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# RELAP5-3D thermal hydraulic analysis of the target cooling system in the SPES experimental facility

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**Abstract.** The SPES (Selective Production of Exotic Species) experimental facility, under construction at the Italian National Institute of Nuclear Physics (INFN) Laboratories of Legnaro, Italy, is a second generation Isotope Separation On Line (ISOL) plant for advanced nuclear physic studies. The UCx target-ion source system works at temperature of about 2273 K, producing a high level of radiation ($10^5$ Sv/h), for this reason a careful risk analysis for the target chamber is among the major safety issues. In this paper, the obtained results of thermo-fluid-dynamics simulations of accidental transients in the SPES target cooling system are reported. The analysis, performed by using the RELAP5-3D 2.4.2 qualified thermal-hydraulic system code, proves good safety performance of this system during different accidental conditions.

Keywords: SPES, thermo-fluid-dynamics simulations, safety analysis, target cooling system, RELAP5.

## 1. Introduction

SPES (Selective Production of Exotic Species) project is part of the INFN (italian national institute of nuclear physics) road map for the nuclear physics development in Italy, supported by the whole italian nuclear physics community and mainly by LNL (laboratori nazionali di legnaro) and LNS (laboratori nazionali del sud) [1-2].

This project is focused on the development of a radioactive ion beam (RIB) facility to produce intense neutron-rich RIBs according to the Isotope Separation On Line (ISOL) technique [3] with an UCx (Uranium Carbide) direct target.

The facility is devoted to basic research in nuclear physics and astrophysics as well as to interdisciplinary applications, ranging from the production of radionuclides of medical interest to the generation of neutrons for material studies, nuclear technologies and medicine.

The INFN capability to play a role in this research field is supported by the consolidated know-how in accelerators and detectors construction. The most significant facilities are PIAVE superconducting RFQ (electric field provided by a radiofrequency quadrupole), ALPI (acceleratore lineare per ioni) superconductive linac, able to re-accelerate exotic ions at 8÷13 MeV/u, and the EXCYT project, an ISOL RIB facility for light ions.

The major difference between SPES facility and the existing ISOL plants is the target design. This system includes as primary accelerator a cyclotron able to supply at least 40 MeV 0.2 mA proton beam on an UCx direct target to produce a fission rate of about $10^{13}$ fission/s [4-6]. Very high estimated level of radiation and nuclear activations (about $10^5$ Sv/h) are produced in the target area, so special infrastructures, radiation management and control systems are designed.


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The target-ion source system must operate stably at temperature of about 2273 K for long periods of time to determine good characteristic of intensity, beam quality, and number of radioactive beams that can be provided for experimental use. High temperature and vacuum are two essential requirements to enhance the radioactive isotopes mobility, extraction and ionization. To assure the operating temperature, the production target and the surface ion source are located inside a cylindrical chamber cooled by an "ad hoc" water cooling system. Obviously, cooling system faults can produce malfunctions in the target-ion source devices, with possible consequent loss of target chamber structural integrity.

The paper reports the analysis of thermo-fluid-dynamics accidental transients of the target cooling system performed by RELAP5-3D 2.4.2 advanced qualified thermal-hydraulic system code. In particular, loss of water coolant and over-power accidental conditions have been examined by using a detailed cooling system nodalization.

The results prove the good safety performance of the water coolant system against the hazards examined in this paper.

## 2. Target/ion source description

The UCx target is a critical safety item of the facility due to the large level of radioactivity induced by the fission reactions. It follows the design already developed in several laboratories where radioactive beams have operated recently or for long time as EXCYT or ISOLDE (CERN) and HRIBF (ORNL), however the proposed target represent an innovation in term of capability to sustain the primary beam power.

In the context of the facility SPES, the target chamber is used to contain and support the target-ion source complex in an high vacuum environment, providing electrical current to heat by Joule effect both the production target and the ion source in order to operate stably at high temperature of about 2273 K for long periods of time. A water cooling system in the cover of the target compensates the high power deposited by the proton beam channel.

The design is carefully oriented to optimise the radiative cooling taking advantage of the high operating temperature of the target system. In fact a lot of studies have been performed to evaluate the thermo-mechanical behaviour with the ANSYS code [7-11] and, in addition, experimental tests of the target principle were performed at the HRIBF facility (ORNL-USA). The main result is that, in the adopted configuration, the target does not melt and it is rather necessary to supply external power to reach the operating temperature.

The inner container of the target disks is a cylinder with a double entrance window and a beam dump for low energy protons. All these elements are made up of graphite. The window is made by two layers of graphite with a thickness of 0.5 mm. Two window layers are used to separate the reaction chamber from the proton driver beam pipe, this choice is suggested by thermal calculation and in order to improve the safety of the system. The melting point of the graphite is 3773 K well above the temperature of operation of the target.

Number 7 UCx co-axial disks (diameter and thickness of 40 and 1.3 mm respectively) are impinged by 40-50 MeV proton beam (characterized by a current intensity of 0.2 mA), generating approximately $10^{13}$ fissions per second. Thus, a total beam power of about 8 kW has to be managed [12]. The gap between the disks allows an efficient cooling of the system by thermal radiation. The total amount of the U fissile material is only 28 g and the radioactive isotopes produced by the fissions are driven through the transfer line.

