PERFOMANCE OF 1 MW CLASS TARGET CIRCUIT TC-1 FOR ADS

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ABSTRACT

The experience gained in developing, creating and testing 1 MW class pilot lead-bismuth target TC-1 with window for accelerator-driven systems (ADS) is analyzed with the focus on substantiation of main equipment structures, assessment of working parameters and maintenance of safe operation in various modes.

INTRODUCTION

Molten metal targets in which proton beam interacts with liquid metal flow have advantages over solid targets, in particular, with 1 MW and higher beam power [1]. The following advantages can be pointed out:

- no radiation damage of target material that does not have crystalline structure;
- easier target cooling under operation;
- easier decay heat removal after accelerator shutdown.

During 1998-2008 the IPPE [2] and GIDROPRESS [3] specialists under the auspice of the International Science and Technology Center [4] have developed, created and twice tested the pilot molten lead-bismuth target circuit TC-1 of 1 MW power with the window for ADS. The initial objective was to deliver TC-1 to US for irradiation under LANSCE accelerator proton beam at Los Alamos National Laboratory (LANL) with proton energy ~800 MeV and proton current ~1.25 mA. Because of scrapping the US DOE program on the subject in question the TC-1 has been actually delivered to Harry Reid Center for Environmental Studies, University of Nevada, Las Vegas (UNLV). At present TC-1 is a lead-bismuth loop operating at UNLV at the coolant temperature up to ~300°C.

The goal of this paper is to present the experience gained in developing, creating and testing TC-1 as a full-scale prototype of 1 MW target circuit for ADS.

TC-1 DESIGN

The target complex TC-1 is a lead-bismuth loop [5]. As it is shown in Fig. 1, the TC-1 components (neutron-generating target itself, magnetic hydro-dynamic (MHD) pump, volume compensator (VC), heat exchanger (HE), drainage tank (DT), siphon interruption device (SID), pipelines, sensors and other components) are arranged inside supporting rectangular metal truss with dimensions 640x710x4075 mm.

For the tests under LANSCE accelerator proton beam at LANL TC-1 is installed in the sealed steel container, which in turn is placed in the well in the beam-stop area in the iron shielding. Specific feature of TC-1 design was arrangement of DT above the target. Thus, the coolant drainage from loop into DT and back was realized by means of formation of necessary gas pressure above coolant free surface in DT and VC. This makes the TC-1 operation more complicated.

General view of target part of TC-1 is presented in Fig. 2. The target has the body 4, the window 1, the inner channel 12 with the diffuser plate 10, and the inlet (18) and outlet (14) branch pipes for coolant. The target length is 660 mm and its inner diameter is 185 mm.

Cold coolant from the inlet pipe flows into circular inlet chamber, enters the annular gap between the body 4 and the inner channel 12, flows about the window and then flows through the orifices of the diffuser plate to the outlet pipe 14 (being heated with proton beam) and the heat exchanger. The diffuser plate “presses” coolant flow to the window and ensures its proper cooling down in this way. Near the inlet chamber there is the drain vessel 16, through which coolant is pushed from DT into the loop and vise versa. The vessel contains coolant residues drained from filling-draining pipeline after drainage.

The window and the diffuser plate subject to high radiation and thermal fields are made of ferritic-martensitic steel EP-823. The target body and other components of TC-1 are made of austenitic stainless steel 08X18H10T.

