Document Type	Requirement Specification
Document Number	ESS-0287373
Date	Dec 10, 2018
Revision	1
State	Released
Confidentiality Level	Internal
Page	1 (10)

Postulated TSS limits including timing

	Name	**Role/Title**
Owner	Per Nilsson	CFD Specialist
Reviewer	Emil Lundh Kristoffer Sjögreen Jens Harborn Mikael Olsson	Simulation Engineer Work Unit Leader Target Wheel, Drive and Shaft Work Unit Leader Target Helium Cooling Control Engineer Target Controls and Safety
Approver	Linda Coney	Group Leader Target Controls and Safety

TABLE OF CONTENT PAGE

1. SCOPE

The Target Safety System, TSS, turns the proton beam off in events which would lead to unacceptable radiological consequences to the public from the target if it was kept on. This is done independently based on the magnitude of five different quantities:

- target helium mass flow rate
- target helium system pressure
- target helium inlet temperature
- wheel rotation speed,
- monolith vessel pressure

Most of this document is about the three quantities in the helium cooling system. (The rotational speed and monolith pressure are treated in separate sections, 6 and 7.) The term "operating space" here refers to the combinations of the three operating parameters in the helium cooling system. A number of corner points of the TSS operating space are discussed based on limits in terms of the following quantities: target wheel helium mass flow rate, outlet pressure and inlet temperature. (It is strictly not a volume but an eighth of an infinite space, as the TSS is only limiting on one direction of the three quantities. The other boundaries are set by other limitations by other systems or what is physically possible.)

The purpose is to specify TSS trip limits including timing and serve as input for detailed studies, e.g. simulations and measurement assessment that can confirm and fixate those limits. I.e., confirmation of the sufficiency and appropriateness of the limits is not provided here.

Ideally, the limits should be derived based on combinations of all requirements. One requirement it that structural design conditions shall be respected, another is that the inadvertent safety stops should be minimized for availability and yet another that the setpoints of the control, protection and safety systems should have sufficient margin. That is however not straightforward, because there is a multitude of complicated and sometimes contradictory requirements (as described in section 3 below). Therefore, a set of points is chosen here based on rough estimates of the requirements. Then each limiting point shall be checked to confirm that the spanned TSS volume is appropriate.

One specific point, the combination of minimum flow rate, minimum pressure and maximum temperature, corresponds to the most severe corner. From there, changes in each variable at a time can be investigated. This is to provide data for further improvements and to confirm the monotonous behavior of the loads and consequences at these variations.

The limits are applicable for maximum beam power and starting from conditions within the possible operational space. The possible operational space may include more than the nominal, e.g. up to MPS limits. The facility should however also be possible to operate a limited power with the same limits.

2. PROCESS

This is a description of the steps required to verify the safety limits including timing for each of the five quantities. If the limits are not possible to meet, changes are required.

Deciding on the corner point coordinates may be an iterative process for each point:

1) The steady state conditions of the wheel are calculated.

   The first quantity to be checked is the maximum tungsten temperature. If that is limited below 700 C, many accident consequences are ruled out.

   The second check is whether the structural integrity of the wheel is verified, or could possibly be verified at the corner point:
   a) When the conditions are better than the conditions at which the component has been verified, the component is considered available for the safety function. That is if the temperature and pressure are lower than what is used in the design calculations the component is available. (It may be noted that a low pressure is a lower load for the vessel, whereas a high pressure gives a better cooling.)
   b) If the conditions (e.g. temperature) are worse than what has been verified, but are within what is possible to analyze, verification is possible and the component is considered possibly available for the safety function.
   c) Otherwise the verification is not possible and other systems have to carry any required safety function.

   It should be noted that the design limits depend on the operating condition (SF2 - SF4 in RCC-MRx), which in turn depends on the event class (H2 - H4).

2) The mitigated accident analysis sequence is revisited including:

   a) What safety functions are available.
   b) The timing of the detection and beam stop is included.
   c) The consequences of this specific development, compared to the acceptable.

3) If there are problems in any of the above, either the safety function choices or the limit values are changed and a new test is made for the affected points.
   If that is not possible, it may be required to cut the corner (as will be detailed below) and introduce new points based on the physically possible processes.

As the basis for a safety group system, all analyses will have to be verified accordingly.

The possibility to operate the system with high availability within the different points should also be verified, see comments below.

3. REQUIREMENTS

3.1. Safety consequences

The beam shall be turned off at the limiting values of rotational speed, monolith vessel pressure, minimum helium flow rate, minimum helium outlet pressure and maximum inlet temperature to prevent a development to unacceptable radiological consequences. The development of the scenario, the consequences in terms of dose and the chosen mitigations are described in the accident analyses (AA).

3.2. Availability

The operational volume lies within the machine protection volume. This in turn lies within the TSS volume. For availability, the operational volume should be as large as possible.