Section view of the production target, transfer line and surface ion-source is showed in figure 1. The target configuration is described in detail in [7, 8].

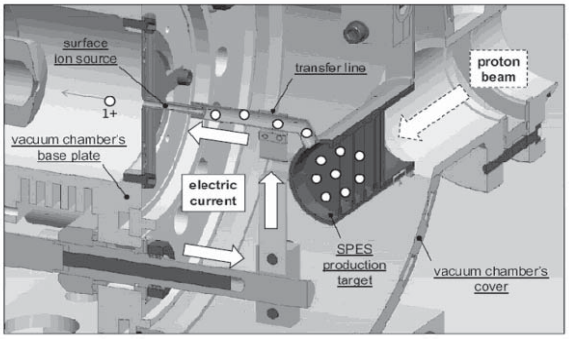
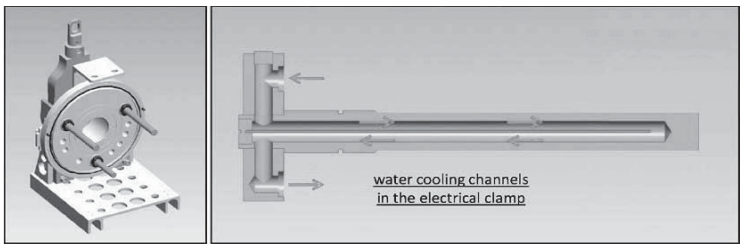



**Figure 1.** Production target, transfer line and surface ion-source (section view).

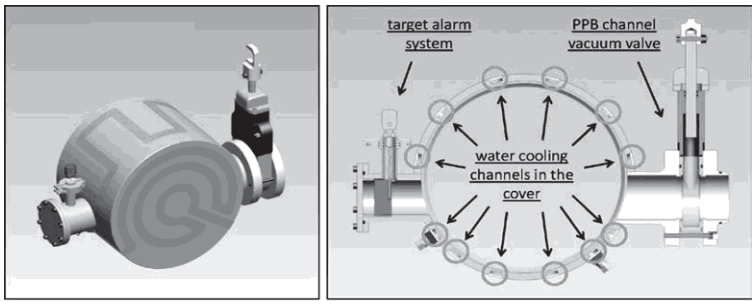
The surface ion source and the transfer line are kept at high temperature thanks to a dedicated and independent 10 kW power supply, able to deliver a maximum electrical current and a maximum potential difference of 1000 A and 10 V, respectively. The electrical current flows first through Tantalum (Ta) transfer line and then through the tungsten (W) tubular ionizing cavity, also called hot-cavity, and dissipates by the joule effect the power which enables the system to reach the desired temperature level. The Ta transfer line consists of a tube with an external and an internal diameter of 9 and 8 mm respectively, and a length of approximately 38 mm, connected to the W hot-cavity.

An ion source electrical clamp and two target electrical clamps are used to provide the high electrical currents needed to heat the ion source and the target, respectively. It is worth to mentioning that the electrical clamps should be cooled down to 1357.15 K being the melting point of the Copper (Cu).

Some sub-assemblies of the la target chamber are reported in figure 2. The main plate (figure 2a) supports the cover, the electrical clamps and all secondary components of the target chamber (for example the shutter of the RIB channel). The water cooling channels in the electrical clamps (figure 2a) and in the cover (figure 2b) allow to remove the power produced by the target-ion source system and to operate stably at temperature of 2273 K.




**(a)**




**(b)**

**Figure 2.** Sub-assemblies of the target chamber: (a) main plate and cooling channels in the electrical clamp, (b) target cover and cooling channels in the cover.

## 3. The cooling system

The cooling system consists of two loops (figure 3): the primary loop (Loop A) uses demineralized water as coolant of the target system, the secondary one (Loop B) uses soft water to cool the primary loop. The platform, where the target-ion source system is located, has to be maintained for experimental purposes at 250 kV voltage. The cooling system removes a power of 27 kW in the target chamber and 9 kW in the instrument and measurement devices [2].

A redundant primary coolant feed system allows demineralized water circulation by magnetic drive centrifugal pumps (PS1 and PS2 in figure 3). A distributed control system (DCS) allows to start the auxiliary pump in case of primary pump malfunctions and switches off the beam (target-ion source system trip) if auxiliary pump failures occurs. Each coolant feed pipeline is equipped with check valves to avoid flow inversions.

A pressure gauge installed downstream of the redundant pipeline, called PT1 in figure 3, measures the pressure and proceeds via DCS with pump regulation according to the operating condition of water mass flow rate (0.83 kg/s). The primary coolant is pumped into the corrugated heat exchanger where heat is transferred from the primary coolant (demineralized water) to the secondary coolant (soft water). The inlet and outlet temperatures of the primary coolant in the heat exchanger are 303 and 292 K, respectively;

control and safety systems allow a tolerance of + 0.2 K. The soft water enters in the secondary side of the heat exchanger at temperature of 280 K and exits at temperature of 285 K. A temperature gauge, TT1, allows, via temperature controller system RT, the secondary coolant flow control by using a mixing three-way valve, VM, (figure 3); this regulation allows to keep the primary coolant temperature at 292 K (+ 0.2 K).

At the exit of the heat exchanger, the primary coolant flows into parallel mixed beds (beds ion exchange) to be purified. This operation enables to reduce primary coolant specific conductivity before entering within the target platform.

