SYSTEM ARCHITECTURE AND OPERATIONAL CONCEPT FOR PIECE (PIE CELLS AT ESS)

Y. LEE, M. GÖHRAN, P. ERTERIUS, L. ÅSTRÖM, M. HARTL
Target Division, European Spallation Source ERIC
Tunavägen 24, 223 63 Lund – Sweden

M. EVERETT
Science Division, European Spallation Source ERIC
Tunavägen 24, 223 63 Lund – Sweden

ABSTRACT

The European Spallation Source (ESS) will be the world's brightest neutron spallation source delivering more neutrons than the most powerful reactor-based source today. With the beam commissioning scheduled in 2019, it is our intent to plan for PIECE (**P**ost **I**rradiation **E**xamination **C**ells at **E**SS), a post irradiation examination facility at ESS. This facility will be dedicated to examining and characterizing structural components under high dose irradiation to enhance the operational reliability. It will also assist in investigating new materials that are of potential interest to ESS. Furthermore, it is of a fundamental need to understand the impact of radiation on various materials of scientific interests. The PIECE will include irradiation station, hot cells and handling equipment as well as the necessary infrastructure for chemical and physical characterization. This paper provides an overview of the PIECE system architecture and an operational concept, in relation to the ESS scientific research infrastructure.

1. Introduction

The European Spallation Source (ESS) will deliver the world's highest brightness of cold and thermal neutron beams for the basic and applied researches investigating the molecular building blocks of matter [1]. The spallation neutrons will be produced in the tungsten volume by a high energy (2 GeV) and high power (5 MW) proton beam. The spallation neutrons will be moderated to the thermal ($E < 0.625$ eV) and cold ($E < 0.025$ eV) energies before these are sent to the scientific equipment using neutron scattering.

A large fraction of spallation neutrons, thermal neutrons, scattered protons and secondary particles will be dumped to the neighbouring systems surrounding the target and moderators. The systems exposed to high dose of proton and neutron flux will suffer from radiation induced material degradation such as radiation damage, gas production, swelling, solid transmutations, etc. The extent of radiation damage sets the limits on the operational lifetime of the irradiated components. However, there is a scarcity of experimental data for the properties of proton and neutron irradiated materials in spallation environments. For this reason, the material selection and lifetime estimates of the systems in ESS target and accelerator environments are largely based on operational experiences of other high power spallation sources rather than on solid scientific understanding. The uncertainty in the radiation damage effects on materials necessitates a high level of conservatism in the component design lifetime and operation of the ESS target station, which should drive the operational costs upward. It is therefore reasonable to plan an onsite R&D infrastructure at ESS to understand the characteristics and behaviour of the engineering materials that are exposed to proton and neutron fluxes.

Furthermore, the spallation neutron provides a quasi-ideal energy spectrum for the fusion materials research. Recent study showed the feasibility of installing an irradiation module in the vicinity of the spallation target where the neutron spectrum closely simulates that of the fusion reactor. The module with the irradiation volume approximately of 0.1 litres will get a high dose of radiation damage up to 12 dpa/year in an iron specimen. The study shows the potential of an international collaboration on the fusion materials research using the PIECE facility.

In this paper, the scope, the top-level system architecture and the operational concept of the PIECE (PIE Cells at ESS) facility are presented. The PIECE system is broken down into the 6 subsystems according to allocated functionality. The top-level system architecture of the PIECE and the allocated specific functions are summarized in Table 1. Each of these subsystems is described in the following sections.

System	Allocated functions
Irradiation Station	Irradiate the materials at the ESS target station.
Process Cell	Take material samples from the irradiated materials.
Research Hot Cells	Scientifically investigate the activated PIE specimen.
Materials Characterisation Labs	Characterize radioactive and conventional materials.
Handling & Logistic Systems	Handle, transport and dispose radioactive materials.
Utility Systems	Enable the operation of PIECE.

Table 1: Top-level system architecture of the PIECE.

2. Irradiation station

At the ESS target station, the irradiated materials for the PIE can be obtained in two ways, from the irradiated system components and from the dedicated irradiation modules.

2.1 Irradiated system components

The material samples can be obtained from the used components after their lifetimes. These are the target wheel, the moderators, the reflectors, the proton beam window and other systems located in the vicinity to the spallation source. Figure 1 shows the system components at the ESS target station, which are under high dose of proton and neutron fluxes during operation.

