E-01			8.35E-03								300	234.23
22	GBDS-GB5A-002				4.98E-09						1.00E+00	1.00	300	66.93
23	OUTL-ISS-001	1.00E+00			1.00E-06							1.00	300	5150.91
24	OUTL-ISS-003		3.00E-01	7.00E-01								1.00	300	6.34
25	GBDS-GB6-002				4.98E-09						1.00E+00	1.00	300	66.93
26	OUTL-WDS-001	1.00E+00			1.00E-05							1.00	300	5150.91
27	OUTL-WDS-002	1.00E+00			1.00E-05							1.00	300	21619.60
28	GBDS-GB8-002				4.98E-09						1.00E+00	1.00	300	66.93
29	GBDS-GB7-002				4.98E-09						1.00E+00	1.00	300	66.93

No.	Tag	Composition (mole fraction)										Pressure	Temperature	Flowrate
		H_2	D_2	T_2	HT	DT	He	Ar	Xe	O_2	N_2	bar-abs	K	mol/h
30	MBDS-MB8-002				4.98E-09						1.00E+00	1.00	300	66.93
31	OUTL-DTSS-001					9.90E-01	1.00E-02					1.00	300	4.25
32	GBDS-GB9-002				4.98E-09						1.00E+00	1.00	300	66.93
33	GBDS-GB10-002				4.98E-09						1.00E+00	1.00	300	66.93
34	OUTL-M1-01X				4.98E-09					2.10E-01	7.90E-01	1.00	300	223087.58
35	GBDS-GB1X-002				4.98E-09						1.00E+00	1.00	300	66.93
36	MBDS-MB1X-002				4.98E-09						1.00E+00	1.00	300	66.93
37	OUTL-M2-02X				4.98E-09					2.10E-01	7.90E-01	1.00	300	223087.58
38	GBDS-GB2X-002				4.98E-09						1.00E+00	1.00	300	66.93
39	MBDS-MB2X-002				4.98E-09						1.00E+00	1.00	300	66.93
40	OUTL-M3-03X				4.98E-09					2.10E-01	7.90E-01	1.00	300	223087.58
41	GBDS-GB3X-002				4.98E-09						1.00E+00	1.00	300	66.93
42	MBDS-MB3X-002				4.98E-09						1.00E+00	1.00	300	66.93
43	OUTL-TKB-001				2.24E-09					2.10E-01	7.90E-01	1.00	300	892350.32
44	HDR-TG1-100				4.98E-09					2.10E-01	7.90E-01	1.00	300	892350.32
45	HDR-TG2-100				2.24E-09					2.10E-01	7.90E-01	1.00	300	446175.16
46	HDR-TG2-101				2.24E-09					2.10E-01	7.90E-01	1.00	300	223087.58
47	HDR-TG3-100				2.24E-09					2.10E-01	7.90E-01	1.00	300	892350.32
48	HDR-RC2-100				2.24E-09					2.10E-01	7.90E-01	1.00	300	446175.16

Table A-6 – Coordinates table for primary confinement structures and equipment outside the boxes

Name	X	Y	Z
	m	m	m
AWSS-Drain1	36.90	13.80	1.00
AWSS-Drain2	36.90	8.80	1.00
AWSS-Emergency1	51.70	9.80	1.00
AWSS-Emergency2	45.70	9.80	1.00
CB2	4.85	27.35	9.60
CB6	37.35	27.35	9.60
D2SS-1	30.60	16.10	9.60
D2SS-2	33.10	16.10	9.60
GB1	18.80	23.40	14.40
GB2	10.50	23.40	14.40
GB3	23.10	23.40	14.40
GB4A	43.30	23.40	14.40
GB4B	47.45	27.40	9.60
GB5A	14.65	27.40	9.60
GB5B	49.60	23.40	14.40
GB6	31.40	23.40	14.40
GB7	24.50	10.30	0.00
GB8	32.10	18.10	19.20
GB9	27.25	27.40	9.60
GB10	55.90	23.40	14.40
GB11	54.70	18.10	19.20
GB12	51.70	18.10	19.20
GB13	46.70	18.10	19.20
GB14	17.50	18.10	19.20
GB15	14.50	18.10	19.20
GB16	9.50	18.10	19.20
GB21	42.40	18.10	19.20
GB22	36.40	18.10	19.20
GB23	38.40	12.80	9.60
GB31	56.70	12.80	9.60
GB32	51.70	12.80	9.60
GB33	47.70	12.80	9.60

Name	X	Y	Z
	m	m	m
GB34	42.70	12.80	9.60
GB35	23.50	12.80	9.60
GB36	18.50	12.80	9.60
GB37	14.50	12.80	9.60
GB38	9.50	12.80	9.60
H2SS-1	30.60	13.10	9.60
H2SS-2	33.10	13.10	9.60
MB4A	30.85	3.75	9.60
MB8	31.45	9.15	0.00
MB11	55.70	8.80	14.40
MB12	51.70	8.80	14.40
MB13	47.70	8.80	14.40
MB14	18.50	8.80	14.40
MB15	14.50	8.80	14.40
MB16	10.50	8.80	14.40
MB21	41.40	8.80	14.40
MB22	37.40	8.80	14.40
MB23	37.40	3.50	9.60
MB31	55.70	3.50	9.60
MB32	51.70	3.50	9.60
MB33	47.70	3.50	9.60
MB34	43.70	3.50	9.60
MB35	22.50	3.50	9.60
MB36	18.50	3.50	9.60
MB37	14.50	3.50	9.60
MB38	10.50	3.50	9.60
O2SS-1	30.60	14.60	9.60
O2SS-2	33.10	14.60	9.60
WDFT-H1	17.80	14.50	1.00
WDFT-H2	20.40	14.50	1.00
WDFT-L1	19.40	9.90	1.00
WDFT-L2	19.40	5.30	1.00

Coordinates given at the base of each unit.

The zero-point reference is located at the SW corner of the B2 level of the tritium plant.

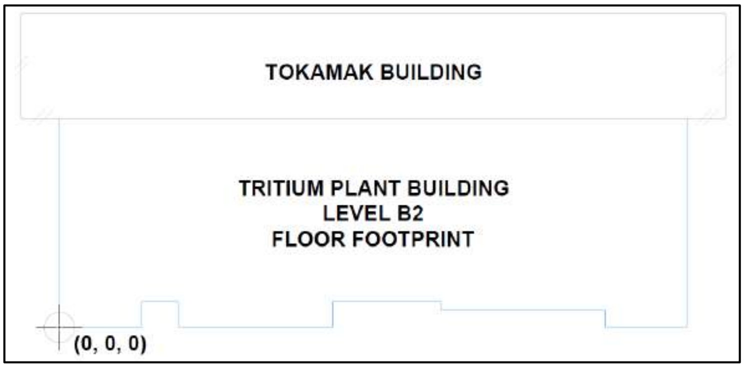


Table A-7 – Resulting tritiated pipes sized for the optimized base case under normal operation in modes A and B.

No.	Tag	Phase	$T_{2,eq}$ mole fraction	Pressure	Temp.	Mode	Length	OD	t	ID	Volume	Matter / Mass		Linear Density
				bar-abs	K		m	mm	mm	mm	m^3	mol (total)	g $T_{2,eq}$	g $T_{2,eq}$ / m
1	INTL-RPS-001	Gas	4.76E-01	1.00	300	A & B	2.50	16	1	14	0.00038	0.015	4.43E-02	1.77E-02
2	INTL-EPVS-001	Gas	4.95E-01	1.00	300	A & B	3.10	16	1	14	0.00048	0.019	5.71E-02	1.84E-02
3	GBDS-GB1-002	Gas	2.49E-09	1.00	300	A & B	1.70	16	1	14	0.00026	0.010	1.58E-10	9.28E-11
4	INTL-PRS-001	Gas	3.18E-03	1.00	300	A & B	15.80	8	1	6	0.00045	0.018	3.44E-04	2.18E-05
5	GBDS-GB2-002	Gas	2.49E-09	1.00	300	A & B	1.70	16	1	14	0.00026	0.010	1.58E-10	9.28E-11
6	INTL-IRPRS-004	Gas	4.98E-01	1.00	300	A & B	2.50	14	1	12	0.00028	0.011	3.41E-02	1.36E-02
7	INTL-IRPRS-003	Gas	3.30E-01	1.00	300	A & B	7.10	8	1	6	0.00020	0.008	1.60E-02	2.26E-03
8	GBDS-GB3-002	Gas	2.49E-09	1.00	300	A & B	1.70	16	1	14	0.00026	0.010	1.58E-10	9.28E-11
9	OUTL-HCL-001	Gas	2.50E-09	80.00	500	B	3.65	139.7	7.1	125.5	0.04515	86.892	1.31E-06	3.59E-07
10	OUTL-HeCPS-001	Gas	2.50E-10	80.00	500	B	3.65	139.7	7.1	125.5	0.04515	86.892	1.31E-07	3.59E-08
11	OUTL-HeCPS-002	Liquid	2.00E-05	5.00	300	B	2.15	6	1	4	0.00003	1.495	1.80E-04	8.39E-05
12	GBDS-GB4B-002	Gas	2.49E-09	1.00	300	B	2.05	16	1	14	0.00032	0.013	1.90E-10	9.28E-11
13	OUTL-CVCS-001	Liquid	6.19E-07	120.00	500	A	2.50	12	1	10	0.00020	9.153	3.42E-05	1.37E-05
14	OUTL-WCPS-001	Liquid	6.30E-08	120.00	500	A	2.50	12	1	10	0.00020	9.153	3.48E-06	1.39E-06
15	OUTL-WCPS-002	Liquid	3.09E-05	5.00	300	A	1.00	6	1	4	0.00001	0.695	1.30E-04	1.30E-04
16	GBDS-GB4A-002	Gas	2.49E-09	1.00	300	A	1.70	16	1	14	0.00026	0.010	1.58E-10	9.28E-11
17	MBDS-MB4A-002	Gas	2.49E-09	1.00	300	A	0.90	16	1	14	0.00014	0.006	8.35E-11	9.28E-11
18	OUTL-TERS-001	Gas	3.37E-03	1.00	300	B	2.50	48.3	1.6	45.1	0.00399	0.160	3.26E-03	1.30E-03
19	OUTL-HTCS-001	Gas	2.32E-03	1.00	300	B	2.50	16	1	14	0.00038	0.015	2.16E-04	8.65E-05
20	OUTL-HTCS-002	Gas	3.55E-03	1.00	300	B	19.40	20	1	18	0.00494	0.198	4.24E-03	2.18E-04
21	OUTL-TERS-002	Liquid	1.55E-04	5.00	300	B	1.90	6	1	4	0.00002	1.321	1.23E-03	6.49E-04
22	GBDS-GB5B-002	Gas	2.49E-09	1.00	300	B	1.70	16	1	14	0.00026	0.010	1.58E-10	9.28E-11
23	OUTL-TERS-003	Gas	4.18E-05	1.00	300	A	3.65	139.7	7.1	125.5	0.04515	1.810	4.56E-04	1.25E-04
24	OUTL-WTCS-001	Gas	4.20E-06	1.00	300	A	3.55	139.7	7.1	125.5	0.04391	1.761	4.46E-05	1.26E-05
25	OUTL-WTCS-002	Gas	4.18E-03	1.00	300	A	16.95	16	1	14	0.00261	0.105	2.64E-03	1.56E-04
26	GBDS-GB5A-002	Gas	2.49E-09	1.00	300	A	0.65	16	1	14	0.00010	0.004	6.03E-11	9.28E-11
27	OUTL-ISS-001	Gas	5.00E-07	1.00	300	A & B	17.30	48.3	1.6	45.1	0.02764	1.108	3.34E-06	1.93E-07
28	OUTL-ISS-003	Gas	7.00E-01	1.00	300	A & B	2.50	8	1	6	0.00007	0.003	1.20E-02	4.79E-03
29	GBDS-GB6-002	Gas	2.49E-09	1.00	300	A & B	1.70	16	1	14	0.00026	0.010	1.58E-10	9.28E-11