At the exit of the mixed beds, the primary coolant flows inside a non-conductive material helical pipe (50 m length and 32 mm outer diameter) to minimize parasitic current flows production, then it removes the heat produced in the target chamber, reaching outlet temperature of 303 K. A mass/flow density meter, placed at the inlet of the platform, is used to operate via DCS the target-ion source system trip in presence of vapor or mass flow rate reduction. Two non-conductive material spiral pipes at the platform exit lead the coolant into a return pipeline (50 m length and 25 mm outer diameter), where an expansion tank of 100 liter volume is located.

The facility is also equipped with several automated safety and control systems (i.e. visual emergency alarm system, detection system for target temperature and pressure measurements, radiation monitoring system, interlock systems to stop the beam, mass flow and density meter).

Moreover the control room typically houses three computer working stations: one for accelerators controlling, one for the target, one for controlling and monitoring the radiation protection and the safety systems, cooling system included.

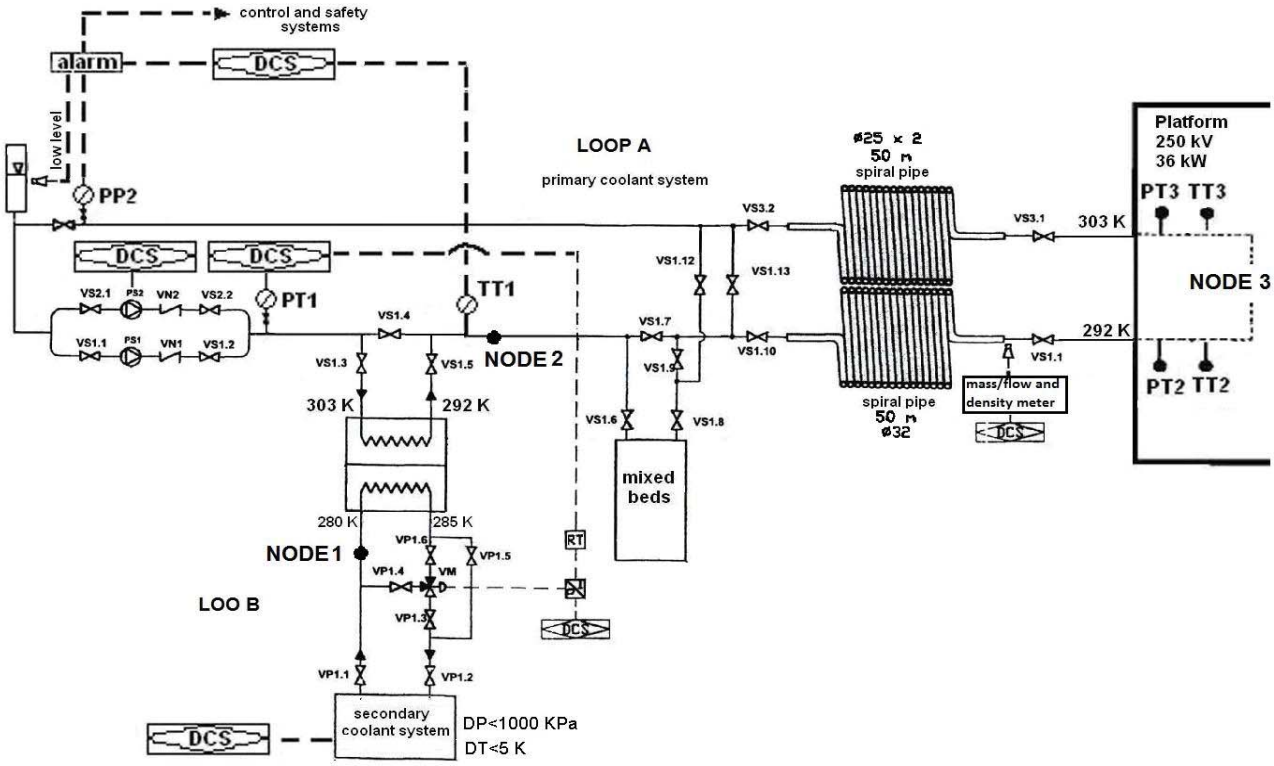



**Figure 3.** Target cooling system design in the SPES facility.

## 4. Analysis and results

RELAP5 code has been used, preliminary, to perform the tuning of nodalization behaviours in steady state conditions respect to thermal-hydraulic physical parameters such as pressures drops, water temperatures in the primary and secondary loops, mass flow rates, temperature of target, temperature of instruments and measurement systems.

The variation of each parameter is set according to reasonable variations achieved during the plant nominal operation. The steady-state simulation has shown results congruent to physical expectations.

Subsequently, different accidental scenarios have been hypothesized:

- Loss Of Coolant Accidents (LOCAs), under difference cases for break scenarios;
- Overpower transients, under difference conditions for uncontrolled power production.

Moreover, occurrence of failures of the safety and control devices are assumed to be worse conditions.

*4.1 RELAP5 nodalization*

The RELAP5 nodalization used for the accidental scenarios simulation is shown in figure 4; moreover the three dimensional representation of the plant model described in the RELAP5 input file, which runs by the RELAP5 Graphical User Interface, is shown in figure 5.

