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Development of the Personnel Safety System for the ESS

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Abstract. The 5 MW European Spallation Source (ESS), scheduled to begin operations in 2019, will be the brightest source of spallation neutrons as yet built. High-energy neutrons are produced when the 2 GeV proton beam from the ~600 m long linear accelerator interacts with a rotating tungsten target wheel contained within the target monolith. These fast neutrons are slowed down by the target moderators and reflector systems to suitable energies for experiments and then delivered to over 20 different instruments through beam ports. At such a facility, safe operations is of utmost importance, and, as such, requires the implementation of several layers of control and safety systems. At the ESS, a comprehensive control system will be implemented throughout the facility, including the accelerator, target, and neutron-scattering instruments. This integrated control system (ICS) will bring together all segments of the machine into a unified structure. The Personnel Safety System (PSS) is one of the core systems of ICS, along with the Machine Protection System (MPS) and timing system. The PSS is an active safety system that protects workers from radiation, both prompt and residual, stemming from operation of the proton accelerator. Protection is achieved by controlling access to restricted areas, interrupting beam operation upon the detection of non-nominal conditions, and generating alarms via area radiation monitors being interlocked to the proton beam source. The system is segmented to facilitate configuration control, support multiple operational modes, and address the specific needs of the accelerator, target, and instrument areas. This paper will describe the development of the PSS, including the definition of requirements, functional specification for each segment, and evaluation of interfaces with other ESS systems.

1. Integrated Control System Scope

The Integrated Control System (ICS) at ESS is the control system to monitor and control the proton Accelerator, Target Station Systems, Neutron Instruments and Conventional Facility infrastructures. ICS will be based on the EPICS control system framework. While the ICS itself is not a safety critical system, the ICS organization is also responsible for delivering to the facility not only the personnel safety systems (PSS) but also systems related to oxygen deficiency hazards (ODH) and area radiation monitoring interlocked to the beam (ARM), and these systems will be safety qualified.

To understand why ICS has been selected to develop the PSS at ESS some context for the decision is required. ESS is a green field laboratory whose purpose is neutron spallation based material research. The ESS, an accelerator driven neutron source with an average proton beam power of 5 MW is currently under construction in Lund, Sweden and is aiming to be the world's brightest neutron source by the end of the decade. First spallation neutrons should be available in late 2019. An organization being built literally from the ground up such as ESS cannot have the Environmental, Safety and Health (ESH) personnel in place from early on, providing either the technical requirements for personnel safety relative to prompt radiation or the technical means to implement a design to meet such requirements. The ICS organization, on the other hand, will provide integrated control systems for the whole facility, and will have the technical means to implement systems ensuring safe access as well as providing the processes necessary to enforce safe practices during entry to the technical facilities such as the accelerator tunnel, target station systems and neutron instruments. Controls organizations such as at SNS, Oak Ridge Laboratory/USA have previously had this same responsibility so there is precedence for the ICS organization at ESS to provide the personnel safety systems. However, there are areas related to personnel and public safety for which ICS should not be responsible, and so a scope definition for ICS personnel safety systems is required.

The budget and schedule to deliver that scope will be proposed to ESS management in early 2015. A team is being hired composed of four engineers and technicians and ICS expects to have completed this recruitment by early 2015. Then the work of designing, manufacturing, installing and commissioning the PSS at ESS will proceed as quickly as possible given that these systems need to be in place very early during ESS installation and commissioning phases as well as at various test stands to be built on site.

2. Scope and Requirements for the Personnel Safety System

The scope of the personnel safety systems for ICS has been identified and approved and will cover the following systems:

- Accelerator personnel safety system.
- Accelerator oxygen depletion system.
- Accelerator radiation monitoring system.
- Accelerator Test Stand personnel safety system.
- Target personnel safety system.
- Target radiation monitoring system.
- Target maintenance cell personnel safety system.
- Neutron Instrument (LOKI) personnel safety system.
- Neutron Instrument (ODIN) personnel safety system.
- Neutron Instrument (NMX) personnel safety system.
- As soon as the initial design of new neutron instruments begins a new personnel safety system will be required. In total there will be 22 neutron instruments.

From the above list there are three critical areas within the facility, which will protect personnel from exposure to prompt radiation arising from operations of the proton accelerator and to protect from oxygen deficiency hazards and finally to generate beam inter-locked alarms from radiation that might exist in restricted technical areas of the facility.