No.	Tag	Phase	$T_{2,eq}$	Pressure	Temp.	Mode	Length	OD	t	ID	Volume	Matter / Mass		Linear Density
			mole fraction	bar-abs	K		m	mm	mm	mm	m^3	mol (total)	g $T_{2,eq}$	g $T_{2,eq}$ / m
30	OUTL-WDS-001	Gas	5.00E-06	1.00	300	A & B	13.00	48.3	1.6	45.1	0.02077	0.833	2.51E-05	1.93E-06
31	OUTL-WDS-002	Gas	5.00E-06	1.00	300	A & B	3.30	139.7	7.1	125.5	0.04082	1.637	4.94E-05	1.50E-05
32	GBDS-GB8-002	Gas	2.49E-09	1.00	300	A & B	2.00	16	1	14	0.00031	0.012	1.86E-10	9.28E-11
33	OUTL-WDFT-001	Liquid	2.99E-05	1.00	300	A & B	9.10	6	1	4	0.00011	6.326	1.14E-03	1.26E-04
34	OUTL-WDFT-001B	Liquid	2.99E-05	1.00	300	A & B	1.90	6	1	4	0.00002	1.321	2.38E-04	1.26E-04
35	OUTL-WDFT-002	Liquid	2.78E-06	1.00	300	A & B	11.10	20	1	18	0.00282	156.250	2.62E-03	2.36E-04
36	OUTL-WDFT-002B	Liquid	2.78E-06	1.00	300	A & B	2.90	20	1	18	0.00074	40.822	6.86E-04	2.36E-04
37	OUTL-WDFT-003	Liquid	3.00E-06	1.20	300	A & B	10.90	17.2	1	15.2	0.00198	109.413	1.98E-03	1.82E-04
38	GBDS-GB7-002	Gas	2.49E-09	1.00	300	A & B	24.70	16	1	14	0.00380	0.152	2.29E-09	9.28E-11
39	OUTL-WDS-004	Liquid	6.52E-06	1.20	300	A & B	3.30	20	1	18	0.00084	46.453	1.83E-03	5.53E-04
40	MBDS-MB8-002	Gas	2.49E-09	1.00	300	A & B	3.80	16	1	14	0.00058	0.023	3.53E-10	9.28E-11
41	OUTL-DTSS-001	Gas	4.95E-01	1.00	300	A & B	3.65	8	1	6	0.00010	0.004	1.24E-02	3.38E-03
42	GBDS-GB9-002	Gas	2.49E-09	1.00	300	A & B	2.05	16	1	14	0.00032	0.013	1.90E-10	9.28E-11
43	OUTL-M1-011	Gas	2.49E-09	1.00	300	A & B	1.80	610	6.3	597.4	0.50454	20.228	3.04E-07	1.69E-07
44	OUTL-NEDS1-001	Liquid	2.78E-06	5.00	300	A & B	0.80	12	1	10	0.00006	3.476	5.84E-05	7.30E-05
45	GBDS-GB11-002	Gas	2.49E-09	1.00	300	A & B	1.40	16	1	14	0.00022	0.009	1.30E-10	9.28E-11
46	MBDS-MB11-002	Gas	2.49E-09	1.00	300	A & B	0.80	16	1	14	0.00012	0.005	7.42E-11	9.28E-11
47	OUTL-M1-012	Gas	2.49E-09	1.00	300	A & B	1.80	610	6.3	597.4	0.50454	20.228	3.04E-07	1.69E-07
48	OUTL-NEDS2-001	Liquid	2.78E-06	5.00	300	A & B	0.80	12	1	10	0.00006	3.476	5.84E-05	7.30E-05
49	GBDS-GB12-002	Gas	2.49E-09	1.00	300	A & B	1.40	16	1	14	0.00022	0.009	1.30E-10	9.28E-11
50	MBDS-MB12-002	Gas	2.49E-09	1.00	300	A & B	0.80	16	1	14	0.00012	0.005	7.42E-11	9.28E-11
51	OUTL-M1-015	Gas	2.49E-09	1.00	300	A & B	1.80	610	6.3	597.4	0.50454	20.228	3.04E-07	1.69E-07
52	OUTL-NEDS5-001	Liquid	2.78E-06	5.00	300	A & B	0.80	12	1	10	0.00006	3.476	5.84E-05	7.30E-05
53	GBDS-GB15-002	Gas	2.49E-09	1.00	300	A & B	1.40	16	1	14	0.00022	0.009	1.30E-10	9.28E-11
54	MBDS-MB15-002	Gas	2.49E-09	1.00	300	A & B	0.80	16	1	14	0.00012	0.005	7.42E-11	9.28E-11
55	OUTL-M1-016	Gas	2.49E-09	1.00	300	A & B	1.80	610	6.3	597.4	0.50454	20.228	3.04E-07	1.69E-07
56	OUTL-NEDS6-001	Liquid	2.78E-06	5.00	300	A & B	0.80	12	1	10	0.00006	3.476	5.84E-05	7.30E-05
57	GBDS-GB16-002	Gas	2.49E-09	1.00	300	A & B	1.40	16	1	14	0.00022	0.009	1.30E-10	9.28E-11
58	MBDS-MB16-002	Gas	2.49E-09	1.00	300	A & B	0.80	16	1	14	0.00012	0.005	7.42E-11	9.28E-11
59	OUTL-M2-021	Gas	2.49E-09	1.00	300	A & B	1.80	610	6.3	597.4	0.50454	20.228	3.04E-07	1.69E-07

No.	Tag	Phase	$T_{2,eq}$ mole fraction	Pressure bar-abs	Temp. K	Mode	Length m	OD mm	t mm	ID mm	Volume m^3	Matter / Mass mol (total)	Matter / Mass g $T_{2,eq}$	Linear Density g $T_{2,eq}$ / m
60	OUTL-OEDS1-001	Liquid	2.78E-06	5.00	300	A & B	0.80	12	1	10	0.00006	3.476	5.84E-05	7.30E-05
61	GBDS-GB21-002	Gas	2.49E-09	1.00	300	A & B	1.40	16	1	14	0.00022	0.009	1.30E-10	9.28E-11
62	MBDS-MB21-002	Gas	2.49E-09	1.00	300	A & B	0.80	16	1	14	0.00012	0.005	7.42E-11	9.28E-11
63	OUTL-TKB-001	Gas	1.12E-09	1.00	300	A & B	2.90	610	6.3	597.4	0.81286	32.590	2.20E-07	7.60E-08
64	HDR-TWH-100 (A)	Liquid	2.99E-05	1.00	300	A	51.20	6	1	4	0.00064	35.591	6.41E-03	1.25E-04
65	HDR-TWH-100 (B)	Liquid	2.99E-05	1.00	300	B	49.70	6	1	4	0.00062	34.548	6.22E-03	1.25E-04
66	*HDR-TWL-100*	*Liquid*	*2.78E-06*	*1.00*	*300*	*A & B*	*36.40*	*14*	*1*	*12*	*0.00412*	*227.728*	*3.83E-03*	*1.05E-04*
67	*HDR-TWL-110*	*Liquid*	*2.78E-06*	*1.00*	*300*	*A & B*	*25.40*	*14*	*1*	*12*	*0.00287*	*158.909*	*2.67E-03*	*1.05E-04*
68	*HDR-TWL-101*	*Liquid*	*2.78E-06*	*1.00*	*300*	*A & B*	*9.60*	*16*	*1*	*14*	*0.00148*	*81.748*	*1.37E-03*	*1.43E-04*
69	*HDR-TWL-200*	*Liquid*	*2.78E-06*	*1.00*	*300*	*A & B*	*46.30*	*12*	*1*	*10*	*0.00364*	*201.156*	*3.38E-03*	*7.30E-05*
70	*HDR-TWL-300*	*Liquid*	*2.78E-06*	*1.00*	*300*	*A & B*	*21.00*	*17.2*	*1*	*15.2*	*0.00381*	*210.794*	*3.54E-03*	*1.69E-04*
	HDR-TWL-XYY	Liquid	2.78E-06	1.00	300	A & B	138.70	-	-	-	0.01591	880.335	1.48E-02	1.07E-04
71	*HDR-TG1-100*	*Gas*	*2.49E-09*	*1.00*	*300*	*A & B*	*98.70*	*610*	*6.3*	*597.4*	*27.66543*	*1109.191*	*1.67E-05*	*1.69E-07*
72	*HDR-TG1-1XX*	*Gas*	*2.49E-09*	*1.00*	*300*	*A & B*	*6.95*	*610*	*6.3*	*597.4*	*1.94807*	*78.104*	*1.17E-06*	*1.69E-07*
73	*HDR-TG1-2XX*	*Gas*	*2.49E-09*	*1.00*	*300*	*A & B*	*99.20*	*48.3*	*1.6*	*45.1*	*0.15847*	*6.354*	*9.55E-08*	*9.63E-10*
	HDR-TG1-XYY	Gas	2.49E-09	1.00	300	A&B	204.85	-	-	-	29.77198	1193.648	1.79E-05	8.76E-08
74	HDR-TG2-100	Gas	1.12E-09	1.00	300	A & B	8.90	610	6.3	597.4	2.49465	100.018	6.76E-07	7.60E-08
75	HDR-TG2-2XX	Gas	2.49E-09	1.00	300	A & B	24.10	48.3	1.6	45.1	0.03850	1.544	2.32E-08	9.63E-10
76	HDR-RC2-100	Gas	1.12E-09	1.00	300	A & B	51.25	610	6.3	597.4	14.36528	575.948	3.89E-06	7.60E-08

Table A-8 – Sensitivity analysis to the operational tritium inventory in pipes results with operational mode A as the reference case.

Case	Stage	Pipe Sizing Strategy	Pipes Length	Operational Conditions	Pipe Types No.	Total Volume	Volume OD < 25mm	Small Pipes Volume Variation vs. OBC	Inventory	Inventory Variation vs. OBC
					-	m^3	m^3		g $T_{2,eq}$	
Optimized Base Case (OBC)	Design	Unification Criteria	3D Model	Base Case	10	50.22	0.03662		**0.210**	
Flowrate (-10%)	Design	Unification Criteria	3D Model	**90% Flowrate**	11	50.22	0.03491	*-4.7%*	**0.193**	*-7.8%*
Minimum Flowrate	Design	Unification Criteria	3D Model	**61.6% Flowrate**	11	28.17	0.02546	*-30.5%*	**0.149**	*-28.7%*
Pressure (-20%)	Design	Unification Criteria	3D Model	**80% Pressure**	11	50.31	0.03834	*4.7%*	**0.184**	*-12.0%*
Pressure (-10%)	Design	Unification Criteria	3D Model	**90% Pressure**	10	50.22	0.03722	*1.6%*	**0.203**	*-3.2%*
Pressure (+10%)	Design	Unification Criteria	3D Model	**110% Pressure**	12	50.21	0.03669	*0.2%*	**0.215**	*2.4%*
Pressure (+20%)	Design	Unification Criteria	3D Model	**120% Pressure**	12	50.21	0.03538	*-3.4%*	**0.223**	*6.6%*
Temperature (T-25K)	Design	Unification Criteria	3D Model	**25K Colder**	11	50.22	0.03854	*5.2%*	**0.216**	*3.3%*
Temperature (T+25K)	Design	Unification Criteria	3D Model	**25K Warmer**	11	50.22	0.03717	*1.5%*	**0.207**	*-1.2%*
Pressure (-10%)	**Operation**	Same as OBC	3D Model	**90% Pressure**	10	50.22	0.03662	*0.0%*	**0.192**	*-8.6%*
Pressure (+10%)	**Operation**	Same as OBC	3D Model	**110% Pressure**	10	50.22	0.03662	*0.0%*	**0.228**	*8.6%*
Temperature (T-25K)	**Operation**	Same as OBC	3D Model	**25K Colder**	10	50.22	0.03662	*0.0%*	**0.226**	*7.8%*
Temperature (T+25K)	**Operation**	Same as OBC	3D Model	**25K Warmer**	10	50.22	0.03662	*0.0%*	**0.195**	*-6.7%*
3 Pipe Combinations	Design	**Excessive Unification**	3D Model	Base Case	**3**	51.93	0.08825	*141.0%*	**0.818**	*290.2%*
4 Pipe Combinations	Design	**Excessive Unification**	3D Model	Base Case	**4**	51.90	0.05833	*59.3%*	**0.500**	*138.6%*
6 Pipe Combinations	Design	**Excessive Unification**	3D Model	Base Case	**6**	50.23	0.04674	*27.6%*	**0.240**	*14.5%*
12 Pipe Combinations	Design	**Suboptimal Unification**	3D Model	Base Case	**12**	50.22	0.03577	*-2.3%*	**0.209**	*-0.3%*
Base Case (2º Calc.)	Design	**No Unification**	3D Model	Base Case	**22**	41.95	0.03874	*5.8%*	**0.224**	*6.8%*
Excessive Diameter Reduction	Design	**Each Stream**	3D Model	Base Case	**26**	38.50	0.03392	*-7.4%*	**0.184**	*-12.1%*
Poor Layout Distribution	Design	**No Unification**	**All 53 m**	Base Case	18	86.01	0.32171	*778.5%*	**3.610**	*1622.2%*

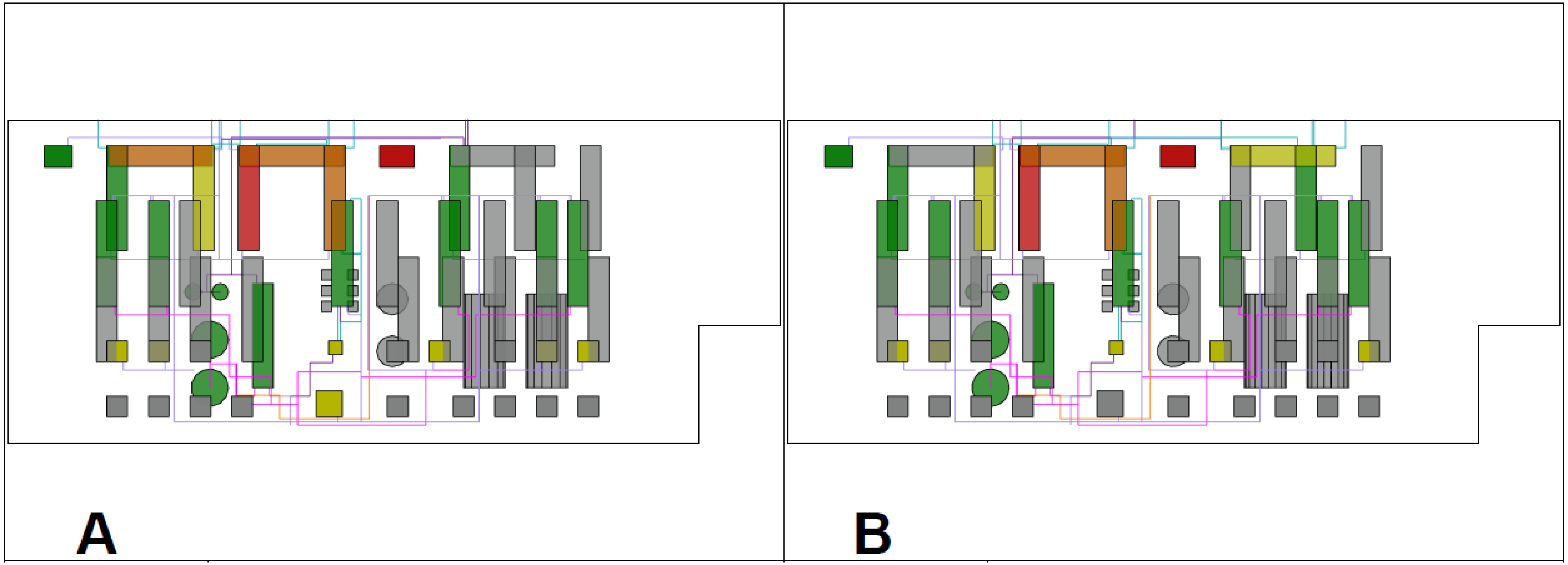


Figure A-1 – Top view of the tritium plant groups and their inventory distribution under operational modes A and B.