In the primary coolant loop, identified with loop A (figure 3), the expansion tank is represented by pipe (095) of 100 liter, connected to the pipe (097) by using a motor valve (096), which is open during both steady-state and accidental conditions. The branch (130) allows to connect the return primary coolant pipeline to the redundant pipeline, where the pumps are located. The components (171) and (172) schematize the two pumps and impose the nominal operating mass flow rates. The input data needed for the homologous curves which describe the pump behavior under single and two-phase flow conditions are in general known only for a few small-scale pumps, so the pump schematization has been extrapolated from existing data, obtained for different designs and scaling factors, used in the RELAP5 code.

The redundant primary coolant feed pipeline is schematized by using pipes from (141) to (221), and the auxiliary feed pipeline is schematized by using pipes from (142) to (222).

The inlet and outlet water temperatures in the loop B (figure 3) are imposed by using time-dependent volumes (010) and (050), respectively (figure 4). These volumes are connected to heat structures to simulate the heat exchange between primary and secondary coolants flowing into the corrugated heat exchanger.

The time-dependent junction (021) imposes the secondary mass flow rate according to nominal operating conditions.

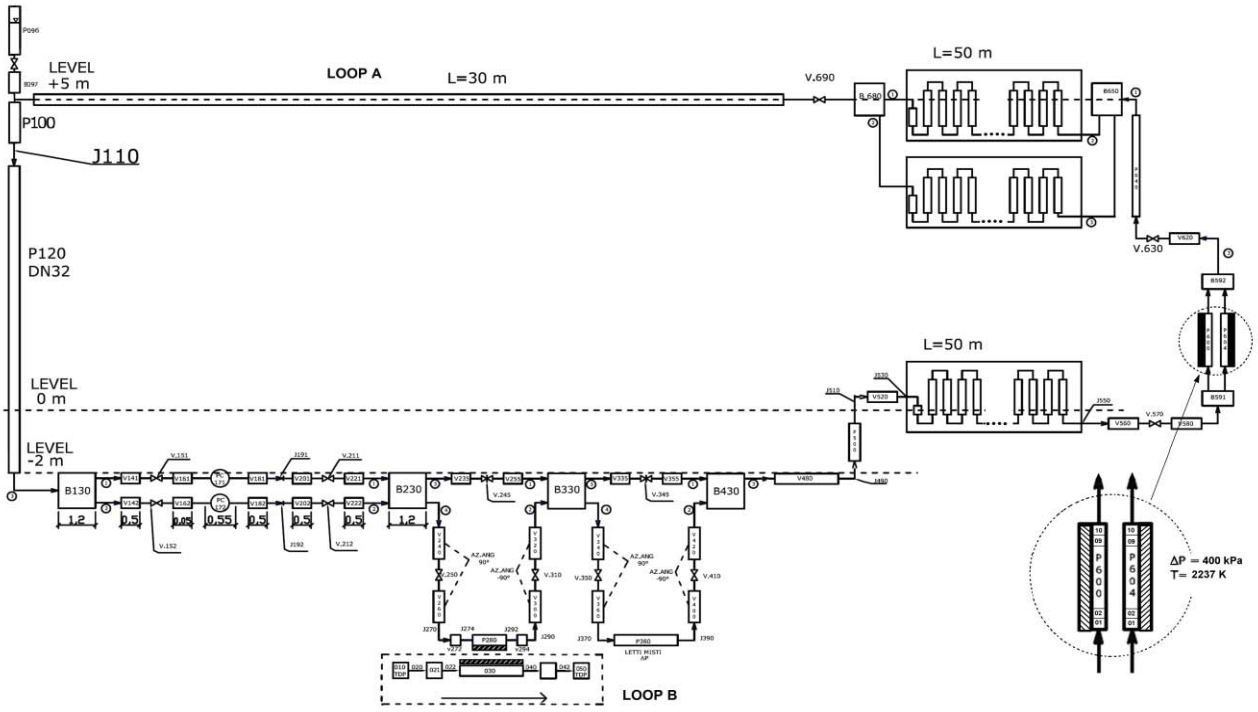



**Figure 4.** RELAP5 nodalization of the target cooling system.

The pipe (380) represents the mixed beds and the pipes (540), (660) and (670) schematize the helical pipes located at the inlet and outlet of the platform. Ninety-nine axial nodes are used to model the horizontal helical shape of the tubes.

The primary coolant pipelines in the target volume and measurement systems, which allow to remove the heat power, are schematized by using pipes (600) and (604) respectively.

Two heat structure nodes are connected to the pipes (600) and (604) and are used to account for heat exchange between the primary coolant and the target chamber.

Appropriate radial peaking factors are defined to distribute the total power within the target and the measurement systems. Four axial nodes were used for both the hydrodynamic components (600) and (604) and ten corresponding sub-structures.

Finally, dedicated integral control variables are modelled to evaluate the heat power exchanged between the primary coolant and the target chamber (cntrlvar 108 for the target system and cntrlvar 109 for the measurement systems), as well between primary coolant system and secondary coolant one (cntrlvar 110).

The technique used to model the break is the one proposed in the RELAP5 user manuals suggested for different break sizes [13]. For small and medium break sizes, a trip valve component (331) is used. This component is connected to the branch (430) of the cold primary pipeline and stays closed during the steady-state phase and opens at the time of the break initiation.