3. PSS (Personnel Safety System related to access)

The ESS Personnel Safety System (PSS) will be designed, manufactured, installed and commissioned in accordance with IEC 61508 [1].

IEC 61508 is an international standard concerned with functional safety achieved by safety related systems that are primarily implemented in Electrical / Electronic and/or Programmable Electronic technologies (E/E/PE). The PSS is an example of this and falls within the scope of IEC 61508. This standard provides an overall safety lifecycle structure for functional safety systems as detailed in figure 1.

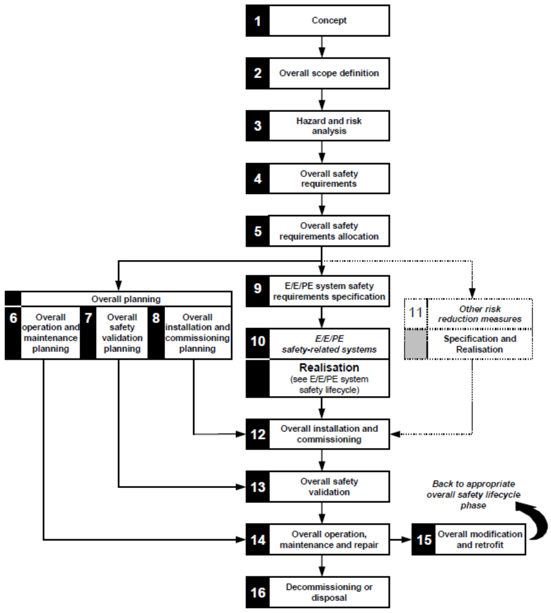

Figure 1. IEC 61508 Safety Lifecycle

To be able to complete the overall safety requirements, a Hazard and Risk Analysis must be undertaken for the ESS Accelerator, Target station and subsequent Neutron Instruments. This will be completed in conjunction with the personnel who are aware of all the hazards within each part of the facility.

A decision can then be made on the risks that the PSS will have to reduce, and a safety requirements allocation can be formulated.

To be able to calculate the safety integrity level (SIL) that the PSS will be designed to, all other risk reduction methods must be understood. Their level of risk reduction to the overall safety system can then be calculated. These external risk reduction methods could include but are not limited to:

- Human factors.
- Radiation shielding.
- External non-electrical signs.
- Training.

A detailed quantitative risk analysis using appropriate methods will be carried out, and this will enable the calculation of SIL's for each part of the PSS. The system will then be designed to the appropriate SIL.

The PSS is also governed by the Stral Sakerhets Myndigheten (SSM) (The Swedish Radiation Safety Authority) rules on ionizing radiation and will also operate within the ESS safety framework. The maximum tolerable risk level will be 10^{-6} or at H4 level in the SSM terminology.

The PSS design for the accelerator is in its infancy. Here are the basic principles of the system. The PSS system will be designed using Safety PLC's, Safety relays and also using a trapped key philosophy. The Safety PLC and hardware manufacturer has not yet been appointed.

The function of the ESS PSS is to prevent personnel remaining in or entering the Accelerator, Target or Neutron instruments when hazardous conditions exist. This will be achieved by means of physical searches supervised by a safety controller, access controlled by mechanical interlocks and the facility to request an ESS beam trip or exit the associated areas in the event that a potentially hazardous situation arises. Accordingly, the PSS will be made up of 3 major sub-systems, which are described in more detail for the accelerator in the following:

Sub-System 1 (Safety Controller + I/O): A Safety Controller will monitor and control all safety related devices in and associated with the ESS Accelerator. The Safety Controller will facilitate and monitor the status of the accelerator search sequences. These searches ensure that no personnel remained in the areas of the accelerator tunnel or in other associated PSS controlled areas under search; and when complete the safety controller will release the trapped keys on the corresponding doors to allow locking of these doors. The Safety Controller will also monitor the safety devices and trigger a stop of beam operation if hazardous conditions exist and the access gates to the accelerator are opened. The Safety Controller will also provide information on system status and other visual/audio status indications. The Safety Controller will interface with the system via I/O Safety Modules.