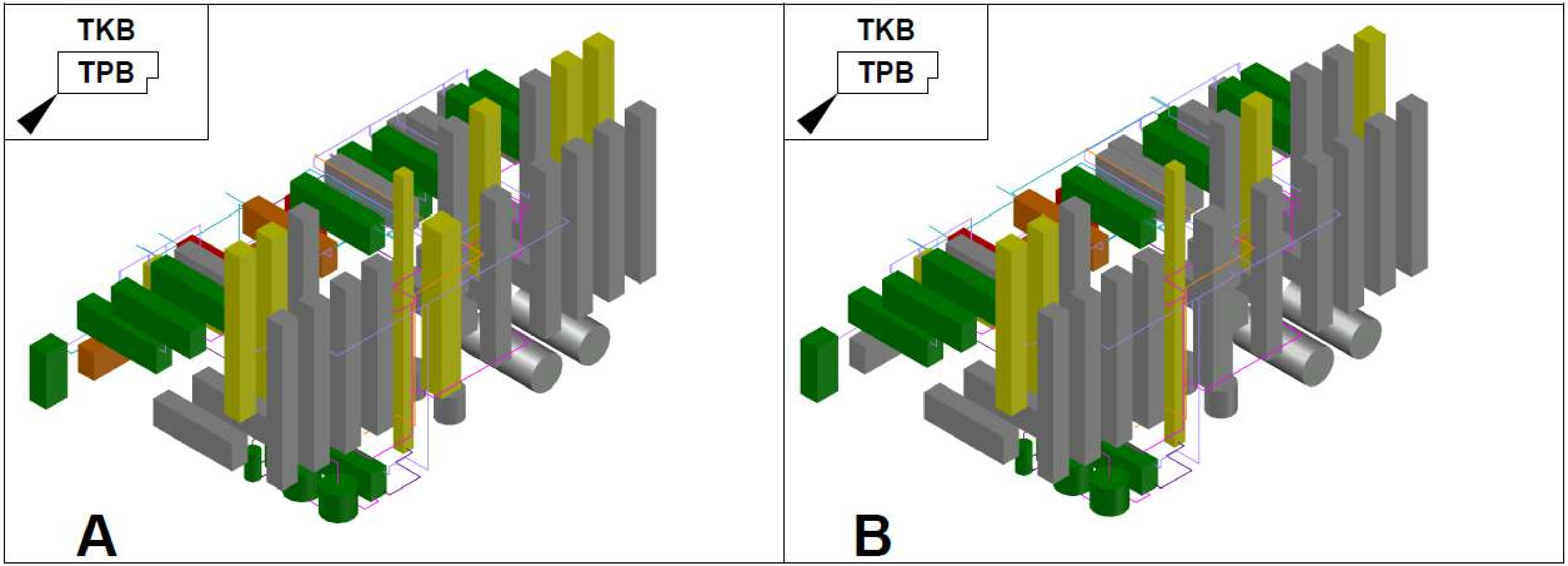


Figure A-2 – SW view of the tritium plant groups and their inventory distribution under operational modes A and B.

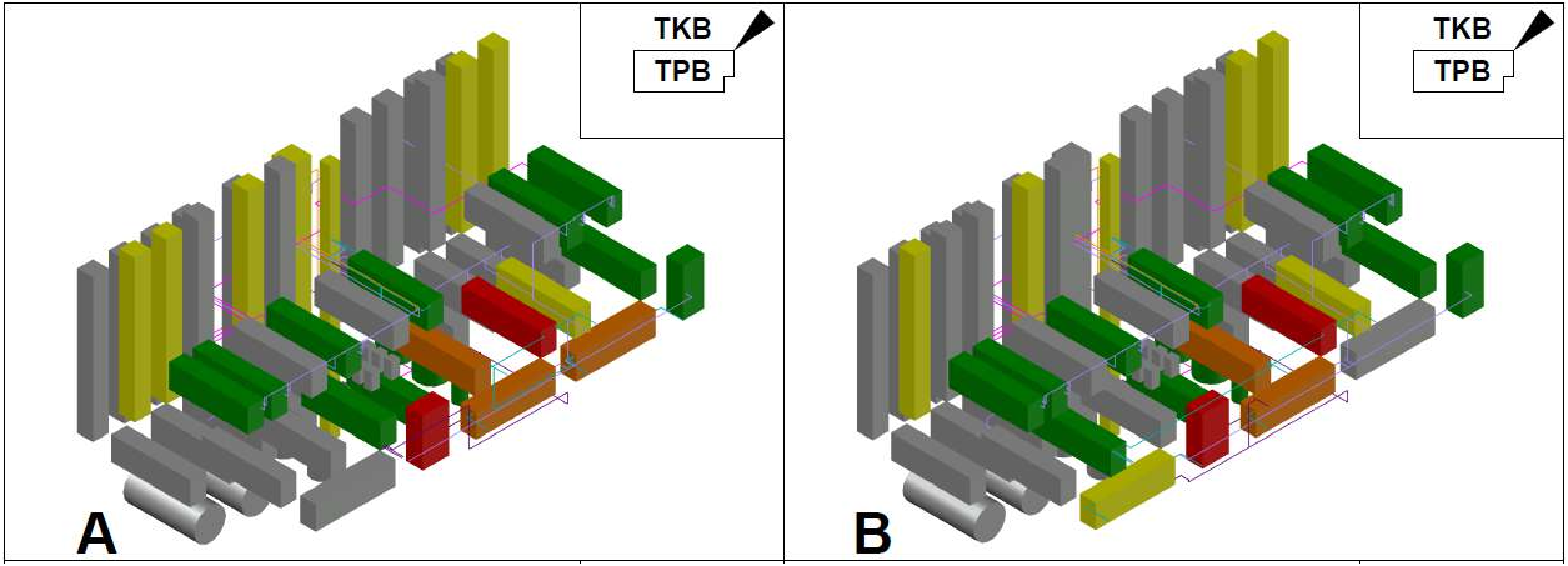


Figure A-3 – NE view of the tritium plant groups and their inventory distribution under operational modes A and B.

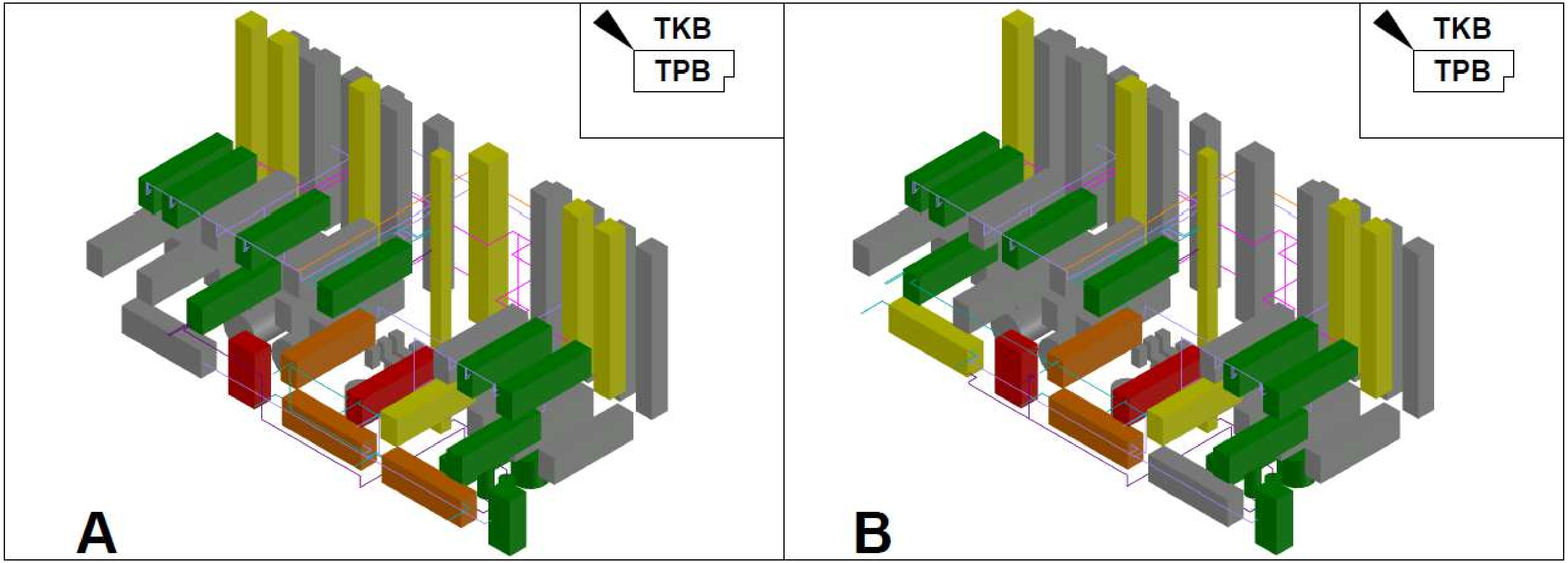


Figure A-4 – NW view of the tritium plant groups and their inventory distribution under operational modes A and B.

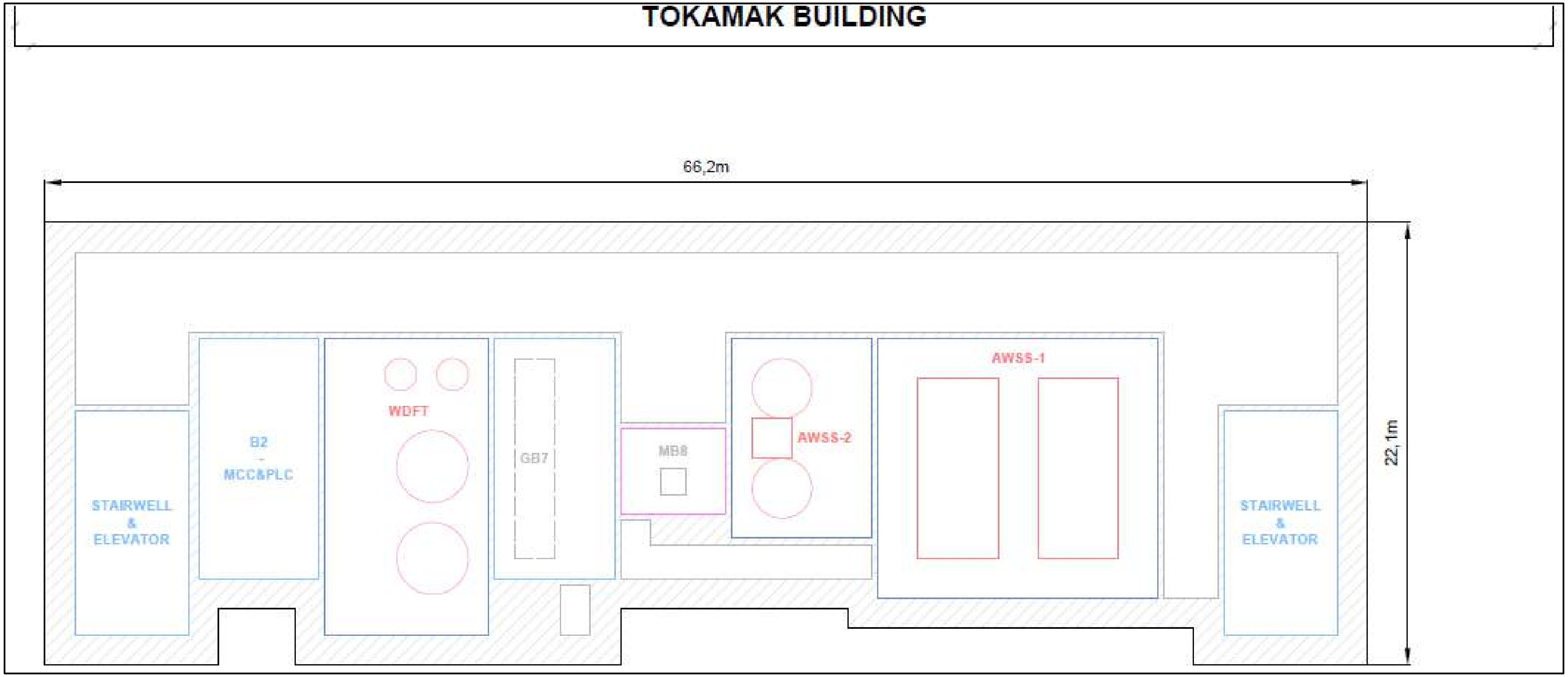


Figure A-5 – Top view of level B2 of the tritium plant building.