The abrupt area change option was enabled to account for the additional pressure losses due to the sudden contraction and expansion of the flow at the break. The default chocked flow model is enabled to take into account chocked condition at the break during the phases of the accident. For all the break scenarios, the discharge volume is simulated with a time-dependent volume.

The elevation change of volumes and sub-volumes are set according to plant specifications.

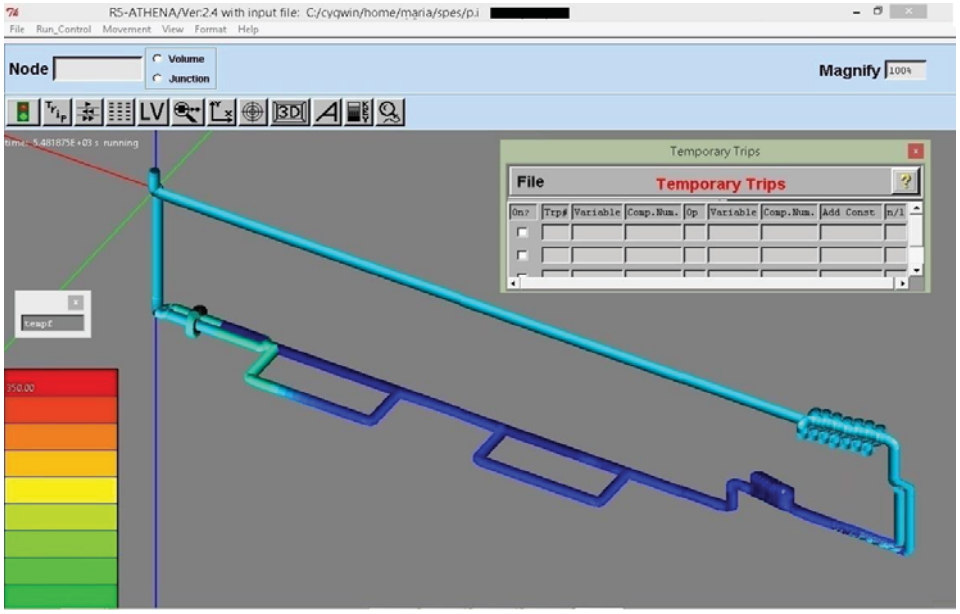



**Figure 5.** Three dimensional representation of the plant model described in the RELAP5 input, this view is done by using the RELAP5-3D Graphical User Interface.

## 5. LOCA transients

The accidental event occurs at t =10100 s, during nominal operating condition, when the trip valve (331) opens. Different breaks are tested, as reported in table 1, where the ratio of break area to pipeline area, $A/A_0$, and the ratio of break mass flow to pipeline mass flow, $G/G_0$, are shown.

**Table 1.** Break area used to simulate Loss Of Coolant Accidents.

| Break area/pipeline area $A/A_0$ [%] | Break mass flow rate/pipeline mass flow $G/G_0$ [%] |
|---|---|
| 1 | 18 |
| 2 | 36 |
| 3 | 54 |
| 4 | 72 |
| 5 | 85 |

Figures 6 through 12 show the results obtained by LOCA transients characterized by break of 1% and 5%, which are compared to each other. In particular, figure 6 shows the break mass flow for both the accidental events; as expected the 5% break involves more significant loss of water coolant: approximately,

the break mass flow rate is about 85% of the nominal mass flow rate (table 1). The primary coolant system pressure quickly decreases (more for the break of 5%), as shown in figure 7, where the pressure in the inlet pipeline of the target system is represented. Consequently, the pump increases the mass flow rate (figure 8), till vapour production in the pump suction volume (figure 9) causes pump degradation and drastic mass flow rate reduction. The pump degradation occurs much sooner for the break of 5% (after about 130 s from the beginning of the accident).

The water temperatures in the inlet and outlet coolant pipelines placed in the target system and measurement systems, respectively, show a little increase when the break occurs, as shown in figures 10 and 11. In fact, as above said, the pump regulation increases the mass flow rate, so the heat exchange between the primary coolant system and the target chamber is guaranteed. However, when the degradation pump occurs and the regulation stops, the water temperatures quickly increase (figures 10 and 11) and the pressure further decreases (figure 7).

As consequence, the heat structure temperatures, which schematize the target system, increase and exceed about 1500 K at about t=10800 s for break of 1%, and about t=10350 s for break of 5 % (figure 12), moreover the heat structure temperatures, which schematize the measurement systems, increase and exceed about 1000 K at about t=10820 s for break of 1%, and about t=10360 s for break of 5 % (figure 13).