3.3. Virtual corners and cutting corners

Some combinations of the quantities may not even be possible to achieve due to physical limits of the systems. That may e.g. be that the compressor will not deliver the flow at a too low pressure or work at a too high temperature. The corner points are used here anyway though, in order to define simple limits for the safety systems, that are without combinations of quantities. The alternative would be to cut the corner of the box, possibly adding three additional corner points to analyze.

3.4. Timing

There is a timing requirement; the beam has to be stopped at a certain time to provide a sufficient safety function. That includes several steps of consideration:

a. It takes time to detect a change in a quantity and generate a signal. This time may be long if there is e.g. thermal inertia in the measurement equipment.
b. After receiving the signal, it takes some time to turn off the beam.
c. Even if the beam is stopped, the event may continue to evolve. Therefore, the steady state conditions are analyzed for the system. It means that the state of the system is calculated with a constant set of the three quantities.

This means that for each point:

1. The steady state conditions shall be possible to maintain with acceptable radiological consequences, this can e.g. include a verified structural integrity or temperature of a barrier in steady state (c).
2. There shall be sufficient time for detection (a) and beam stop (b) functions.

3.5. Uncertainty

The numbers given here are the limits of the quantities. Margins due to uncertainty has to be added to give the setpoints.

4. TSS VOLUME IN HELIUM COOLING SYSTEM

The volume is sketched in Figure 1 and the corner values are given in Table 1.

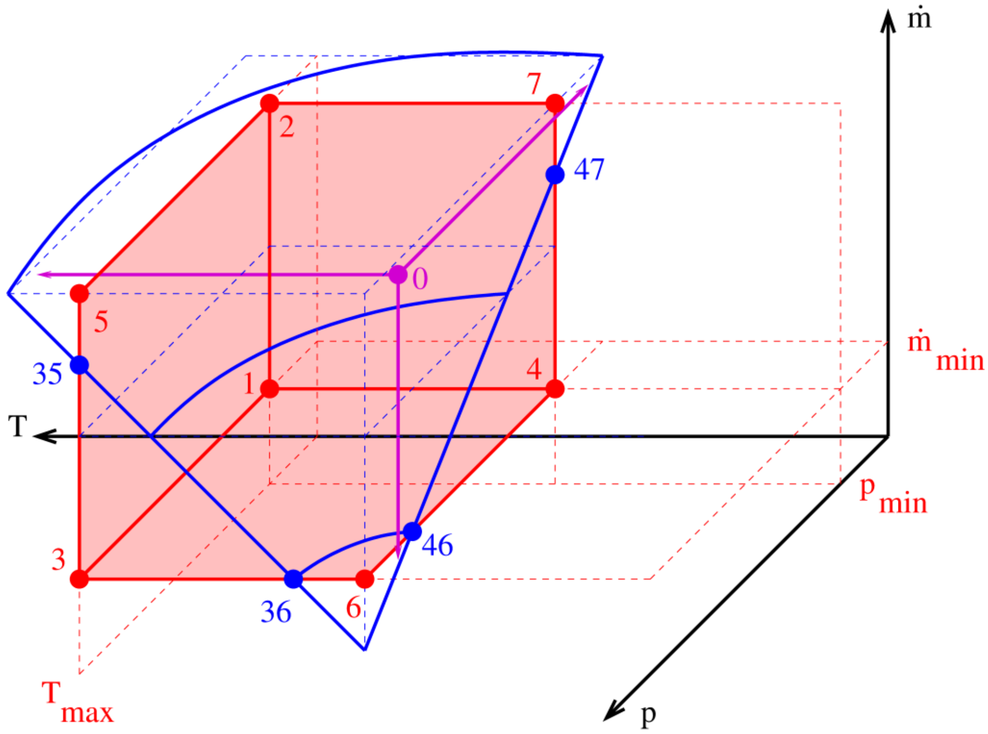

Figure 1 TSS volume diagram

The blue cone represents operability limits of the system, i.e. there may be intersecting points, at which the conditions should be assessed.

The postulated limits are m_{min} = 1.75 kg/s, p_{min} = 8 bar and T_{max} = 70 °C, see Table 1. The opposing numbers (2.85, 12.5 and 40, in gray) are not limiting but only given as indications of possible states to provide some feeling for the size of the volume.

Table 1 Corner values

Corner	m [kg/s]	p [bar(a)]	T [°C]
1	1.75	8	70
2	2.85	8	70
3	1.75	12.5	70
4	1.75	8	40
5	2.85	12.5	70
6	1.75	12.5	40
7	2.85	8	40
8	2.85	12.5	40

5. BACKGROUND TO CHOSEN HELIUM COOLING NUMBERS

This section contains short arguments about the chosen TSS limit values for the target helium cooling system. First the TSS limit is given. Then the other end, corresponding roughly to what is physically possible though not a safety problem to exceed, is given.

The numbers are comparable to the draft assessment in [1], except for the inlet temperature which there turns out to be a higher sensitivity to.