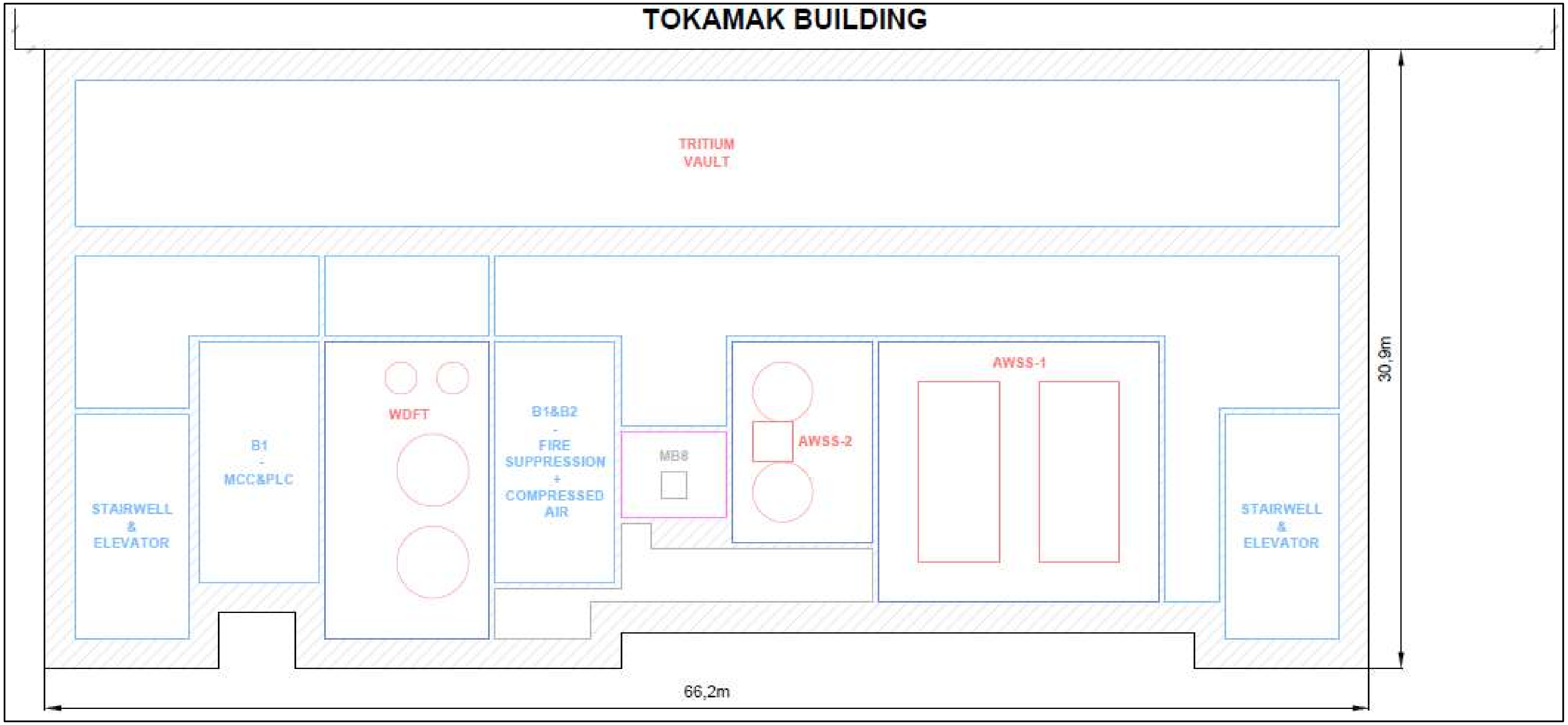


Figure A-6 – Top view of level B1 of the tritium plant building.

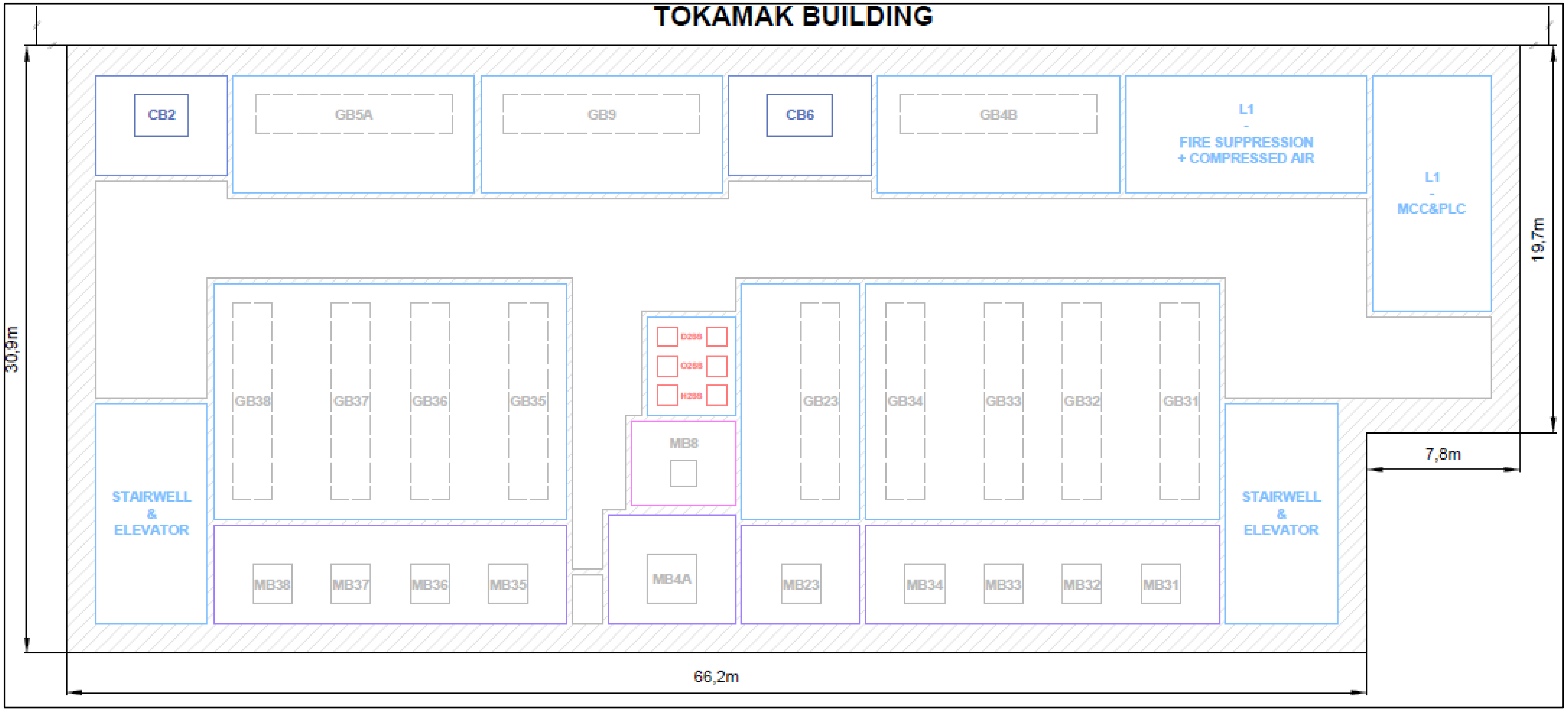


Figure A-7 – Top view of level L1 of the tritium plant building.

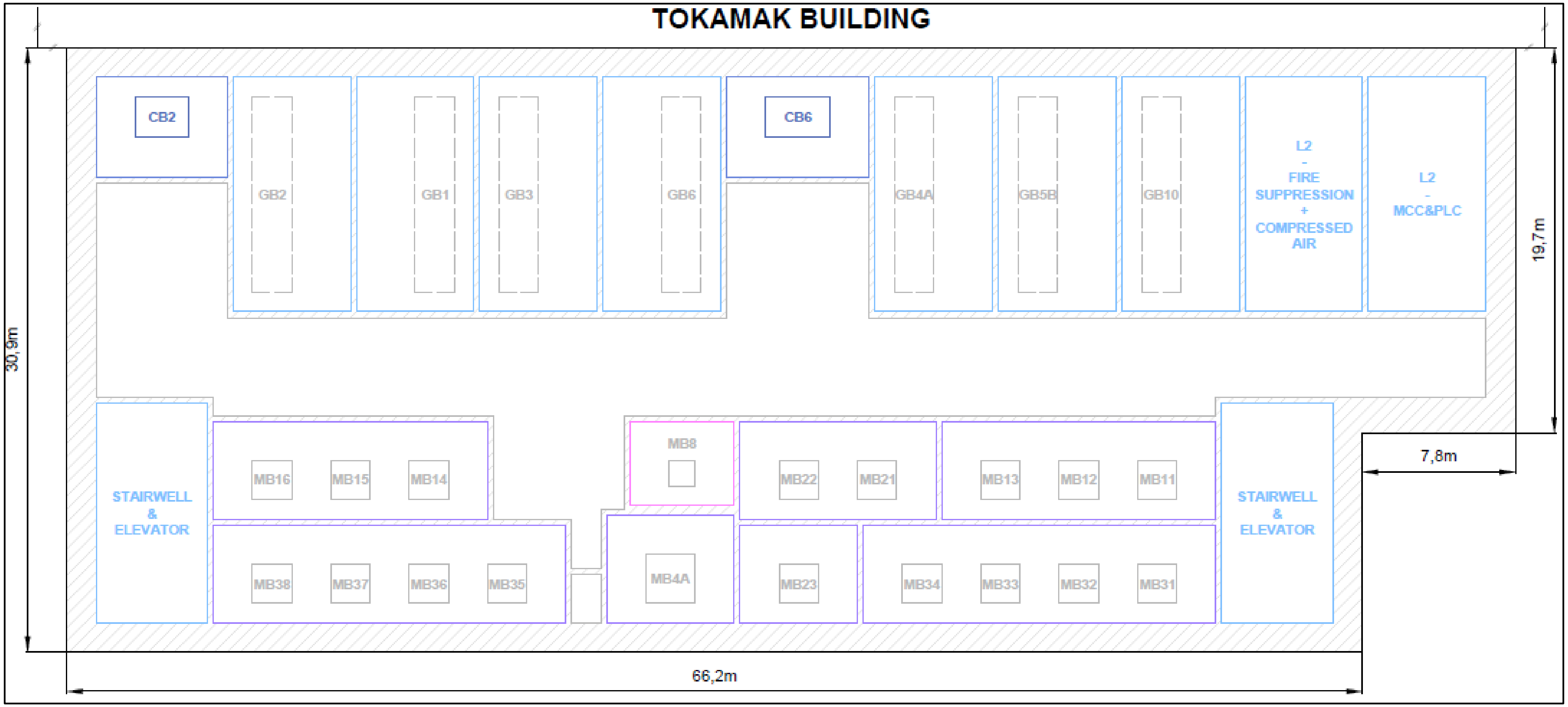


Figure A-8 – Top view of level L2 of the tritium plant building.

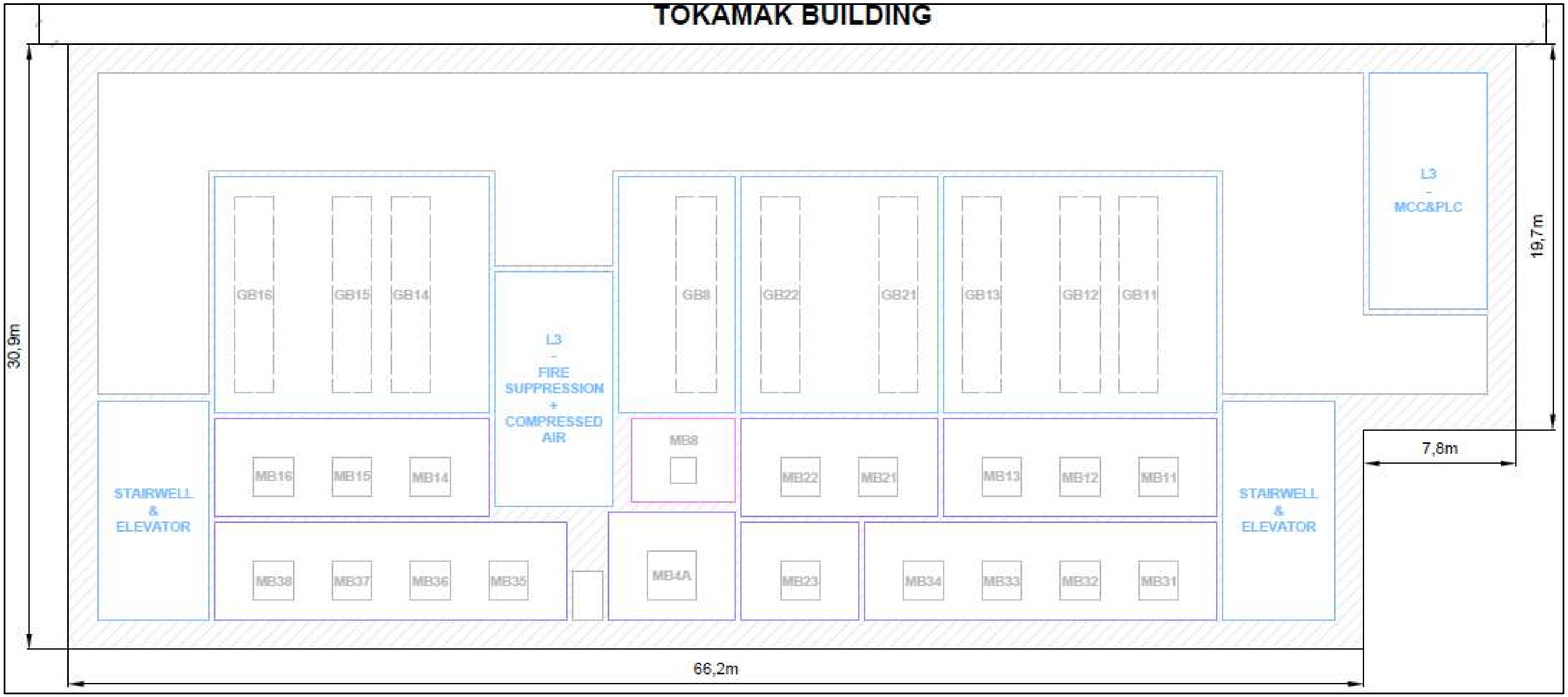


Figure A-9 – Top view of level L3 of the tritium plant building.