Sub-System 2 (Trapped Key Units): A variety of trapped key devices will ensure that if hazardous conditions exist the gates which provide access into the PSS controlled areas and any protective removable shielding cannot be unlocked and various key-controlled permits cannot be issued.

Sub-System 3 (ESS Beam Trip): The system will provide a means for either authorised workers working in the tunnel or Sub-System 1 to request an ESS Beam Trip at any time. A permit is to be continuously issued from the PSS during normal operating conditions. Removing this permit constitutes requesting an ESS Beam Trip. An ESS Beam Trip will be requested if a Beam Off Button (BOB) is pressed or the Safety Controller issues an ESS Beam Trip signal.

There will be two main access entrances into the accelerator tunnel. Entrance 1 is at the front end near to the proton source. This will be the main access. Entrance 2 will be at the transition between the high beta elliptical cavities and the HEBT (see figure 3). Personnel will enter a PSS controlled area via an entry station. Each entry station will have two gates to ensure that personnel only enter the area when conditions are safe (a third door is provided for emergency egress only). A diagram of an entry station is shown in Figure 2. A swipe card system will be installed to ensure only authorised and fully trained staff can enter the tunnel.

A Public address system will also announce the status of the PSS system to personnel whilst in the tunnel.

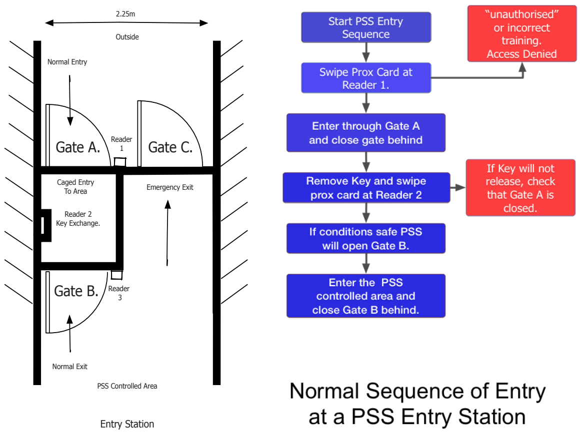

Figure 2. Entry Station

The accelerator will be divided into seven separate zones see figure 3 for the accelerator tunnel zones:

Table 1. Accelerator Tunnel Zones

Zone	Equipment in each zone	Zone Length (metres)
1	Proton source and low energy beam transport (LEBT), Radio frequency quadrupole (RFQ) and Medium energy beam transport (MEBT).	30
2	Drift tube linac (DTL).	23
3	Spoke Resonators	55
4	Medium energy Beta cavities	77
5	High energy Beta cavities	179
6	High energy beam transport (HEBT)	139
7	Accelerator to Target (A2T)	100

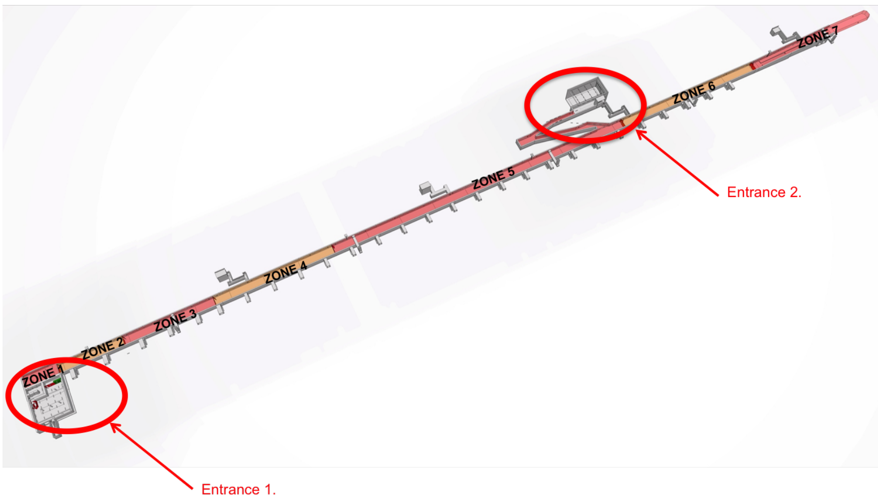

Figure 3. Accelerator Entrances and Tunnel Zones

A fenced gate will separate each of the seven zones allowing for independent search areas. Zones 1 to 4 will be searched from Entrance 1, and Zone's 5, 6 and 7 will be searched from Entrance 2. This will produce the most efficient way to service and search the tunnel.