The timing for the cooling system reaction, with maintained rotation, is based on the following: Stainless steel melts at about 1400 C. The normal operation temperature of the tungsten is about 400 C. The time to heat the tungsten the differing 1000 C, estimating the heatup in each pulse to 100C, is given by 1000/(100*14Hz/36) ~ 26 s. Therefore the maximum time to the beam is turned off is estimated to 25 s as a starting value. It is not yet decided though that the melting of the stainless steel will be the criterion for the assessment of the sufficiency of 25 C. It might be shown in other ways that the mitigation is sufficient.

5.1. Massflow

The mass flow rate is required to maintain the wheel temperature.
If the mass flow is lost, the beam has to be off within **25 s**, estimated from earlier drafts of the accident analyses. The timing is based on that the flow stops instantaneously.

1.75 kg/s is a possible mass flow rate with one compressor. This may be a difficult limit due to measurement uncertainty. It may be lowered depending on the wheel strength.

2.85 kg/s is the maximum rate with two compressors at 40 °C and 11 bar(a) at the compressor inlet. The mass flow rate may possibly be higher, e.g. with a higher compressor speed, but that gives better cooling.

5.2. Pressure

The helium pressure is required to have a sufficient density and thus cooling capacity.
If the pressure is lost, the beam has to be off within **25 s**.
The timing is based on that the pressure is lost instantaneously.

8 bar(a) is the highest practical low-pressure limit with a reasonable margin to normal operation, which is above that. A higher pressure limit would mean that normal operation could be affected. Lower operating pressures would on the other hand result in that larger amounts of helium would have to be pumped in and out of the system while the state changes.

12.5 bar(a) is roughly about the pressure downstream of the wheel with the design pressure 13 bar(a) upstream the wheel, at a minimum low flow rate with one compressor. The pressure is limited by a pressure safety relief. The pressure may thus go up to this value. A higher pressure gives a better cooling.

5.3. Temperature

The inlet temperature is required to maintain the temperature in the wheel.
If the temperature increases above that, the beam has to be off within **25 s**.
The timing is based on that the temperature increases instantaneously.

70 °C is the maximum temperature with a reasonable margin to normal operation.

40 °C is about the normal operation temperature. There may be lower temperatures, down to 15 °C, but that will give lower loads than at 40 °C.

6. TARGET WHEEL ROTATION SPEED

Target rotation is required to distribute the heat around the wheel, not to put several consecutive pulses on the same tungsten blocks.

A full stop is postulated in the accident analyses, but a value of rotational speed is required for the definition. For the normal operating control and the machine protection systems, the phase error is more relevant than the speed. Also, an error in speed leads to a phase error, which makes the phase error the only required criterion. The beam has to be off within **3 s**, estimated from earlier drafts of the accident analyses.

One criterion for protection is that two sequential beam footprints should not overlap. This gives approximately 17 rpm compared to the normal 23.3. Then the TSS limit is set as about half of 17, i.e. **less than 9 rpm** is considered to be a full stop.

7. MONOLITH VESSEL PRESSURE

The monolith vessel pressure is used as an indicator of a leak in the target wheel that is so small that it is not detected in the helium cooling system. This type of indication is required for leaks caused by a non-expanded and non-rastered beam, where the leak itself is not the primary problem, but the fact that the power density is so high that it may also damage the tungsten. For this type of event it is estimated that high power density pulses may occur for an entire rotation of the wheel before the wheel damage and flow is large enough to increase the pressure. Then an additional rotation is estimated to be acceptable before the beam is turned off. I.e. the beam has to be off in 36/14 s ~ **2.5 s.**

The monolith pressure may also be used as a diverse indicator for other accidents with failure of the wheel. Then the timing of this alternative detection must be taken into account.

The monolith vessel is normally evacuated to some Pa and a leak in there leads to a rise in pressure. The speed of the rise depends on the leak size. A large break of the target wheel would e.g. lead to that the monolith is pressurised to its relief pressure in a fraction of a second.

The lower the limit pressure, the faster the leak is detected, but it also implies approaching the normal operation. This would increase the risk for unnecessary TSS action and also limit the MPS space. On the other hand, a higher limit pressure delays the TSS action. Therefore, the chosen limit for monolith vessel pressure is **0.5 bar(a).**

8. GLOSSARY

Term	Definition
AA	Accident Analysis
TSS	Target Safety System
RCC-MRx	AFCEN Code for nuclear mechanical components
SF	Service level in RCC-MRX
H2, H3 etc	Event classes, essentially decreasing probability of accident event

9. REFERENCES

[1] Simplified Estimates of Limits for Pilot TSS (ESS-0049507)

DOCUMENT REVISION HISTORY

Revision	Reason for and description of change	Author	Date
1	First issue for TSS CDR, including updating due to reviewer comments	Per Nilsson	2018-12-04