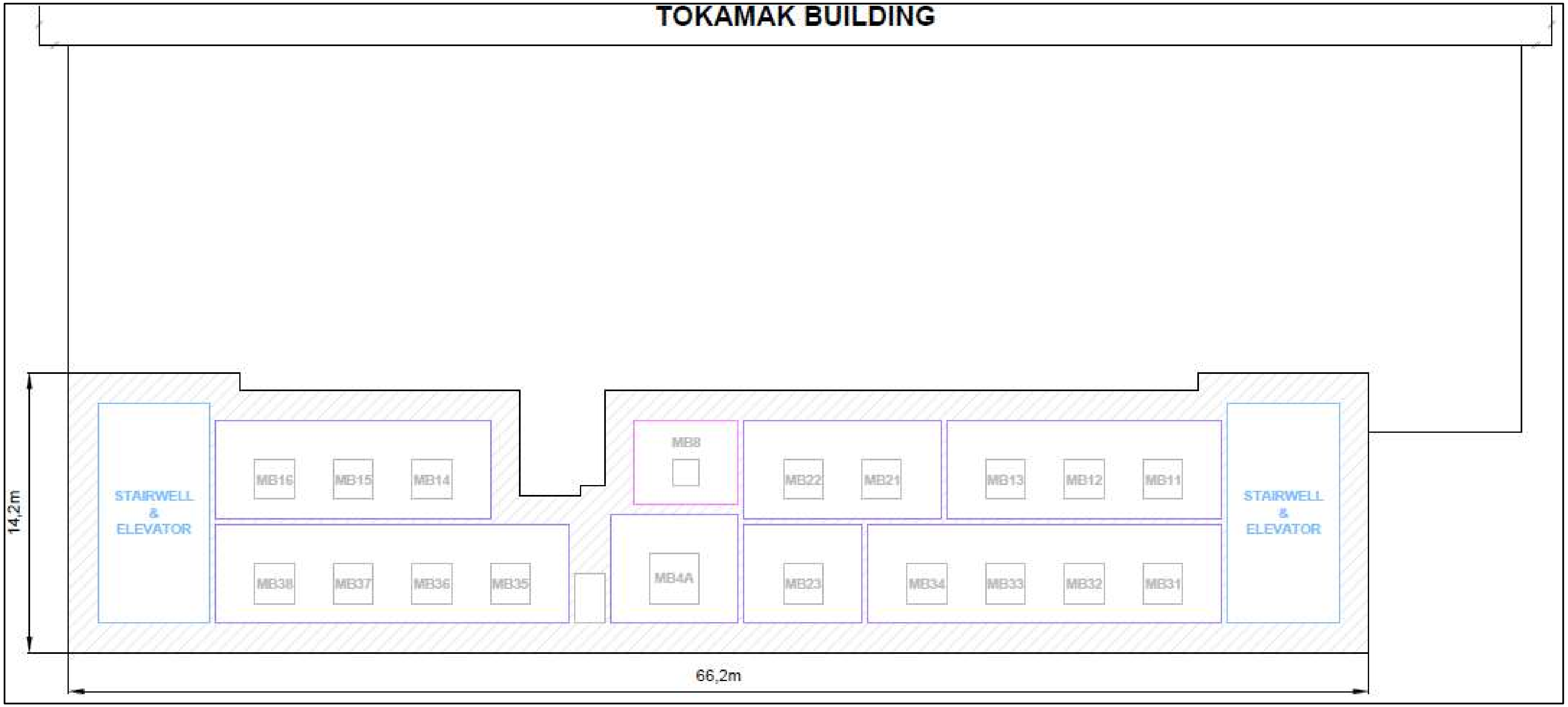


Figure A-10 – Top view of level L4 of the tritium plant building.

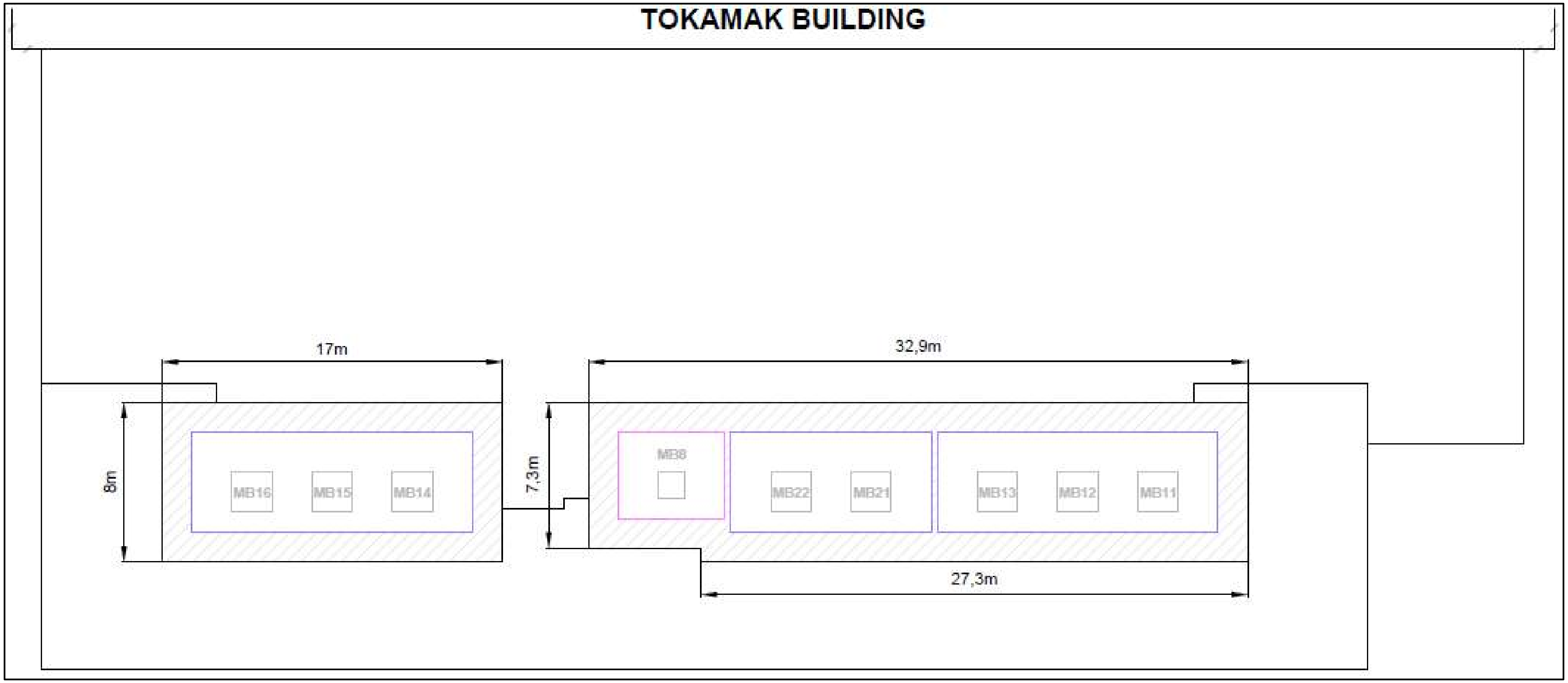


Figure A-11 – Top view of level L5 of the tritium plant building.

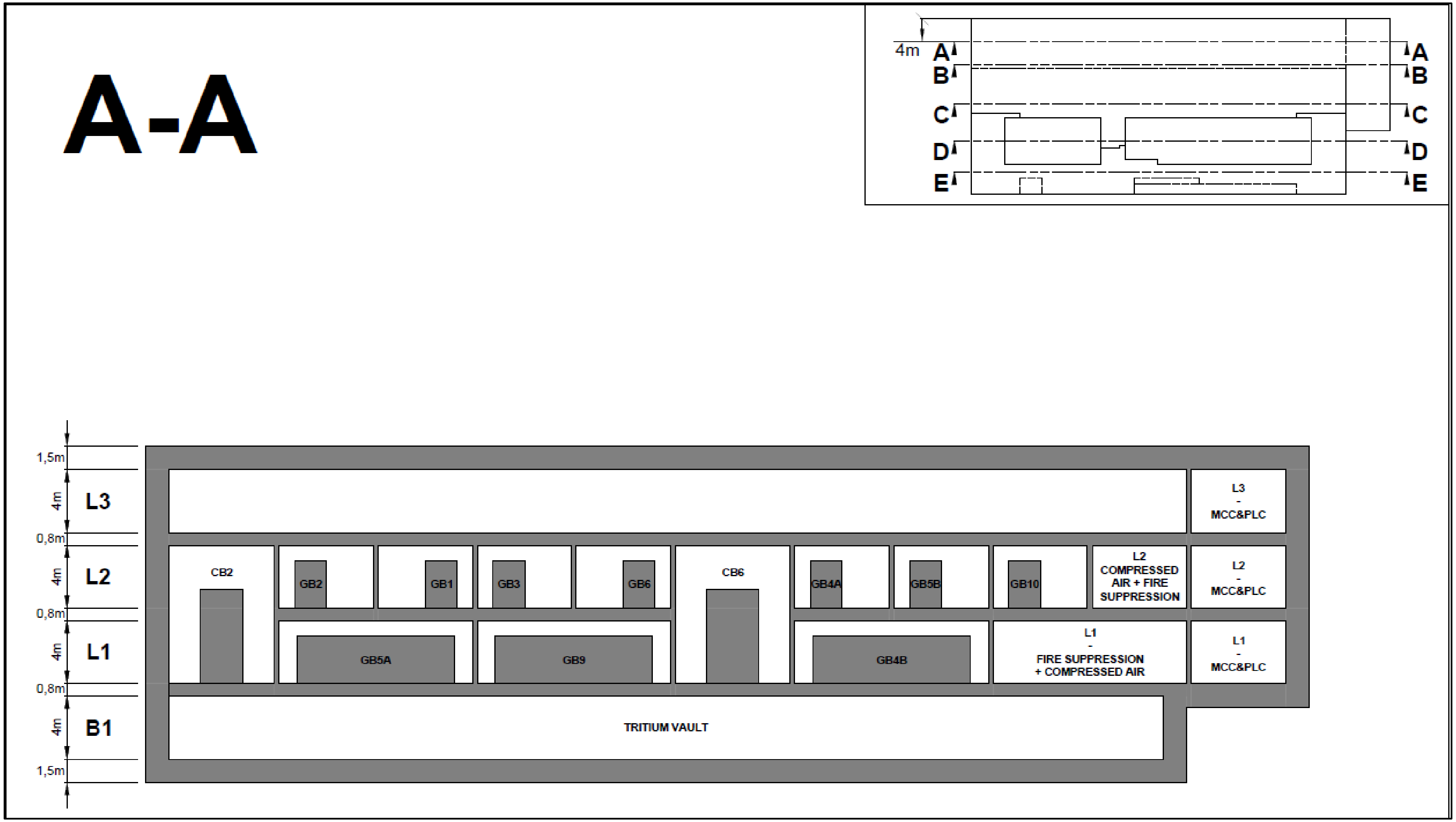


Figure A-12 – Section view of the tritium plant building at 4 m from the TKB.

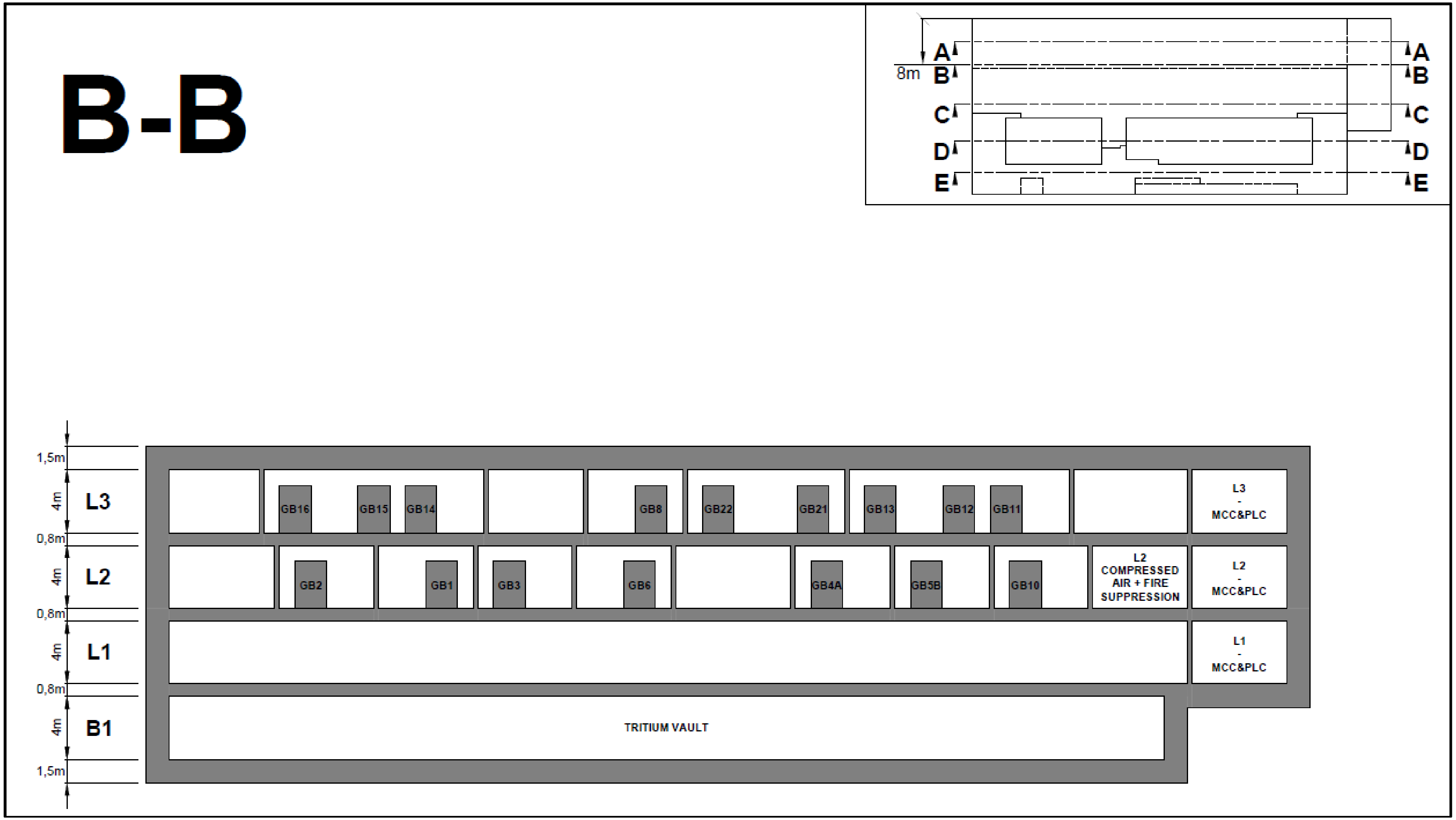


Figure A-13 – Section view of tritium plant building at 8 m from the TKB.