Search and beam off stations will be placed between 10 and 20 metres apart along the full length of the tunnel.

4. Oxygen Deficiency Hazard (ODH)

The ESS will use superconducting technology for the majority of the LINAC sections in the accelerator. The cryogenic system will have a total inventory of approximately 2,000 kg of liquid helium in the accelerator tunnel at a temperature of 2 K. Such a large amount of helium inventory in the 600 m long tunnel could create a serious hazard to personnel in the event of a release. In order to mitigate these hazards a risk analysis will be performed to identify protective features including fixed alarms, emergency exhaust fans and special work control procedures for certain operations. The risk analysis will be part of the design lifecycle for a permanent mitigation system that will be designated the Oxygen Deficiency Hazard (ODH) system. While several systems will be required for the facility the following only addresses the system provided for the accelerator tunnel.

4.1 *Design Lifecycle*

The ODH system will be provided by the Protection Systems group in ICS that is also responsible for the PSS. While both systems will be designated as safety critical systems there is a basic difference between the ODH system and the PSS. The PSS can terminate beam operation and RF production to totally eliminate the hazard arising from prompt radiation; the ODH system can only detect and mitigate the hazardous condition by alarming personnel and/or triggering a ventilation system. In this sense the ODH system is similar to fire and gas detection systems found in industry. The design lifecycle is similar to that used by the PSS, but the results of the risk assessment are used to identify mitigation strategies.

The results of the unmitigated risk assessment will be used to define work control processes, personnel protective equipment requirements and the ODH system risk reduction requirements including safety functions and reliability. When the design is complete, a mitigated risk assessment will be performed to ensure that risk reduction targets have been met, and the risks from the cryogenic systems are acceptable.

Excellent work has been performed at CERN, the European Organization for Nuclear Research, Geneva/Switzerland, in this area, and ESS intends to use their work as a basis for the analysis that will be performed at ESS.

4.2 *Tunnel ODH System*

Certain features are planned for the ODH system for the tunnel. Three basic functions are planned:

- Detection
- Area alarms
- Passive or active ventilation

The ODH system will be controlled by a logic solver that will tie together these functions and also provide information to operator displays.

4.2.1 *Detection*. Releases of inert gases are normally detected by monitoring the oxygen level inside the enclosure. A normal oxygen level is 20.9% by volume. Levels below 19.5% generally require a response, but physiological effects on healthy persons are minimal at oxygen concentrations above 18% (near sea level).

Oxygen concentration can be detected via several different methods but measurements can be perturbed by the presence of helium in the gas mixture. Electrochemical cells have typically been used but special sensors are required when helium is present in the gas mixture. When using this type of sensor the instrument output is based on the partial pressure of oxygen. The indicated oxygen level can vary based on atmospheric pressure and humidity. As the normal alarm setpoint of 19.5% oxygen is very close to the normal value of 20.9% changes in atmospheric conditions as well as instrument drift can result in false alarms.

Ionizing radiation inside the accelerator enclosure will damage electronic components. Since oxygen detection devices generally have electronics associated with the sensor unit this precludes the use of in-situ oxygen sensors in the tunnel. One solution would consist of a remotely mounted sensor/ electronics package with a flow pump to extract an air sample from the tunnel.

A system under investigation is an oxygen deficiency monitor as manufactured by Oxigraf Inc.[2] The sensor uses laser diode technology to monitor oxygen levels that is not affected by helium or atmospheric conditions and does not require periodic replacement. The unit can be supplied with a high flow sample pump that can obtain a sample measure in 15 to 20 seconds using 30 m of sample tubing. Each unit can be used to sample four different locations.

An important question concerning the sensor placement is the required speed of response. In addition to flow sampling lag discussed above there will be a delay in the response of the system based on the location of the sensor versus the location of the release. Wider sensor spacing will result in slower response times since on average it will take longer for the helium to migrate from the release point to the nearest sensor.

4.2.2 *Area Alarms*. The ODH system will provide audio/ visual evacuation alarms similar to a fire alarm system. These alarms will be used to evacuate workers from the accelerator tunnel in the event of a release. The visual alarms will use a unique color and will be provided along the entire length of the tunnel. The locations of the visual alarms will be coordinated with PSS HMI panels. Visual alarms will also be provided at each tunnel entrance to warn workers that an ODH condition exists inside the tunnel. A “system OK” light will also be provided at each entrance so workers can determine if the ODH system is operating properly prior to entry.