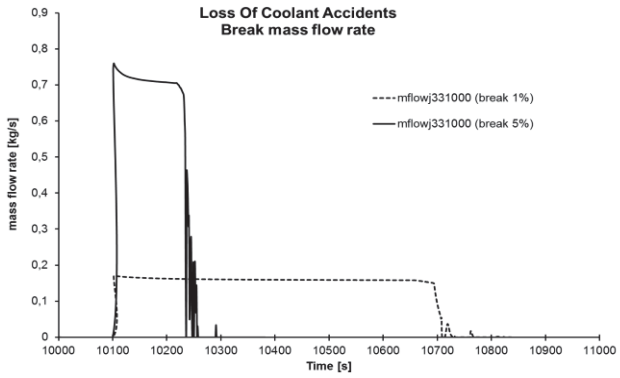



**Figure 6.** Break mass flow rate during LOCA accidents, for break of 1% and 5%.

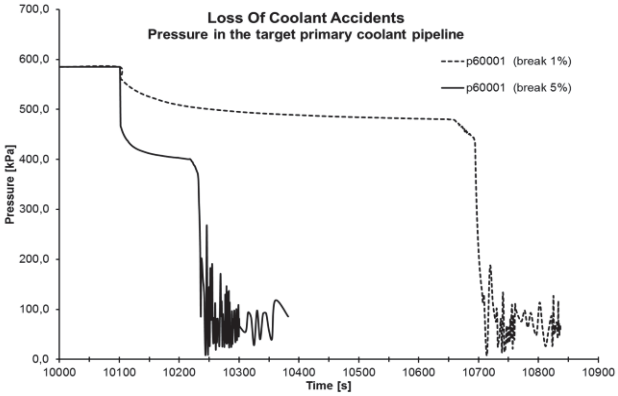



**Figure 7.** Pressure in the inlet pipeline of the target system during LOCA accidents, break of 1% and 5%.

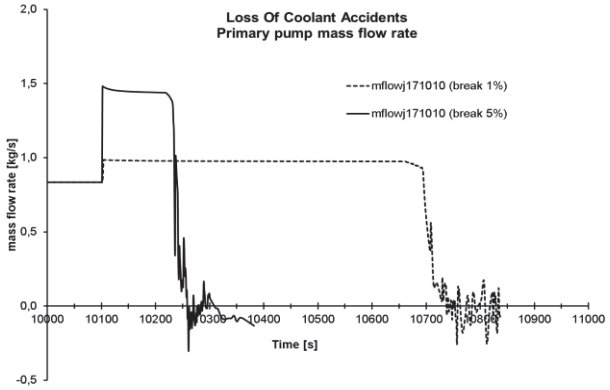



**Figure 8.** Pump mass flow rate during LOCA accidents, for break of 1% and 5%.

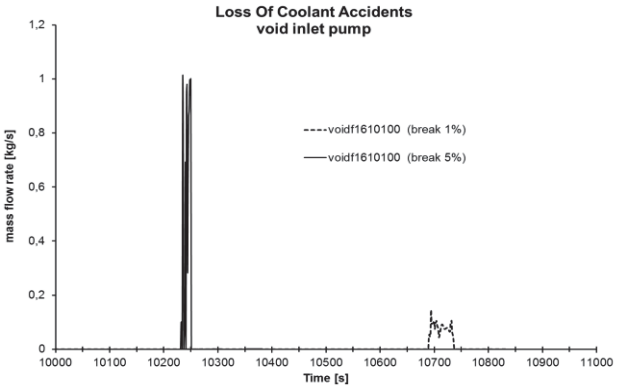



**Figure 9.** Void fraction in the pump suction volume during LOCA accidents, for break of 1% and 5%.

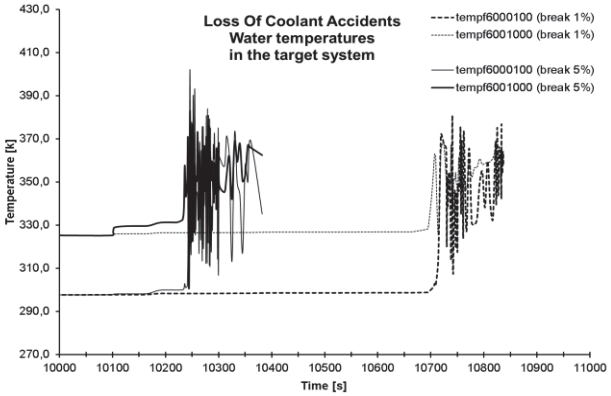



**Figure 10.** Water coolant temperatures in the inlet and outlet pipelines of the target system during LOCA accidents, for break of 1% and of 5%.

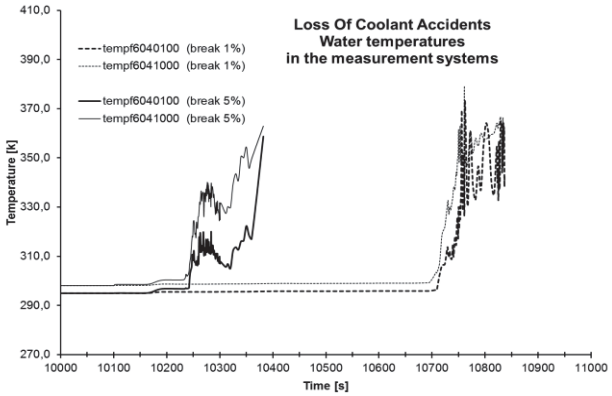



**Figure 11.** Water coolant temperatures in the inlet and outlet pipelines of the measurement systems during LOCA accidents, for break of 1% and 5%.