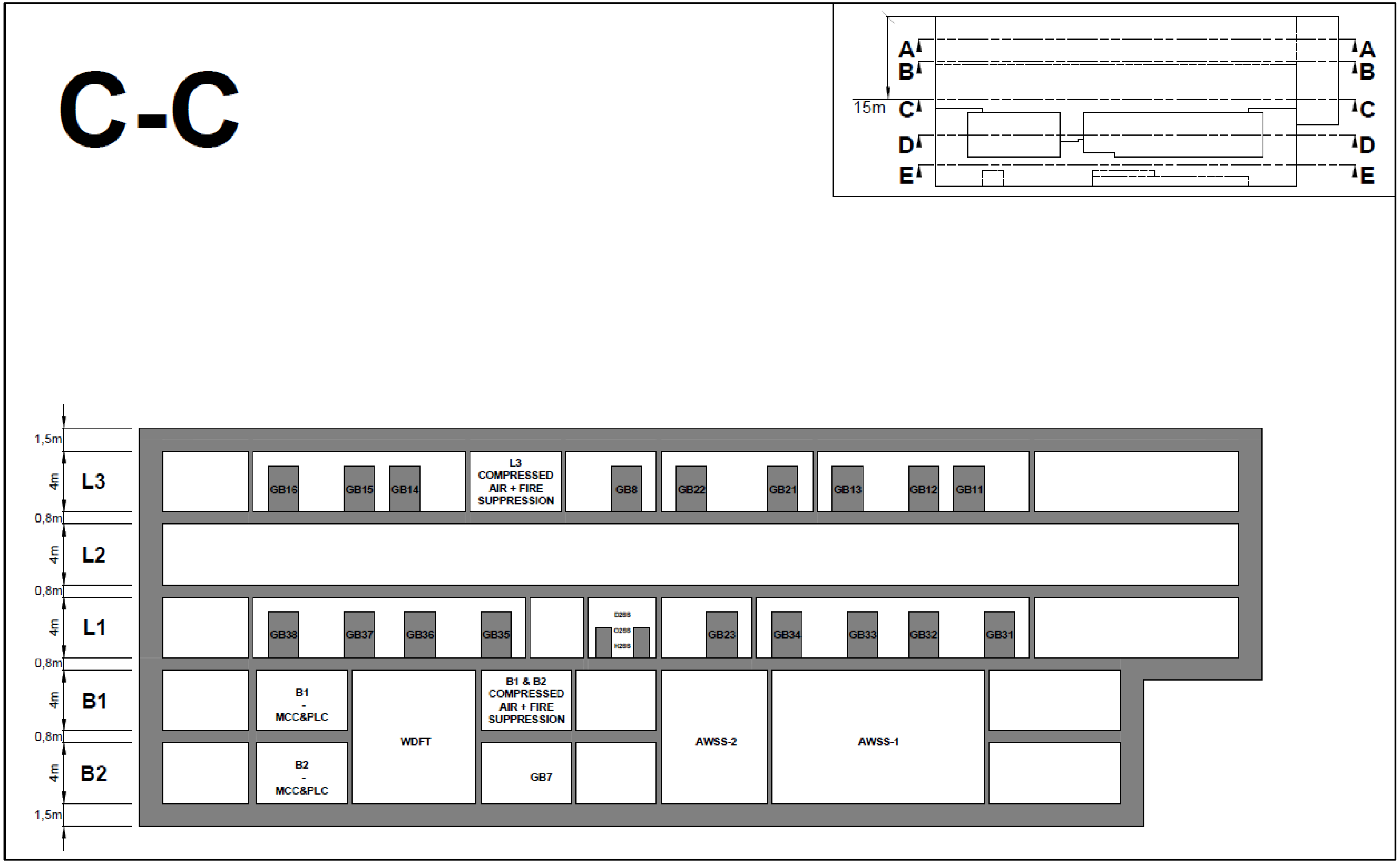


Figure A-14 – Section view of the tritium plant building at 15 m from the TKB.

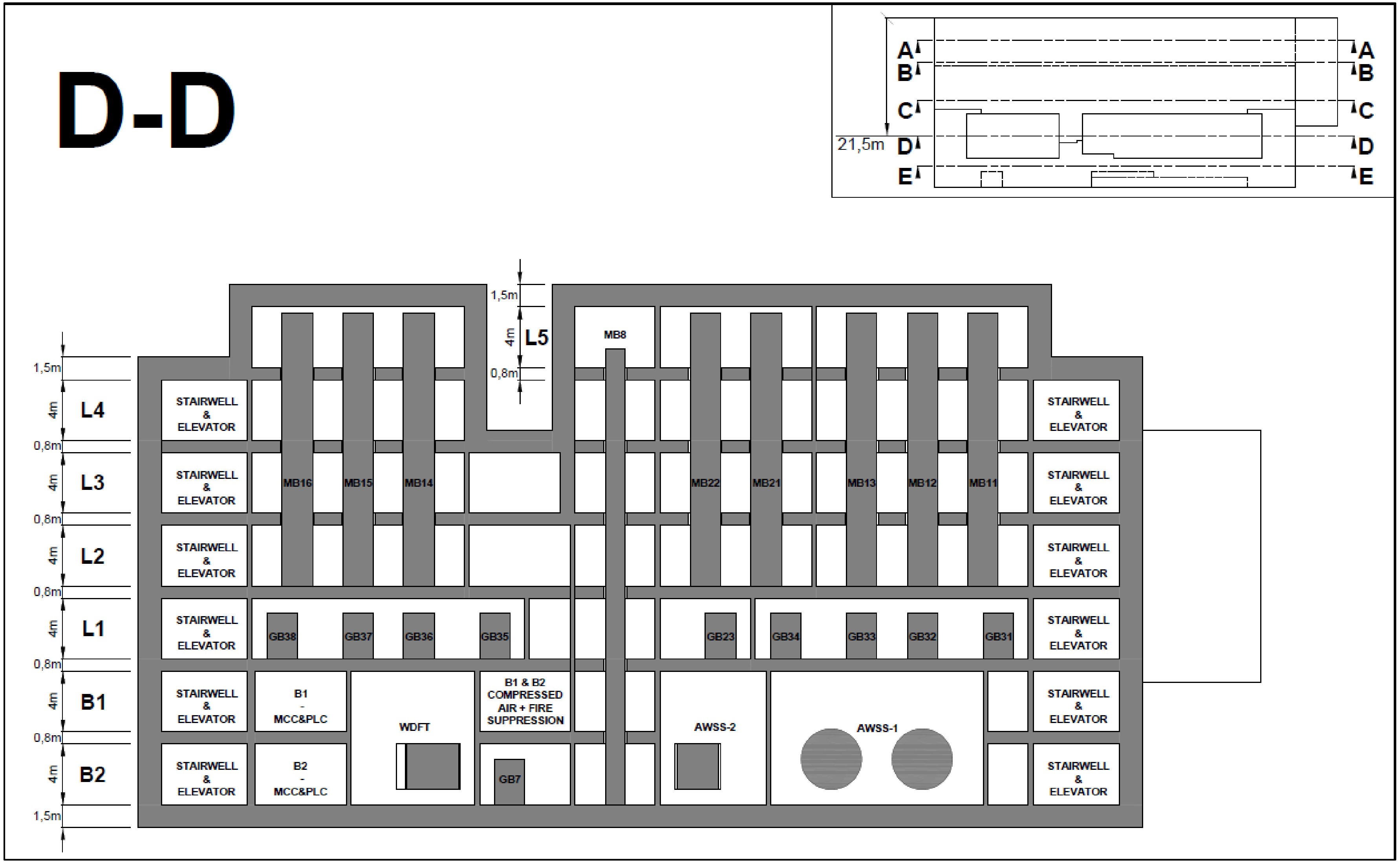


Figure A-15 – Section view of the tritium plant building at 21.5 m from the TKB.

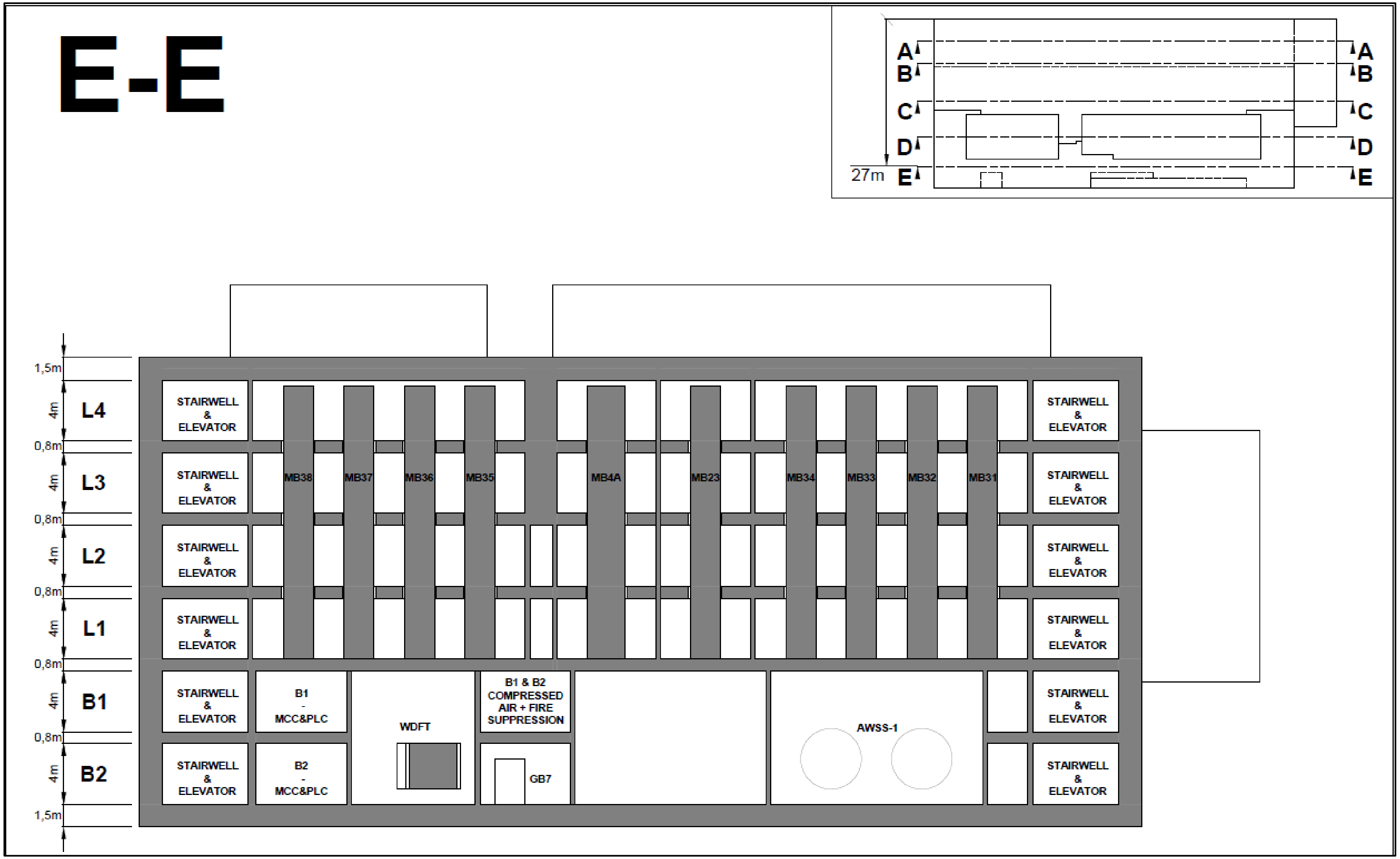


Figure A-16 – Section view of the tritium plant building at 27 m from the TKB.

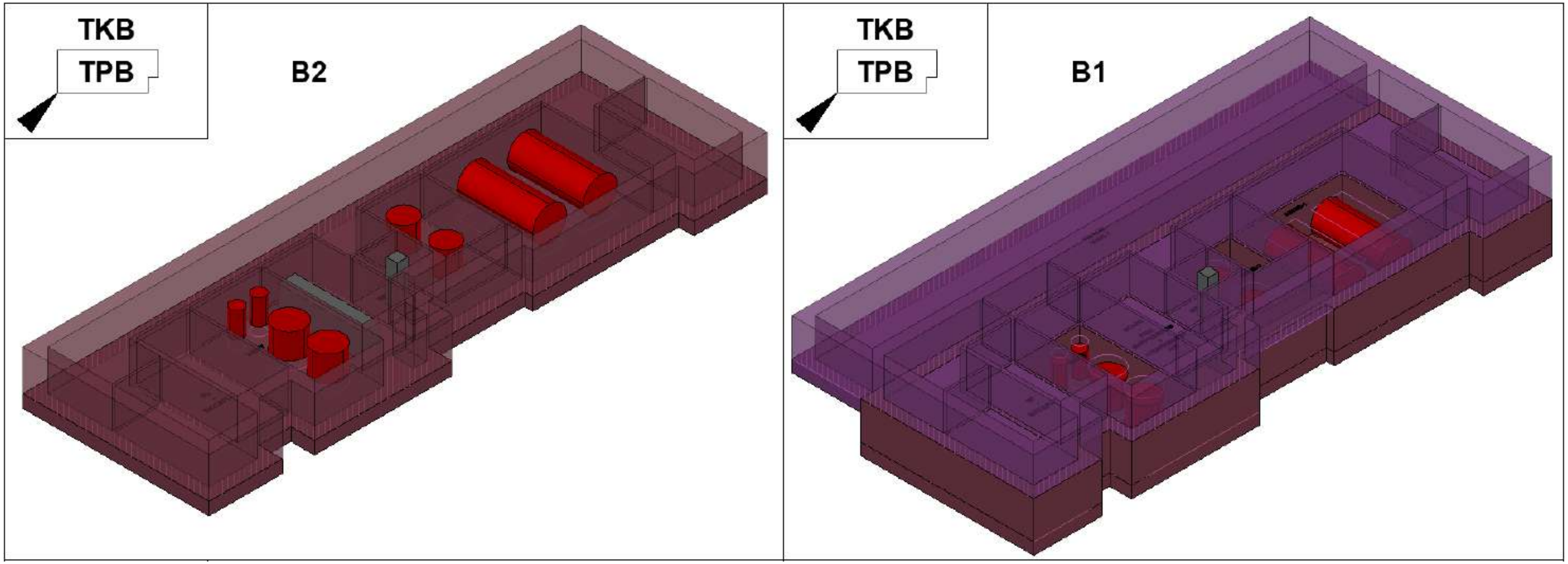


Figure A-17 – 3D view of levels B2 and B1 of the tritium plant building.