The target vessel houses the spallation material and high-pressure helium coolant flow. It will be made of stainless steel alloy 316L, due to its high strength, superb corrosion resistance and known radiation records at other high power spallation sources [2]. The window part of the target vessel will receive the highest proton radiation dose from the impinging high-energy (2 GeV) protons, which will lead to the radiation damage 1.2 DPA per year [1]. The lifetime of the target wheel set for initial operation at ESS is 5 years.

The spallation material tungsten in the target wheel will receive a maximum of 0.9 DPA (displacement per atom) per year at 5 MW beam power [1]. The parts upstream of the tungsten target are largely subject to proton radiation damage, whereas the downstream region will get damages from a mixture of protons and spallation neutrons. The DBTT (ductile to brittle transition temperature) is expected to increase above the operational temperature 400 ^{o}C in tungsten after it receives the damage dose of 0.1 DPA. Therefore, it is fare to assume that the tungsten blocks will be in a brittle regime for the most of the target wheel operational lifetime of 5 years. As the pulsed beam structure induces a periodic thermal stress in the tungsten volume, it is important to keep structural integrity of the spallation volume during the lifetime of the target vessel, though tungsten doesn’t have a structural function.

The proton beam window separates the high vacuum region of the accelerator tunnel from the spallation region, which is surrounded by a sub-atmospheric pressure of helium gas. The window is made of aluminium alloy (6061-T6) and it is under direct proton beam irradiation. From the PIE of beam entrance window of the SINQ target and the operational experiences at PSI [3], the lifetime of the aluminium alloy proton beam window is limited by helium production rate. At 5 MW proton beam operation, the lifetime of the ESS proton beam window is set to be 2500 hours, until the produced helium content reaches 2000 appm.

The moderator and the reflector canisters will be made of aluminium alloy (6061-T6). The aluminium alloy canisters will receive damages mainly from the capture of thermal neutrons and the radiation damage from fast neutrons [4]. In the region subject to maximum fast neutron flux, the aluminium alloy will receive 28 DPA per year. The thermal neutron capture followed by beta decay and silicon precipitation hardening will increase the silicon contents by 0.85% in aluminium alloy per year. Operational experiences from other spallation sources suggest the moderator canister lifetime of one year, based on the estimates for the silicon transmutation rate and radiation damage.

The lifetimes of the systems under high proton and neutron dose are limited by PIE results and operational experiences at other high power spallation sources, which still leave a room for longer lifetime beyond the maximum dose level irradiated so far. With the commissioning of the PIECE followed by PIE activities, the initially set lifetimes could be extended, saving operational costs.