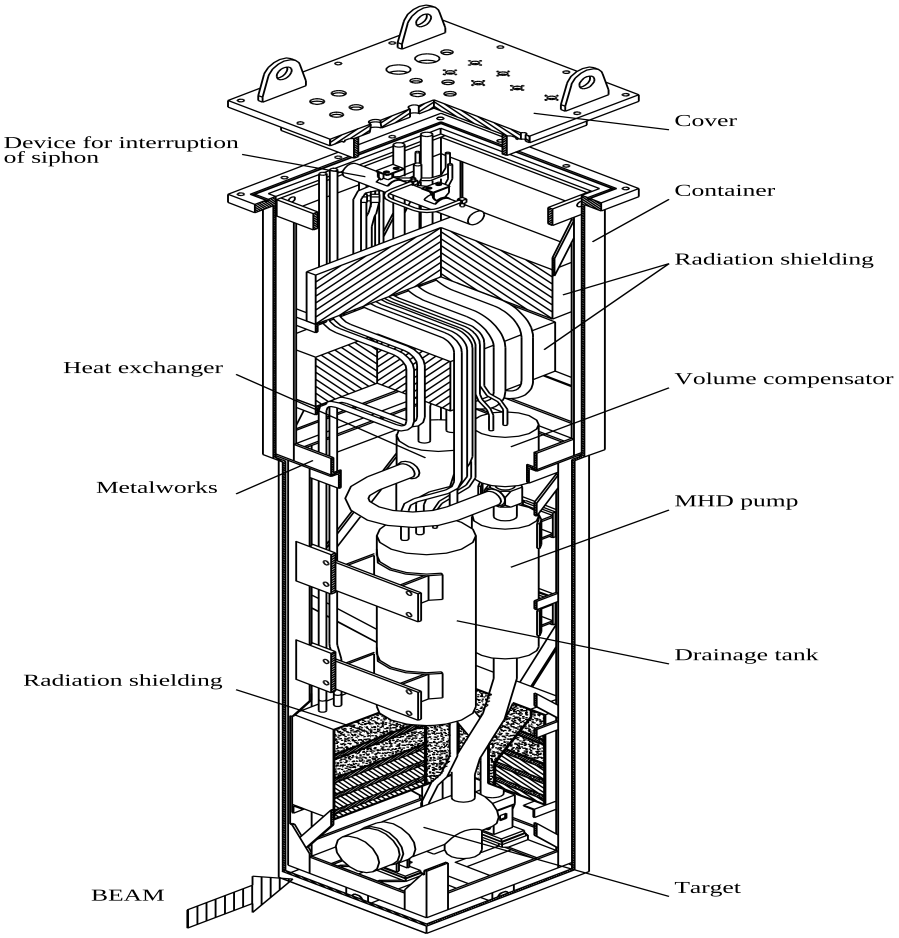

Fig. 1: Main components of TC-1

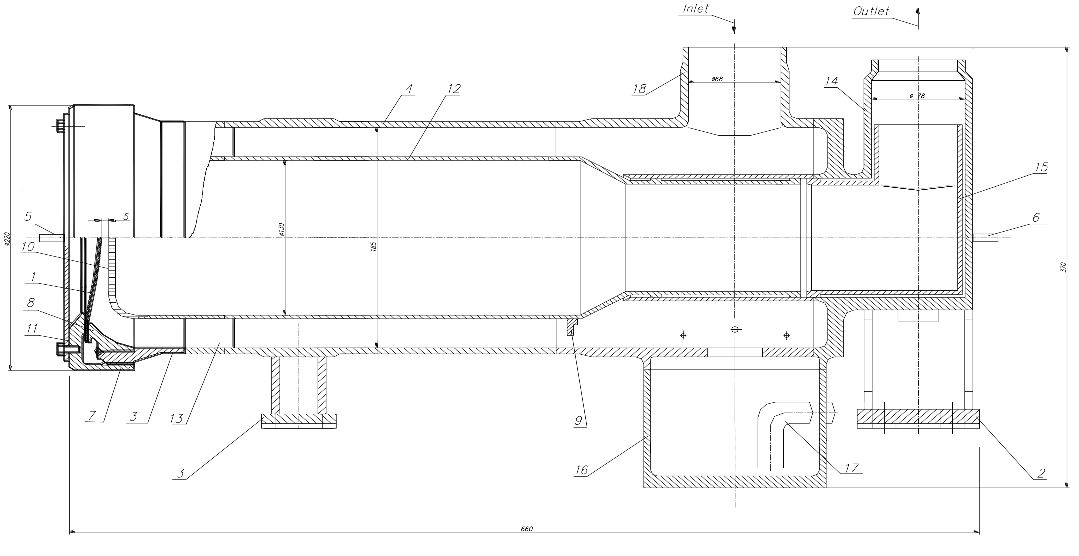

Fig. 2: Neutron-generating target
1 – window; 2 - immovable support; 3 - movable support; 4 - body; 5, 6 – pins; 7 – gut; 8 - transition element; 9 – ring; 10 - diffuser plate; 11 – seal; 12 - inner channel; 13 - transition element; 14 - outlet nozzle; 15 – shell; 16 – drain vessel; 17 – pipeline; 18 - inlet nozzle

MHD-pump is a cylindrical linear induction pump. The general view of MHD-pump is given in Fig. 3. The pump consists of the hull 1, core 3, inductor 2, inlet branch pipe 4, the outlet branch pipe 5, terminal box 6, support 7. The inductor 2 comprises longitudinally burdening faggots with grooves where the winding is placed. The faggots contact each other along the inner diameter where they are fitted to the external shell 8 of the channel 9.