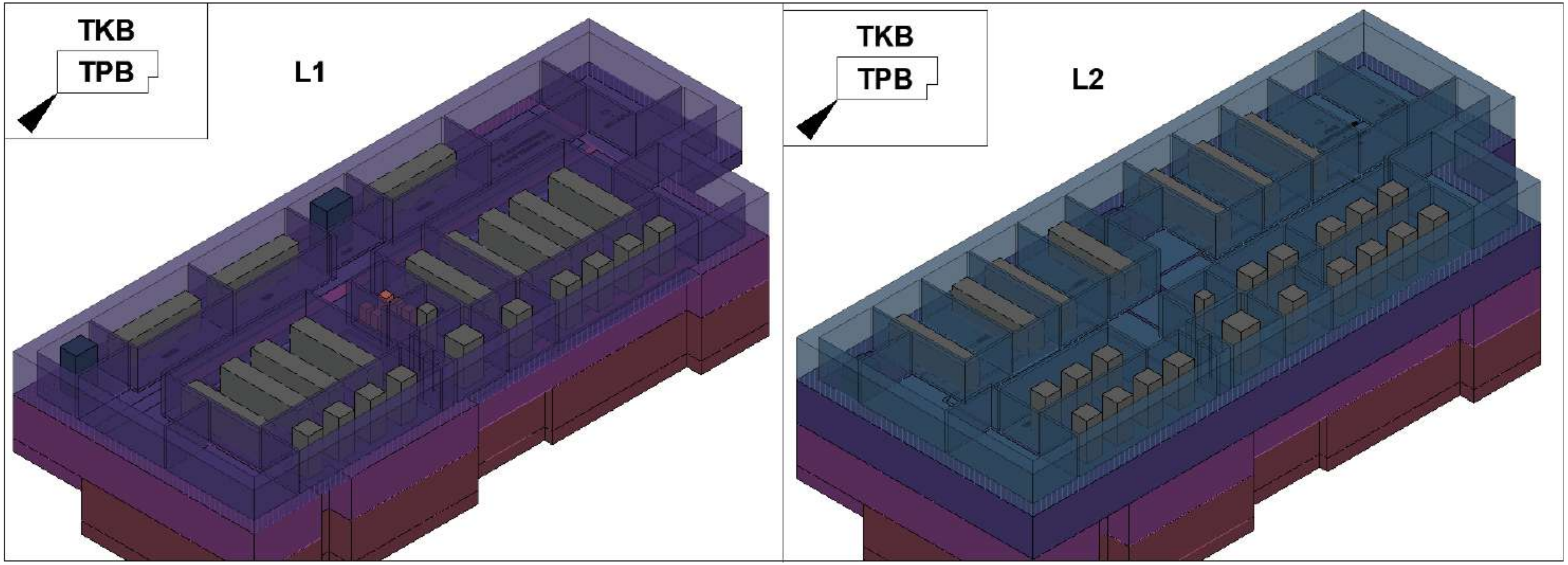


Figure A-18 – 3D view of levels L1 and L2 of the tritium plant building.

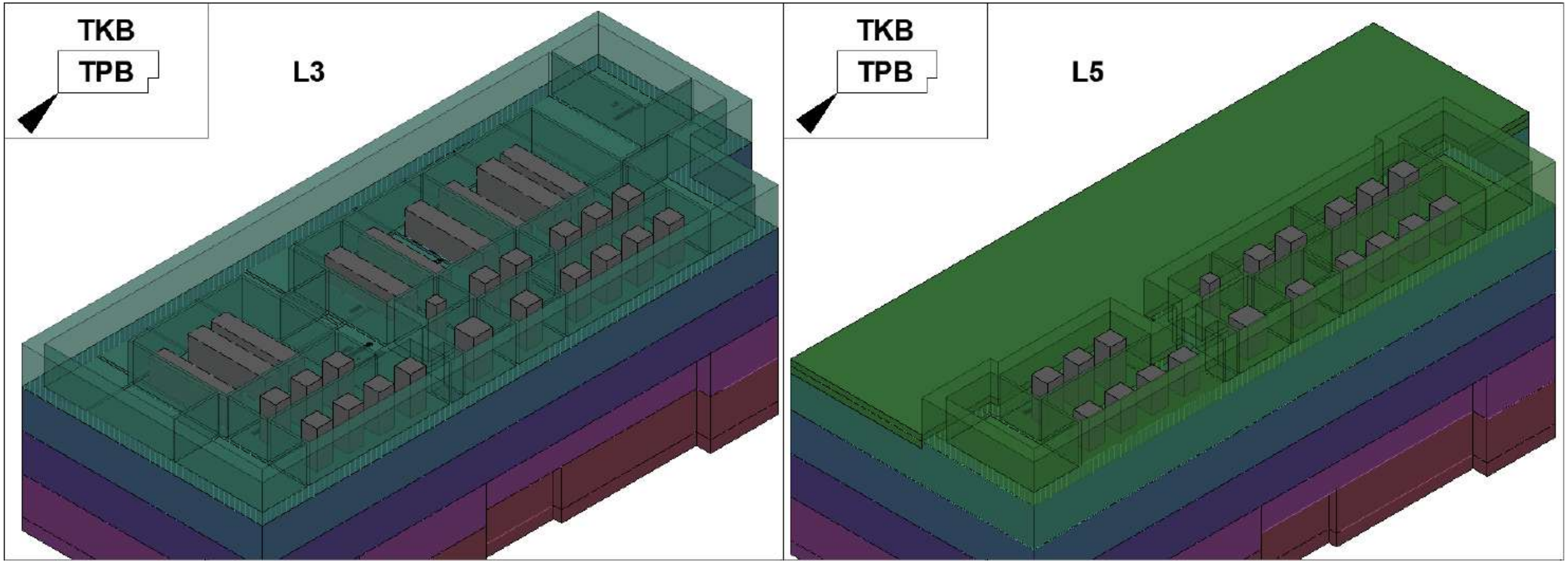


Figure A-19 – 3D view of levels L3 and L4 of the tritium plant building.

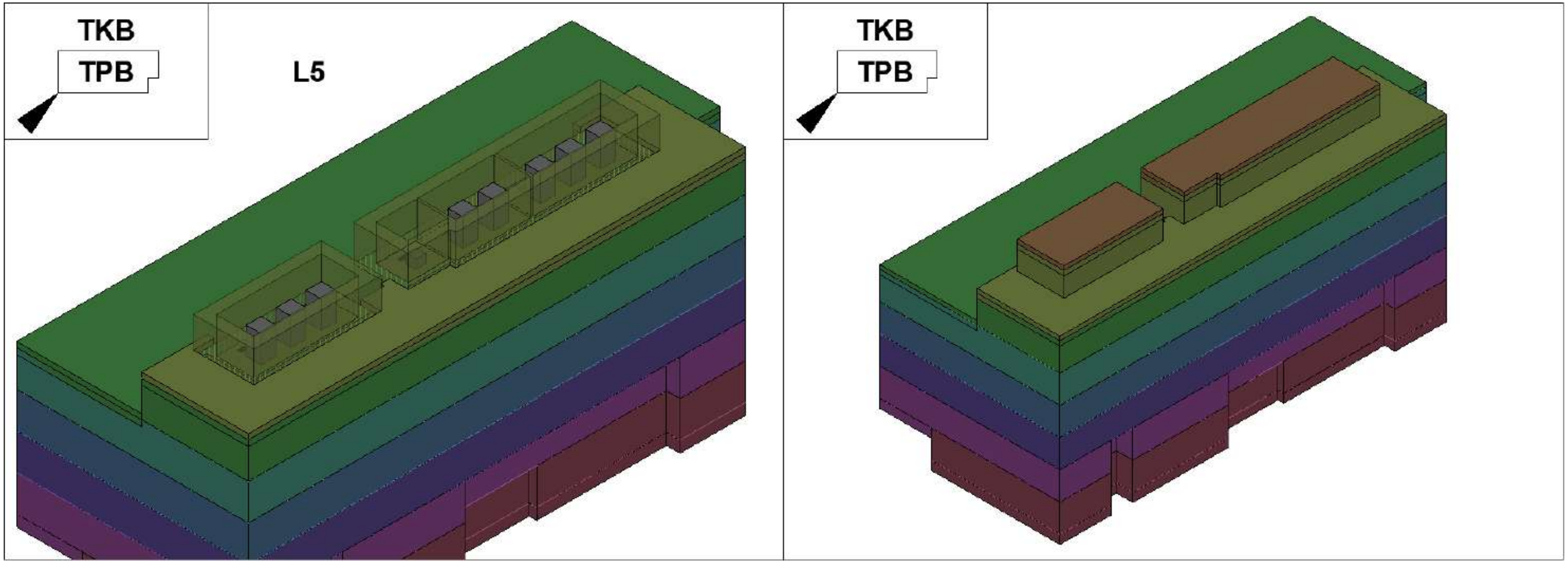


Figure A-20 – 3D view of level L5 and external view of the tritium plant building.

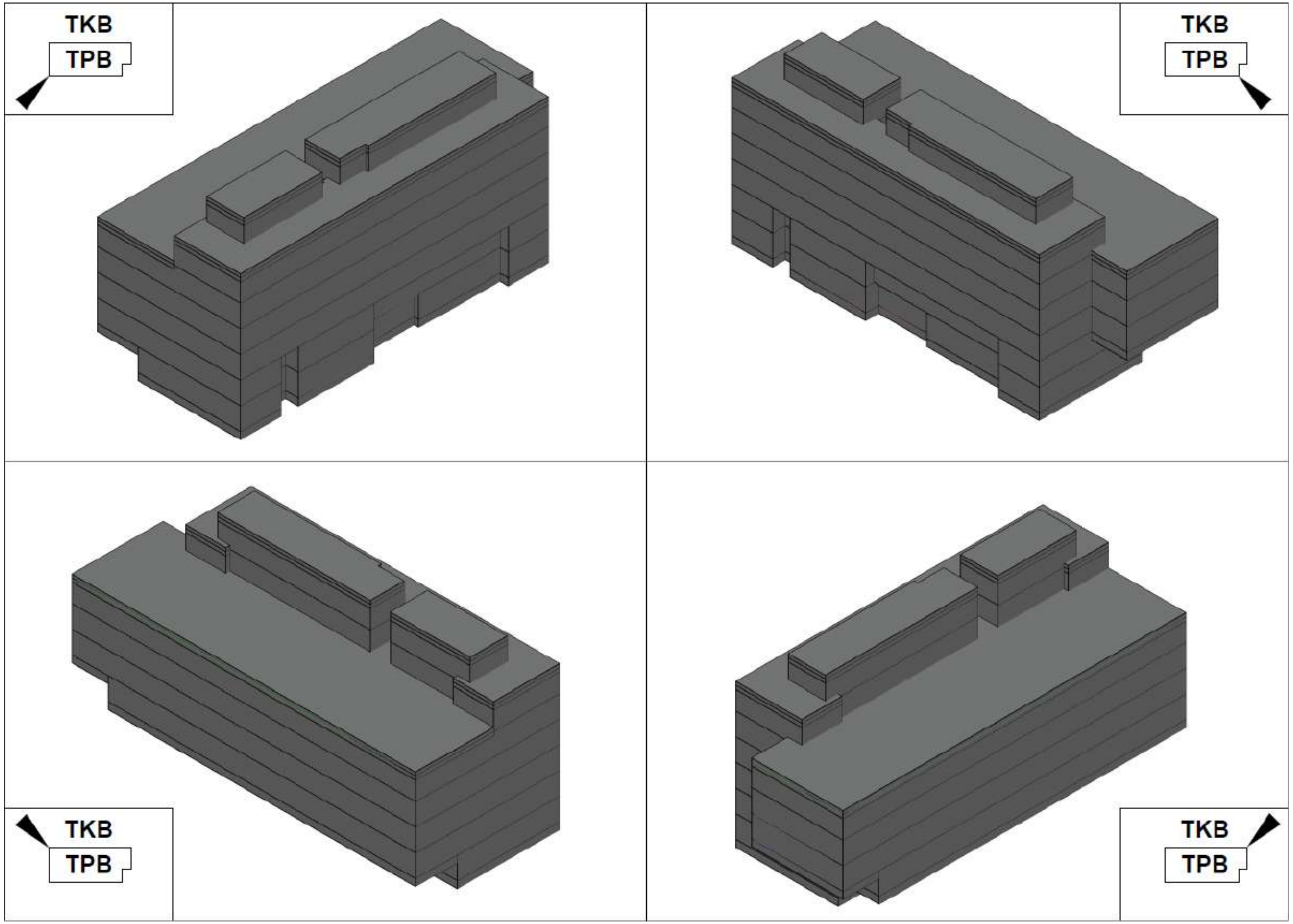


Figure A-21 – External views of the tritium plant building from various directions.