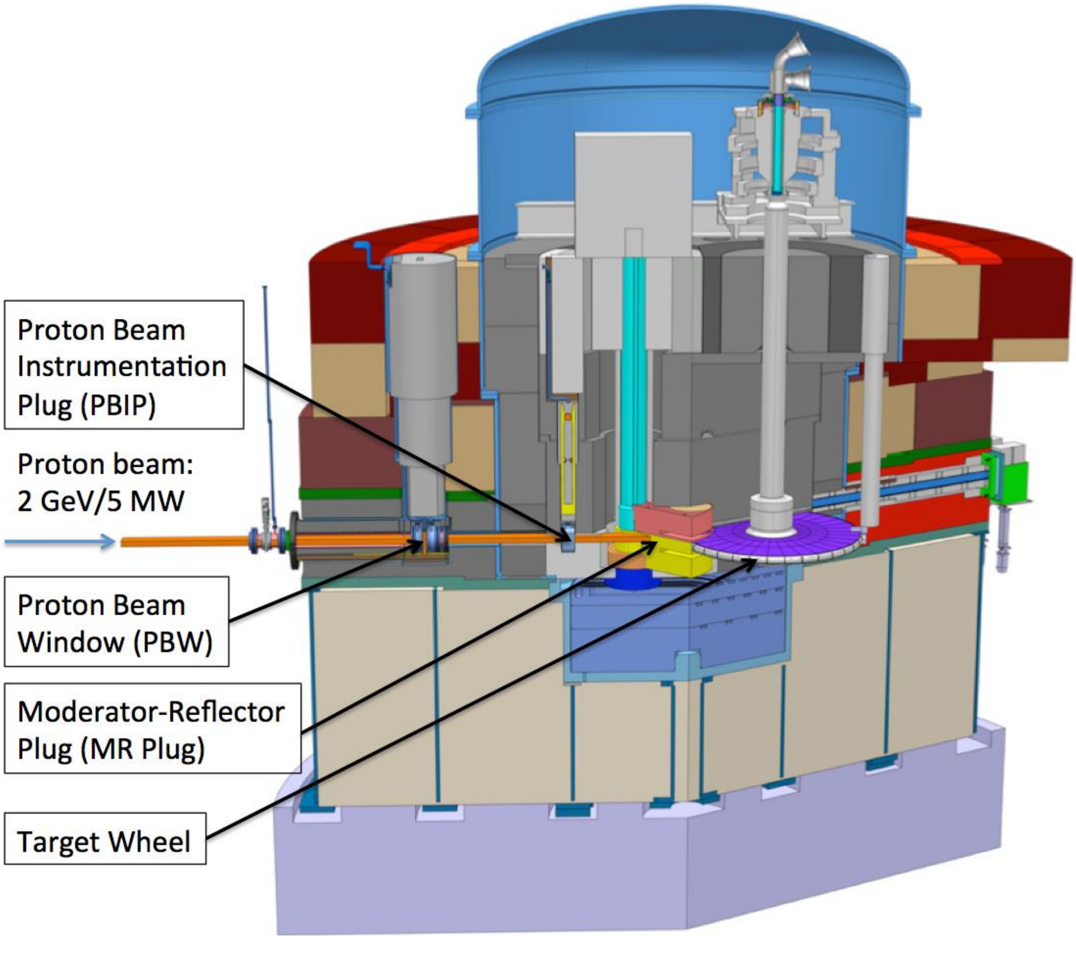

Figure 1: Target systems at ESS that receive high dose proton and neutron radiations.

2.2 Irradiation module

The PIE of the materials from the irradiated components will provide the information about the radiation damage for real operational conditions. Still, it is difficult to investigate the material properties of future candidate materials and other materials of scientific interest under well-defined irradiation conditions. Furthermore, the post treatment adaption of the already radioactive materials to precision test specimens involves handling complications.

The irradiation module is a dedicated system in which materials of interest are irradiated in well-defined conditions. The control parameters for irradiation include the irradiation temperature, and the neutron and proton fluence. The test specimens for the PIE tests can be machined and put into the module before the start of an irradiation campaign.

Three candidate locations surrounding the spallation target are currently under consideration for the installation of the irradiation module. The first one is in the beryllium reflector, which is under a large flux of thermal neutrons. The second one is in the target wheel, which receives a mixed flux of protons and neutrons. The third one is located near to the spallation hot spot, which is exposed to mainly to a large flux of high-energy neutron flux. This, in essence, simulates the radiation damage in fusion reactor environment.

Figure 2 shows a concept studied for a module, which receives mainly the back-scattered fast spallation neutrons from the target. The conceptual design of the irradiation module will be presented at ICFRM-17 in October 2015.