The tunnel audible alarm inside the tunnel will be provided by the PSS/ ODH public address system. The alerting tone provided by the loudspeaker system will be unique to the ODH system.

4.2.3 *Passive or Active Ventilation*. Conventional Facilities (CF) will provide a smoke removal system consisting of five exhaust fans with a capacity of 5 m^3/s each. Each fan is tied to a duct leading down to the tunnel ceiling. A smoke curtain is installed in the tunnel at the entrance of each duct to restrict smoke migration from one area to another. Automatic dampers will be installed on the tunnel ceiling to prevent air from being exhausted from the tunnel when the proton beam is operating.

The ODH system will be designed to directly control the ceiling mounted dampers independently of the CF control system. As the smoke removal fans will not have backdraft dampers helium can be passively vented outside the tunnel in the event of a release. The ODH system will monitor the damper positions both open and closed and (in conjunction with the PSS) will not allow entry into the tunnel unless the dampers are open.

Depending on the results from the risk analysis, the ODH may also directly control the smoke exhaust and makeup air fans to provide active ventilation of the tunnel during a helium release.

4.2.4 *Logic Solver*. The ODH system will use a safety PLC based logic solver separate from other systems such as the PSS. The logic solver will monitor the status of each oxygen monitor, activate alarms and activate the exhaust fans and dampers. The logic solver will use distributed input/ output devices communicating with the PLC via the PSS safety Ethernet network. The logic solver will be integrated with EPICS via a secure firewall to allow remote status display and archiving of system data.

5. Area Radiation Monitoring (ARM)

There will be radiation monitors placed in appropriate positions through the accelerator klystron gallery (actual positions still to be determined)/not in the tunnel as well???. These devices will constantly monitor and record radiation levels and will trigger a stop of beam operation if excessive levels are measured and pre-defined thresholds are exceeded. Figure 4 shows the approximate radiation monitor positions. These will mainly be located at the entrance to the-stubs in the Klystron Gallery and at the Accelerator tunnel main entrances and emergency exits.

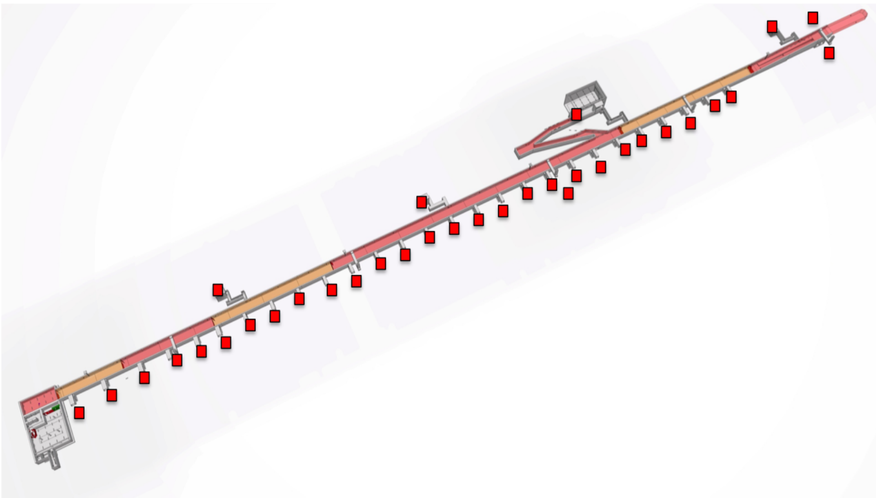

Figure 4 Approximate radiation monitor positions

6. Conclusions

It should be noted that the scope and strategy for each of the ESS Personnel Safety Systems have now been outlined and approved, and whilst the design is in the very early stages the philosophy will remain the same even if the overall design changes.

References

[1] IEC 61508, parts 1-7: 2010, *Functional safety of electrical / electronic / programmable electronic safety-related systems,* Switzerland: Geneva, International Electrochemical Commission, 2010.
[2] Oxigraf, Inc., 1170 Terra Bella Ave. Mountain View, CA 94043.