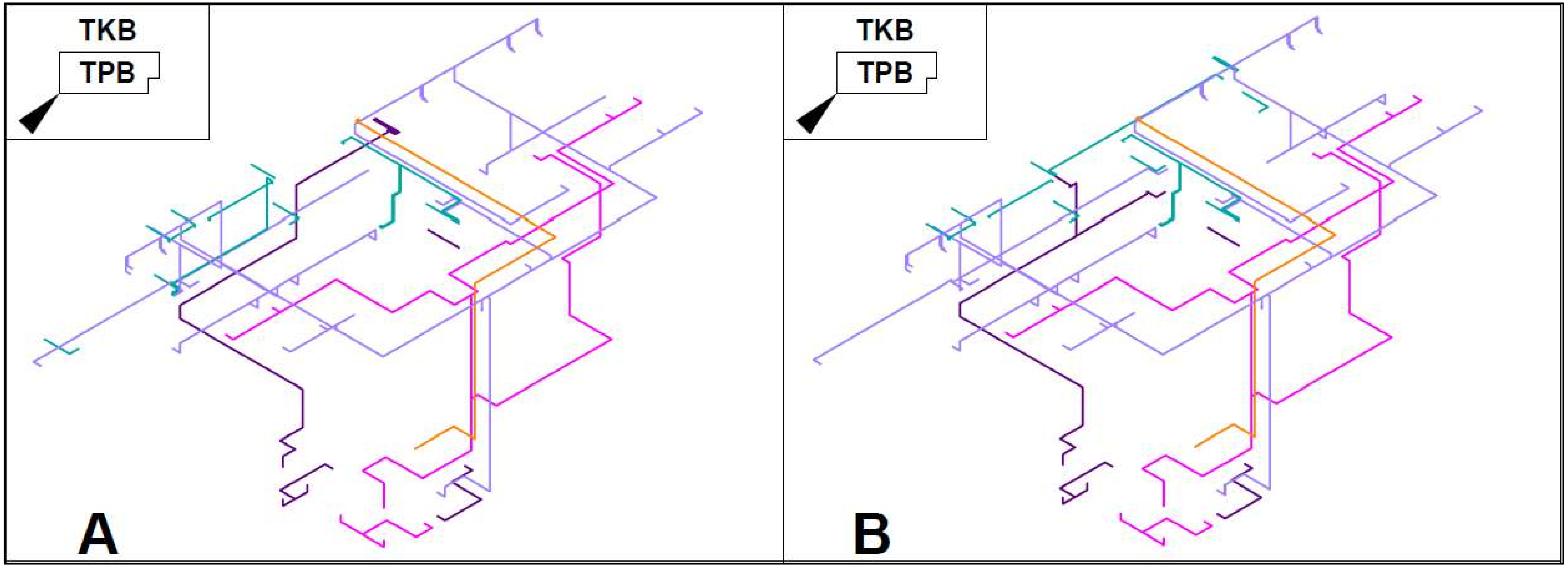


Figure A-22 – Tritium plant piping routing for operational modes A and B. The colors reflect the same scheme as the block diagram (see Figure A-24).

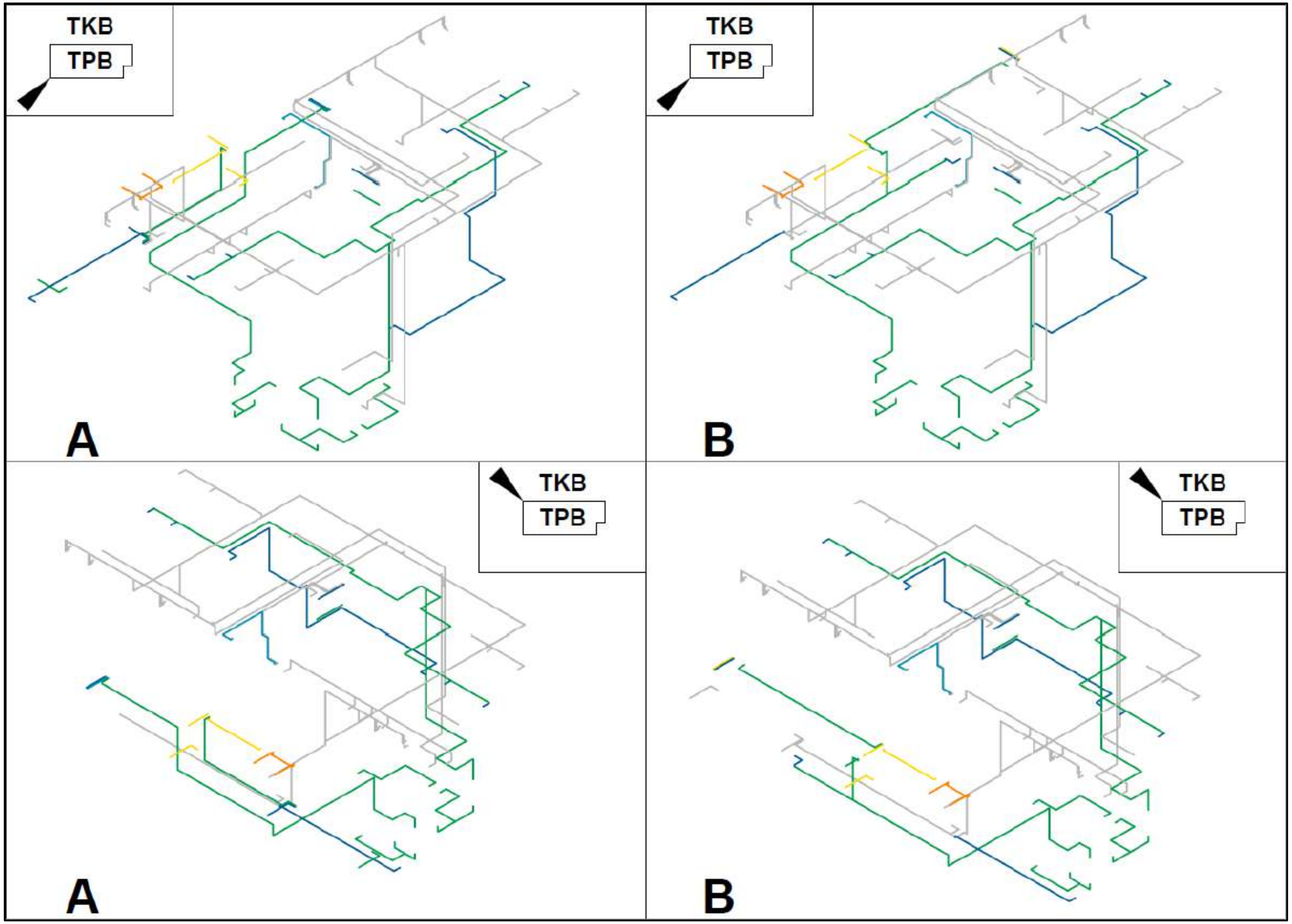
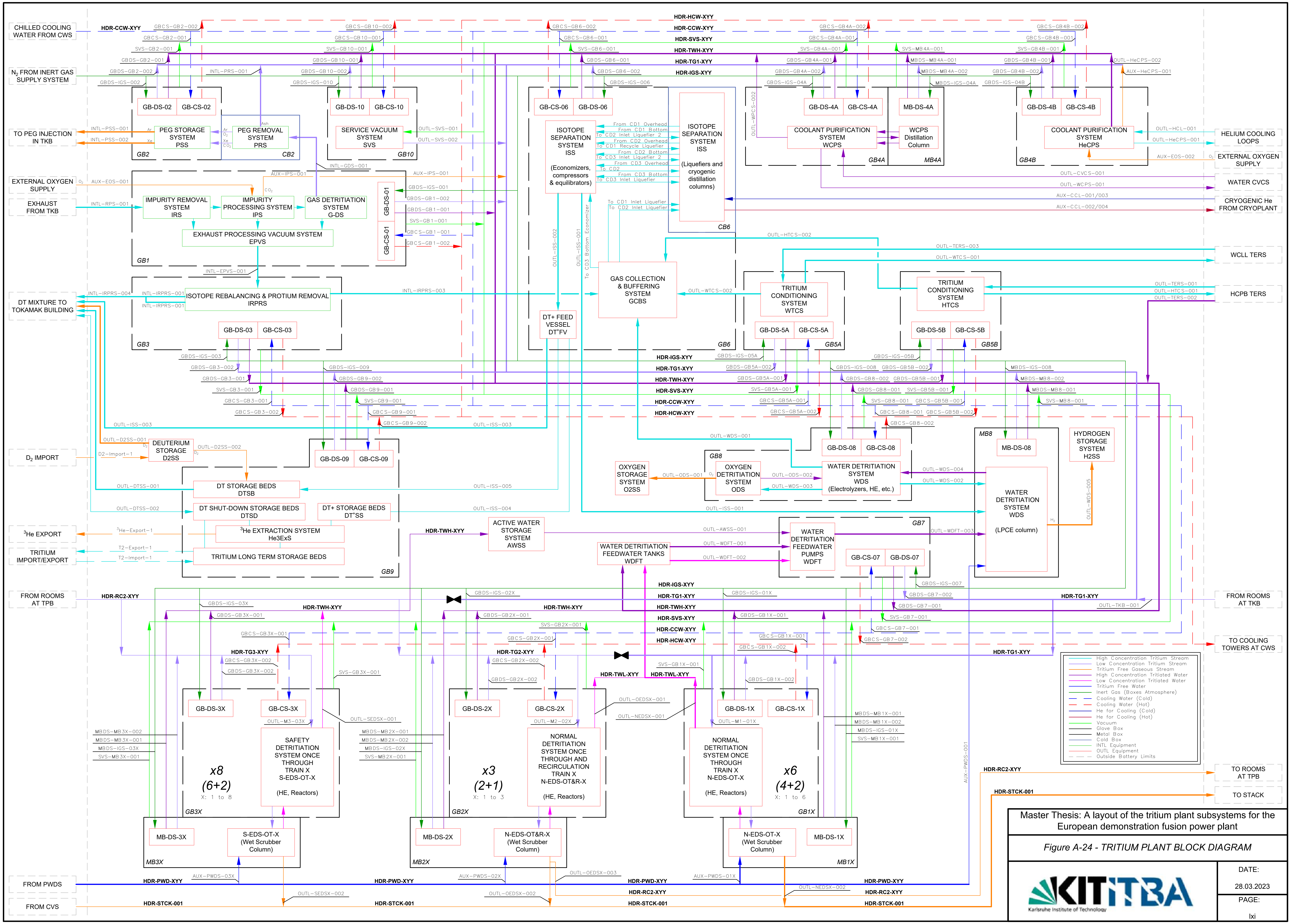


Figure A-23 – Tritium plant piping routing for operational modes A and B. The colors show the linear tritium density (see Table 23).

Figure A-24 – Tritium plant block diagram.



CHILLED COOLING WATER FROM CWS
N2 FROM INERT GAS SUPPLY SYSTEM
TO PEG INJECTION IN TKB
EXTERNAL OXYGEN SUPPLY
EXHAUST FROM TKB
DT MIXTURE TO TOKAMAK BUILDING
D2 IMPORT
3He EXPORT
TRITIUM IMPORT/EXPORT
FROM ROOMS AT TPB
FROM PWDS
FROM CVS
HELIUM COOLING LOOPS
EXTERNAL OXYGEN SUPPLY
WATER CVCS
CRYOGENIC He FROM CRYOPLANT
WCLL TERS
HCPB TERS
FROM ROOMS AT TKB
TO COOLING TOWERS AT CWS
TO ROOMS AT TPB
TO STACK
PEG STORAGE SYSTEM PSS
PEG REMOVAL SYSTEM PRS
SERVICE VACUUM SYSTEM SVS
IMPURITY REMOVAL SYSTEM IRS
IMPURITY PROCESSING SYSTEM IPS
GAS DETRITIATION SYSTEM G-DS
EXHAUST PROCESSING VACUUM SYSTEM EPVS
ISOTOPE REBALANCING & PROTIUM REMOVAL IRPRS
ISOTOPE SEPARATION SYSTEM ISS (Economizers, compressors & equilibrators)
ISOTOPE SEPARATION SYSTEM ISS (Liquefiers and cryogenic distillation columns)
GAS COLLECTION & BUFFERING SYSTEM GCBS
DT+ FEED VESSEL DT+FV
COOLANT PURIFICATION SYSTEM WCPS
WCPS Distillation Column
COOLANT PURIFICATION SYSTEM HeCPS
TRITIUM CONDITIONING SYSTEM WTCS
TRITIUM CONDITIONING SYSTEM HTCS
DEUTERIUM STORAGE D2SS
DT STORAGE BEDS DTSB
DT SHUT-DOWN STORAGE BEDS DTSD
DT+ STORAGE BEDS DT+SS
3He EXTRACTION SYSTEM He3ExS
TRITIUM LONG TERM STORAGE BEDS
ACTIVE WATER STORAGE SYSTEM AWSS
OXYGEN STORAGE SYSTEM O2SS
OXYGEN DETRITIATION SYSTEM ODS
WATER DETRITIATION SYSTEM WDS (Electrolyzers, HE, etc.)
WATER DETRITIATION SYSTEM WDS (LPCE column)
HYDROGEN STORAGE SYSTEM H2SS
WATER DETRITIATION FEEDWATER TANKS WDFT
WATER DETRITIATION FEEDWATER PUMPS WDFT
SAFETY DETRITIATION SYSTEM ONCE THROUGH TRAIN X S-EDS-OT-X (HE, Reactors)
x8 (6+2) X: 1 to 8
NORMAL DETRITIATION SYSTEM ONCE THROUGH AND RECIRCULATION TRAIN X N-EDS-OT&R-X (HE, Reactors)
x3 (2+1) X: 1 to 3
NORMAL DETRITIATION SYSTEM ONCE THROUGH TRAIN X N-EDS-OT-X (HE, Reactors)
x6 (4+2) X: 1 to 6
S-EDS-OT-X (Wet Scrubber Column)
N-EDS-OT&R-X (Wet Scrubber Column)
N-EDS-OT-X (Wet Scrubber Column)
High Concentration Tritium Stream
Low Concentration Tritium Stream
Tritium Free Gaseous Stream
High Concentration Tritiated Water
Low Concentration Tritiated Water
Tritium Free Water
Inert Gas (Boxes Atmosphere)
Cooling Water (Cold)
Cooling Water (Hot)
He for Cooling (Cold)
He for Cooling (Hot)
Vacuum
Glove Box
Metal Box
Cold Box
INTL Equipment
OUTL Equipment
Outside Battery Limits
Master Thesis: A layout of the tritium plant subsystems for the European demonstration fusion power plant
Figure A-24 - TRITIUM PLANT BLOCK DIAGRAM
Karlsruhe Institute of Technology
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28.03.2023
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