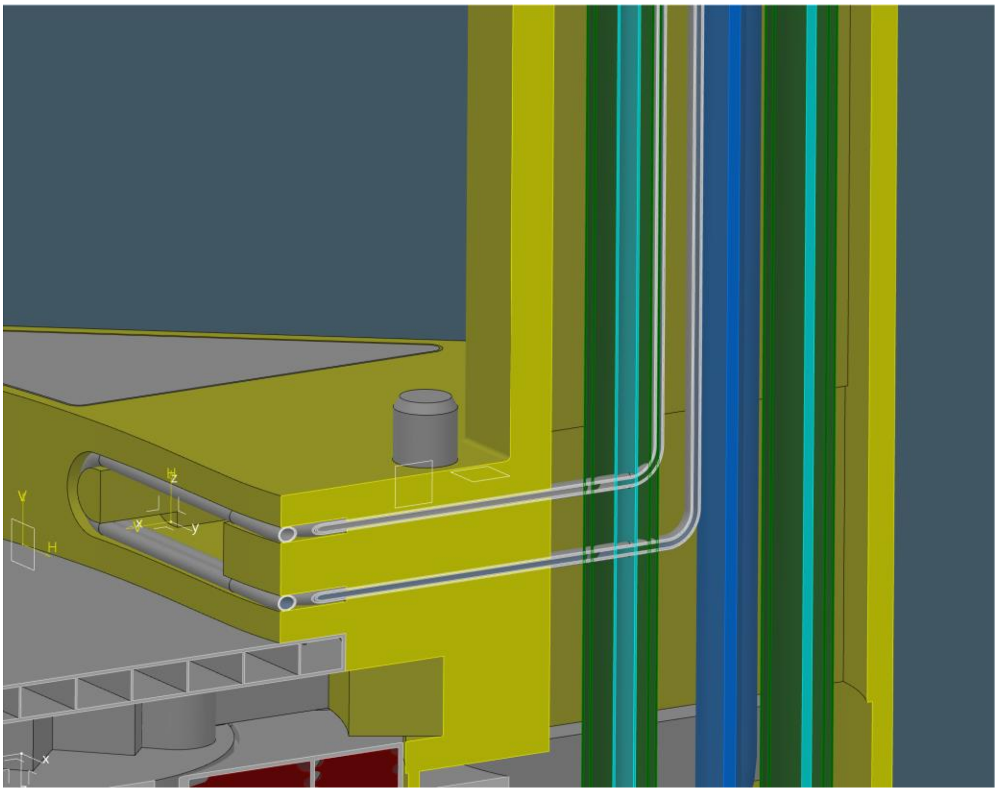

Figure 2: A conceptual visualisation of an irradiation module that is located at the beam upstream region of the target. It receives a high dose of back-scattered fast neutrons from the spallation target, which can be used for fusion materials research.

3. Process cell

The process cell is more than just a subsystem of PIECE. It is a level-4 subsystem in the ESS global system architecture. The process cell fulfills the global functions, which is mainly dedicated to receive radioactive components from the target station, process the components for the intermediate storage, external shipment and refurbishments. The process cell will be equipped with cutting devices that are used to cut big system components like the target wheel into smaller pieces, in order to make it fit to the standard transport casks for final disposal. The cutting devices will be used to fulfill a PIECE requirement, which is dedicated to cutting irradiated components from the operated systems or by extracting samples from the irradiation module. Figure 3 shows the top view of the process cell.

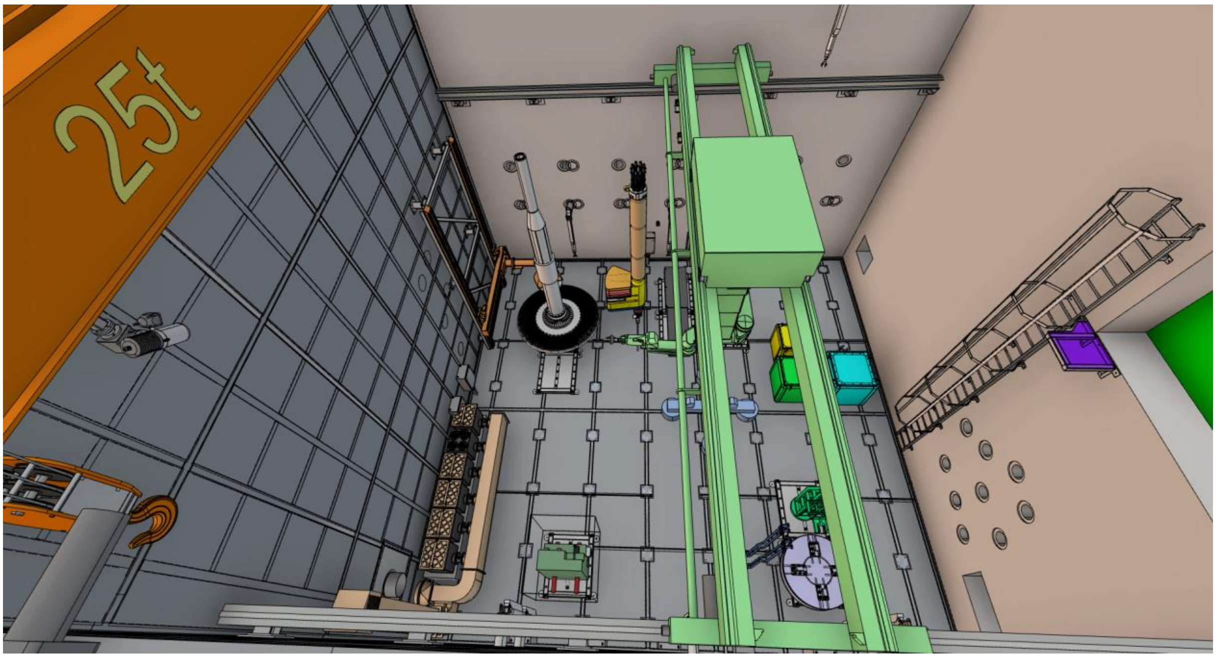

Figure 3: A top view of the process cell, which will be equipped with a wall mounted saw and a milling machine.