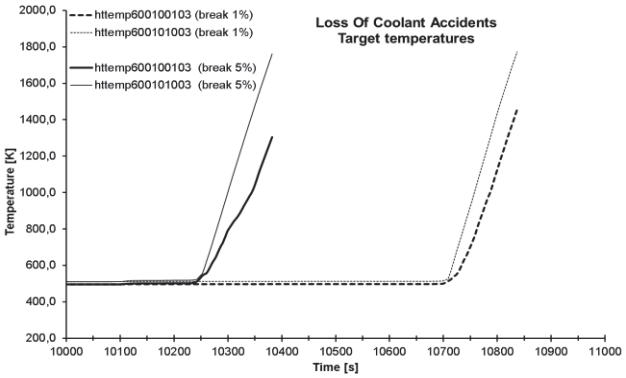



**Figure 12.** Temperatures of the heat structures used to simulate the target system during LOCA accidents, for break of 1% and 5%.

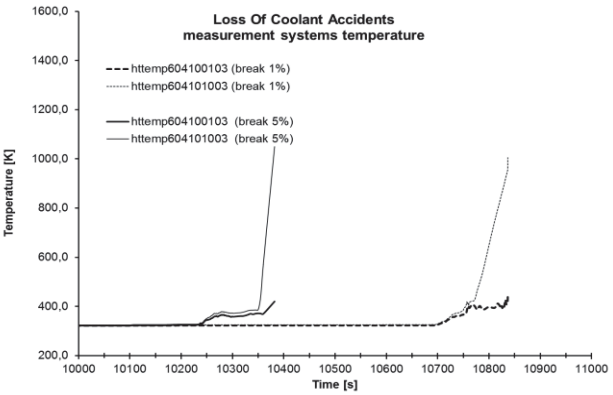



**Figure 13.** Temperatures of the heat structures used to simulate the measurement systems during LOCA, for break of 1% and 5%.

## 6. Overpower transients

The beam-target system subjected to uncontrolled primary beam power or electric current increase leads to overpower transients with immediately mismatch between produced and removed heat power and consequent overheating of sub-assemblies.

Failures of the temperature control safety systems, located in the platform of the target chamber, are considered to be worse conditions. Different accidental situations, namely 20%, 40%, 50% and 100% overpower starting from nominal conditions, have been considered. In the following the results obtained by 100% overpower simulation are reported.

The initiating event start at t =10100 s. A quickly power increase up to about 72 kW takes place, as shown in figure 14 where the total power produced in the beam-ion source target is reported. The inlet and outlet water temperatures in the target and measurement systems increase as showed in figure 15.

However, the corresponding heat structure temperatures do not exceed the acceptance criteria in terms of temperature limits (i.e. well below of the copper melting point) allowed for the target chamber, as shown in figures 16 and 17 [5].