The acquired sample materials will be transported to the neighboring sample preparation cell through a two-way transfer port. The dimension of the two-way transfer port and the allowed total dose to workers limit the size of the test materials from the process cell. A conceptual illustration of the two-way transport port is shown in Figure 4.

A requirement that the two way transfer port must satisfy is that it shall not break the shielding between the process cell and the sample preparation cell, while the sample material is being transported between the two cells.

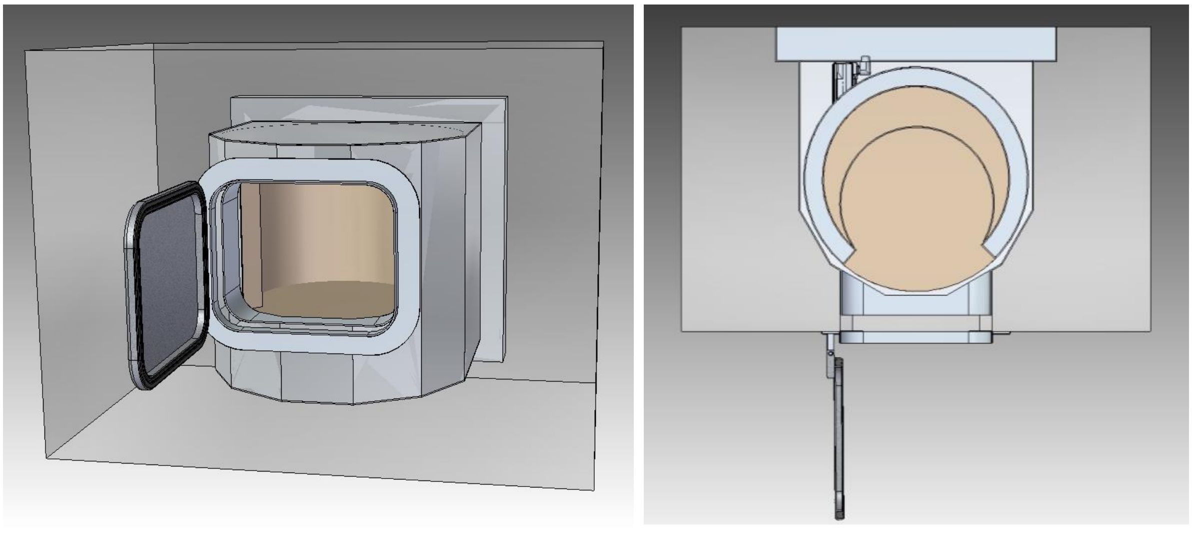

Figure 4: A conceptual illustration of a two-way transfer port from the process cell to the sample preparation cell.

4. Research Hot Cells

In the research hot cells, the radioactive test specimens are prepared for the mechanical and thermal tests, and the PIE of the prepared specimens are carried out to produce scientific data. All these operations will be performed in a shielded environment using remote handling devices. The research hot cells consist of three shielded cells, a sample preparation cell, a mechanical test cell and a thermal test cell, occupying a floor area of 26 square meters with enhanced floor loading capacity. The available floor area inside the shielding walls is approximately 22 square meters, with 2.75 meters in depth. Each of the three cells is equipped with a master-slave manipulator and a lead glass window with 18 inches in diagonal.

A data monitoring and analysis lab supplements the research hot cells, which will be located in the technical gallery of the active cell system. The measurement data from the test equipment in the research cells will be processed and analyzed in the data monitoring and analysis lab.

Figure 5: Top view of research hot cells and its integration to the active cell system, where three subsystems, the process cell, the storage pits and the transfer zone of the active cell system are shown.

4.1 Sample preparation cell

A range of specimen geometries will be machined into precision test samples as required for destructive and non-destructive PIEs. As the radioactivity and the contamination level of the raw materials from the process cell will be high, the sample preparation cells must be shielded and equipped with remote handling devices.

In order to lower the total activation level of the sample specimens, the PIE specimens must be made as small as possible, while keeping the bulk material characteristics.

The sample preparation cell is located next to the process cell, receiving test materials through the two-way transfer port. The cell will be equipped with an EDM (electrical discharge machining) machine to make precision PIE specimens. Ultrasonic cleaner and surface grinder will clean and polish the test samples. Before and during the operation modes, the activity of the samples must be monitored and contamination must be contained.

There is a hatch on the top with an opening of 1.1 meter in width and 1.1 meter in length. This top hatch will be used for lowering down and towing up of the needed equipment to and from the sample preparation cell.

4.2 Mechanical test cell

The mechanical test cell is located between the sample preparation cell and the thermal test cell. It is connected to the neighbouring cells via two-way transfer ports.

It will receive the prepared mechanical test specimens from the sample preparation cell. The standard tests to be performed in the mechanical test cell include tensile tests, compression tests, fracture toughness tests and fatigue tests. Also, the shear punch tests and the ball punch tests will be performed. These tests are to be performed at different temperatures, and all the test equipment shall be furnace compatible.

As for the sample preparation cell, there is a hatch on the top with an opening of 1.1 meter in width and 1.1 meter in length, for lowering down and towing up of the needed equipment to and from the mechanical test cell.

4.3 Thermal test cell

The thermal test cell is a shielded cell equipped with devices measuring thermal properties. Similar to the other cells mentioned above, there is a hatch on the top with an opening of 1.1 meter in width and 1.1 meter in length, for lowering down and towing up of the needed equipment to and from the mechanical test cell.

The thermal test cell houses a laser flash equipment for the thermal diffusivity measurement of irradiated materials. It is also equipped with a differential scanning calorimeter for the specific heat capacity measurement and a dilatometer for the thermal expansion coefficient measurements.

4.4 Semi hot cells

In addition to the heavily shielded hot cells presented above, there are four semi hot cells that will be built in the technical gallery area. The shielding walls will be made of steel with a thickness of 20 cm. These cells will be used for the research of medium and low dose radioactive materials. As other research hot cells, the light hot cells also will be equipped with master-slave manipulators and lead glass windows.

5. Materials characterisation lab

The materials characterisation lab is dedicated to the characterization of pre- and post-irradiated samples. This lab is equipped to handle moderately radioactive and conventional materials, but contamination must be controlled and limited. This lab will be equipped with a scanning electron microscope (SEM) and a transmission electron microscope (TEM) for the microstructure analysis of the material. Furthermore, there will be an X-ray diffractometer for crystal structure analysis and phase identification and an X-ray fluorescence spectrometer for elemental analysis. For polymers, we will have a device determining molecular weight, and stress and strain.

The function of the Materials characterisation lab will be supplemented by the radioactive materials lab, which is planned as a part of ESS science infrastructure. There will be a gamma spectrometer in the radioactive materials laboratory for identifying the nuclides contained in the activated materials. The radioactive materials laboratory is designed to handle radioactive samples. It will allow for chemical elemental analysis and sample preparation for the measurements in the materials characterisation lab.

The labs can be reached from the experimental halls, a supervised zone that connects the target labs with the material characterization and radioactive materials lab. This allows for reasonably fast and uncomplicated transfer between those zones.

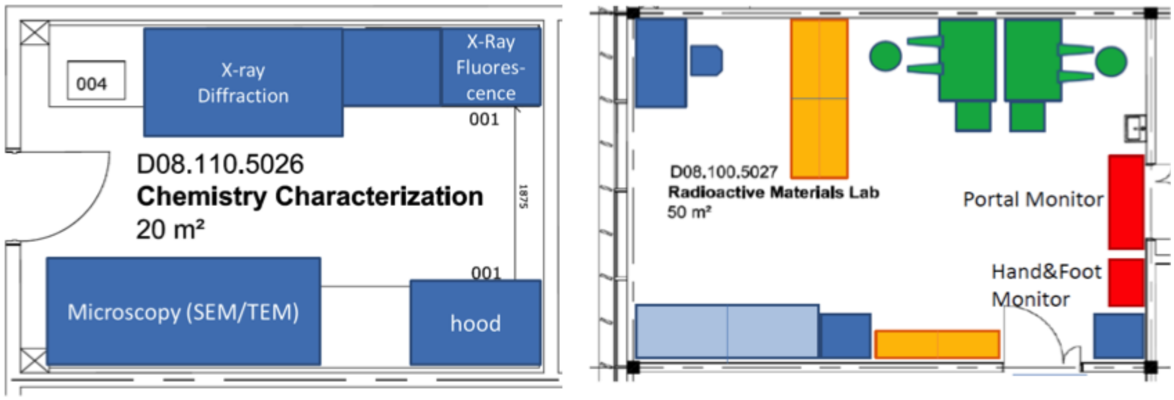

Figure 6: Schematics of the Materials Characterisation Lab.