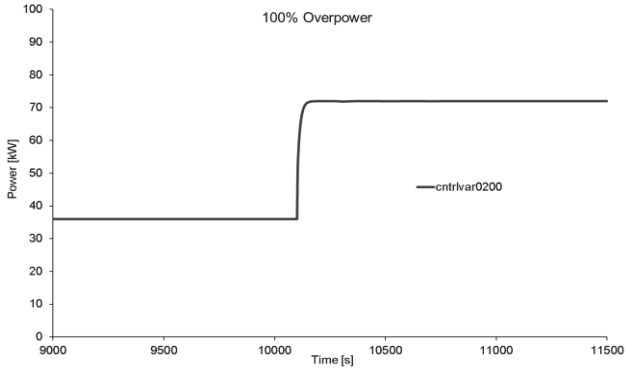



**Figure 14.** Power produced in the ion-source target system.

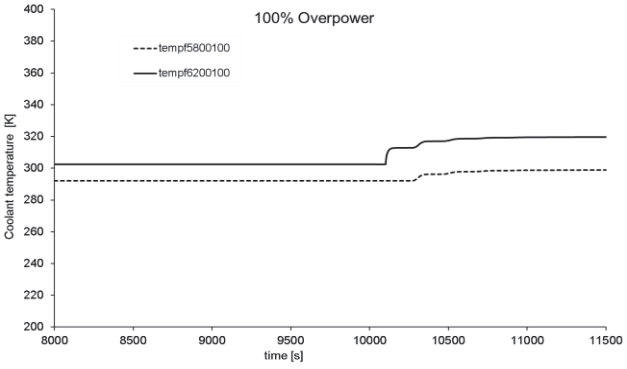



**Figure 15.** Inlet and outlet primary coolant temperatures in the target and measurement systems.

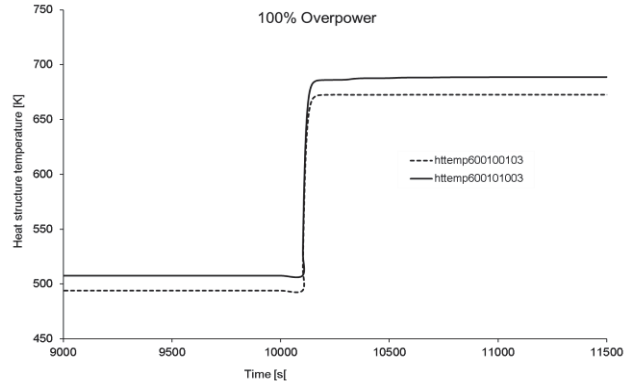



**Figure 16**. First and last heat structure temperatures used to simulate the target system.

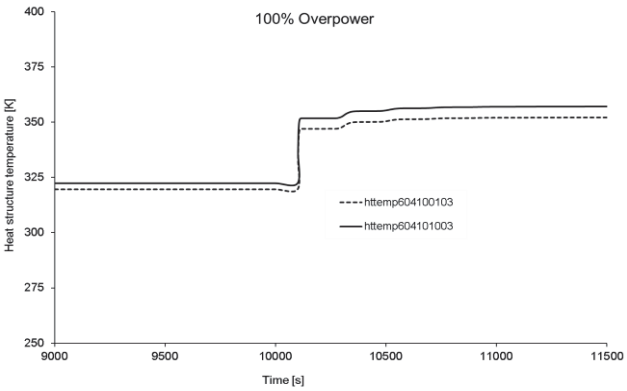



**Figure 17**. First and last heat structure temperatures used to simulate the measurement systems.

## 7. Conclusion

The main goal of the SPES experimental facility is to provide an accelerator system to perform forefront research in nuclear physics by studying nuclei far from stability. In particular, the main purpose of the project is the production of neutron-rich radioactive nuclei with mass in the range 80-160. The emphasis to neutron-rich isotopes is justified by the fact that this vast region has been little explored, at exceptions of some decay and in-beam spectroscopy following fission.

The production method is based on the ISOL technique with direct target: a primary proton beam impinges directly on a UCx target inducing the U fission with a maximum rate of $10^{13}$ f/s. The fission products are extracted, ionized, selected and reaccelerated to produce the secondary radioactive beam. The UCx target is the critical item of the facility from the point of view of the safety due to the large level of radioactivity induced by the fission reactions. As the facility will handle radioactive species, special care is devoted to the radiation protection safety and several systems are added to prevent radiation hazards.

To assure the operational temperature range, the production target and the surface ion source are located inside a cylindrical chamber cooled by a water cooling system.

In this paper safety analysis addressed to verify some design decisions of the water cooling system has been performed.

Different accidental scenarios have been hypothesized and examined by using the RELAP5-3D 2.4.2 advanced qualified thermal-hydraulic system code:

- Loss Of Coolant Accidents (LOCAs), under difference cases for break scenarios;
- Overpower transients, under difference conditions for uncontrolled power production.

In order to simulate worse condition, control and safety system failures have been considered.

The cooling system has shown a good performance during the examined accidental transients, confirming the good safety standards. In fact, the acceptance criteria are not exceeded in case of 100% overpower accident, moreover in case of LOCA accidents the temperature limits in the target chamber go beyond acceptance criteria, but the time interval from beginning of the initiating accidental event is sufficiently to allow the intervention of the operator.

**References**

[1] Prete G and Covello A, 2008, SPES Technical Design Report, *INFN-LNL* 223, http://www.lnl.infn.it/spes /TDR2008/tech_design08_index.htm.
[2] De Angelis G, Andrighetto A, Bassato G, Biasetto L, Calabretta L, Comunian M, Galatà A, Giacchini M, Gramegna F, Lombardi A, Manzolaro M, Prete G, Sarchiapone L, Scarpa D and Zafiropoulos D, 2011 Future Perspectives of the Legnaro National Laboratories: The SPES project, *Journal of Physics*: Conference Series 267 012003.
[3] Lombardi A, Andrighetto A, Bisoffi G, Comunian M, Favaron P, Gramegna F, Maggiore M, Piazza L A C, Prete G and Zafiropoulos D, 2013, SPES project: a neutron rich ISOL facility for re-accelerated RIBS Proceedings of Cyclotrons, Vancouver, BC, Canada.
[4] Andrighetto A, Cevolani S and Petrovich C, 2005, Fission Fragments Production from Uranium Carbide Disc Targets, *Eur. Phys. J.*, **A25**, 41-47.
[5] Andrighetto A, Antonucci C M, Cevolani S, Petrovich C and Santana Leitner M, 2006, Multifoil UCx target for the SPES project -An update, *Eur. Phys. J.* **A30**, 591-601.
[6] Andrighetto A, Antonucci C, Barbui M, et al., November 2007, The SPES direct UCx target, *The European Physical Journal Special Topics,* , Volume **150**, Issue 1, pp 273-274
[7] Andrighetto A, Antonucci C M, Cevolani S and Petrovich C, 2006, ENEA contribution to the design of the thin target for the SPES project, FIS-P815-020.
[8] Andrighetto A, Antonucci C M, Cevolani S, Petrovich C and Santana Leitner M, 2006, Multifoil UCx target for the SPES project - An update, *Eur. Phys. J.* **A30**, 591.
[9] Cevolani S, 2006, Valutazione approssimata dell'effetto della frequenza di pulsazione del fascio sulla termica del target sottile per SPES., FIS-P815-022.
[10] Manzolaro M, Meneghetti G and Andrighetto A, 2010, Thermal-electric numerical simulation of a surface ion source for the production of radioactive ion beams, *Nuclear Instruments and Methods in Physics Research* A, **623** , 1061–1069.
[11] Manzolaro M, 2003, Study, design and test of the target-ion source system for the INFN SPES facility, *PhD Thesis, XXIII PhD Cycle, Department of Mechanical Engineering, University of Padua*.
[12] Petrovich C, 2006, The SPES target – Power deposition and preliminary radiation protection analyses, FPN-P815-007 ENEA.
[13] June 2005, RELAP5-3D Code manual volume **I**: code structure, system models, and solution methods, Idaho National Laboratory INEEL-EXT-98-00834, Revision 2.4.