6. Handling and logistics systems

The handling and logistic system includes the transport canisters, transport carts, manipulators and storage containers. The radioactive PIE specimens will be transported in a certified canister, within the area confined by the target building, instrumental halls and laboratories in the science building. The functionality of intermediate storage and the final waste release will be provided by the existing active cells system of the target station.

7. Utility systems

The utility systems include ventilation system, power supply, water supply and the monitoring systems. It enables the operation of the PIECE.

8. Concept of operation

Below is a brief description of an operational concept of PIECE.

1. Irradiation campaign program is announced and a call for proposals is open.
2. The submitted proposals are evaluated and the beam time for selected projects is granted. Requirements for processing of the irradiated materials and waste disposal are clarified before the experiment.
3. The irradiation station is prepared for the irradiation campaign:
    a. The irradiation module is designed, fabricated and installed.
    b. The system components subject to PIE are installed.
4. The materials are irradiated.
5. The irradiated materials are transported to the process cell:
    a. The irradiation module is transported in a shielded canister to the process cell.

    b. The used components at the end of lifetime are transported to the process cell in a dedicated cask.
6. Sample materials are extracted in the process cell:
    a. Irradiated specimens are extracted from the irradiation module.
    b. A piece of material is cut out from the used component.
7. The sample materials are transported to the sample preparation cell in a canister, via two-way transfer port.
8. Measure the dose of the sample material in the sample preparation cell, and identify appropriate handling rules according to facility safety guidelines.
9. Clean and polish the sample, and cut the sample into test specimens.
    a. Vent out and purify the sample preparation cell atmosphere during operation.
    b. Confine/clean the contamination and dispose radioactive liquid and wastes obeying facility safety guidelines.
10. Transport the prepared test specimens to test cells and materials characterization labs, for mechanical, thermal, and microstructure tests, and chemical analyses.
11. Perform post irradiation examinations (PIE).
    a. Vent out and purify the test cell atmosphere during operation.
    b. Confine/clean the contamination and dispose radioactive liquid and wastes obeying facility safety guidelines.
12. Keep the used test specimens in a regulated mini-container and transfer it to the storage cell. After an appropriate cooling time, dispose the used specimens as wastes.

9. Current project status and conclusion

Not all the features of the PIECE system are included in the scope of ESS construction project, and different PIECE subsystems are in different project status as is described below.

- Conceptual design of the irradiation module is under way. Some of the module options will be realized during the construction phase of the ESS project.
- Process cell is subject to PDR in 2015, and full scope of it will be realized in 2019.
- The floor loading and a plugged in feed-through for the two-way transfer port from the process cell to the sample preparation cell will be ready by 2019.
- The space allocation and floor loading for the heavy shielded research hot cells will be ready with the completion of the target project.
- Enhanced floor loading for additional 4 lighter hot cells is planned for the floor area of 20 square meters in the technical gallery.
- The lab spaces are allocated in the science building for the material characterization labs as a part of the ESS research infrastructure plan.

During construction phase of the ESS project, which ends in 2019, the conceptual design of the PIECE facility will be continued, together with cost estimates. A project proposal will be made in 2020, at the start of the operational phase of the ESS project.

10. References

[1] S. Peggs, editor, “ESS Technical Design Report,” ISBN 978-91-980173-2-8, 2013.
[2] S. Saito, K. Kikuchi, K. Usami, A. Ishikawa, Y. Nishino, M. Kawai, and Y. Dai, “Tensile properties of austenitic stainless steels irradiated at SINQ target 3,” Journal of Nuclear Materials, 343:253-261, 2005.
[3] Y. Dai and D. Hamaguchi, “Mechanical properties and microstructure of AlMg3 irradiated in SINQ target-3,” Journal of Nuclear Materials, 343:184-190, 2005.
[4] K. Farrell, “Materials selection for the HFIR cold neutron source,” Technical Report ORNL/TM-99-208, ORNL, 1999.