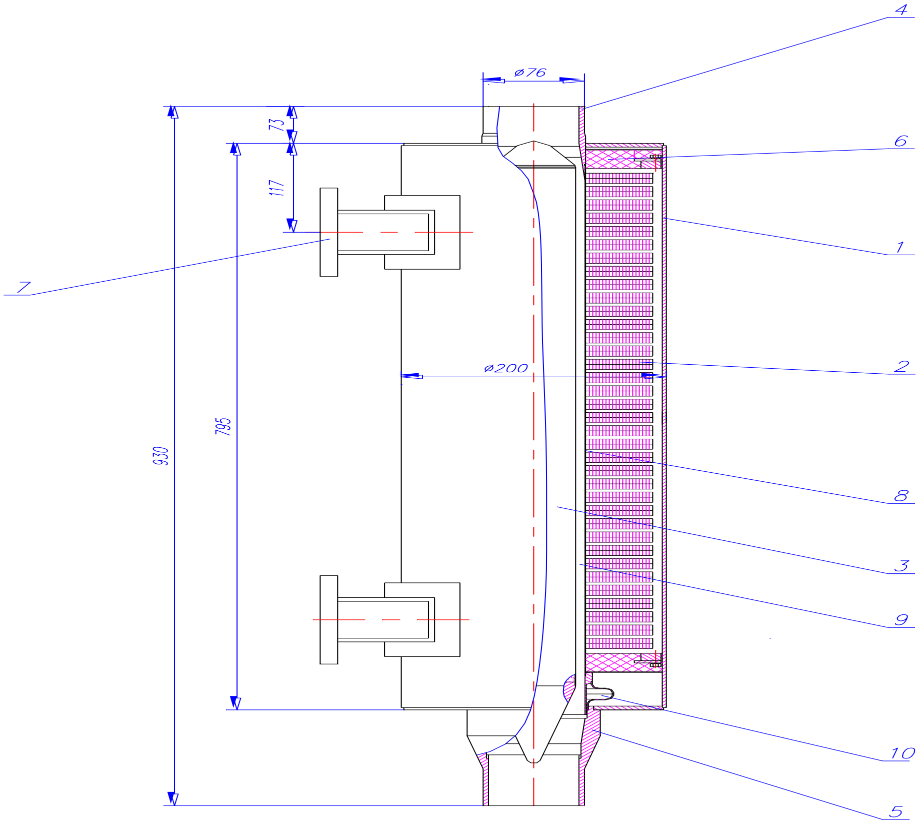

Fig. 3: MHD-pump
1-hull; 2-inductor; 3-core; 4-inlet branch pipe; 5-outlet branch pipe; 6-terminal box; 7-support; 8-shell;
9-working channel; 10-siphon

The core 3 consists of longitudinally burdening faggots made in the form of sectors. The faggots are braced with pins. To improve core magnetic conductivity properties 8 orifices of 12 mm diameter were made in the core brackets, which after assembling formed 8 channels. These channels are filled with ferromagnetic powder. TC-1 components and pipelines have electric heaters covered by thermal insulation (except for the target itself).

Electric heating system has 9 sections with (8 controlled heating zones) 100% reserve (each section has the main and the reserve heaters). The heaters are arranged on external surface of TC-1 components and pipelines. Total power of electric heaters is 17.5 kW.

Thermal monitoring of TC-1 is realized by means of instrumentation system including thermocouples, electric contact level meters and electromagnetic flow meter. 37 regular thermocouples are installed on TC-1 components and pipelines. 29 thermocouples are installed on the component surface and 8 thermocouples in sealed sockets are immersed into the coolant. In each heating zone 2 thermocouples are installed: one for control system and the other – for safety system.

All signals from sensors after processing enter data acquisition and control system.

Technical characteristics of TC-1 are given in Table 1.

Table 1: Main Parameters of TC-1

Parameters	Values
Proton beam parameters:	
proton energy, MeV	800
proton current, mA	1.0
beam effective diameter, mm	100
Target parameters:	
internal diameter, mm	185
length, mm	660
energy release in the target, kW	522
coolant temperature, °C	
target inlet	232
target outlet	319
coolant flow rate through the target, m^3/h	14.2
MHD - pump parameters:	
capacity, m^3/h	15
useful head, MPa	0.102
efficiency, %	8.1
current frequency, Hz	60
supply voltage, V	220
consumed power, kW	5.3
power coefficient	0.29
Heat exchanger parameters:	
thermal power, kW	to 600
cooling water flow rate, m^3/h	27.4
cooling water temperature, °C	
inlet	200
outlet	218
cooling water pressure, MPa	3.5
Parameters of electric supply of electric heating system:	
voltage, V	220
current frequency, Hz	60
nominal power, kW	17.5
Total mass of the TC-1 with internal shielding and coolant, kg	5700
Coolant mass, kg	684
The TC-1 lifetime from the time of its delivery in LANL, months	30
Total time of the TC-1 operation with coolant in the target, months	15
Total time of the TC-1 operation in beam-on conditions, months	12
Target total irradiation, mA∗month	7.5

TC-1 OPERATION MODES

Stationary Modes

Velocity and temperature fields in the coolant and in the structural materials of the target were calculated in 2D and 3D geometry, mainly, for operation with 1 mA current [6]. Maximum temperature of the window surface reaches 423°C value on the beam side and 389°C value on the coolant side. Maximum temperature 424°C of the coolant is reached at the distance 45 cm from the window. Maximum temperature in the diffuser plate is 342°C. 2D and 3D calculations give similar results.

3D calculations demonstrated that essential azimuth irregularity in coolant flow distribution took place in the inlet circular channel. But in the area of energy deposition the target design ensures velocity and temperature field close to axially symmetric.

The total pressure drop through the target tract is 35.5 kPa. Calculations were also made for the loop. Average temperatures of the coolant and water on the target and heat exchanger inlet and outlet are given in Table 2 for different current values at nominal flow rate 14.2 m^3/h.

Table 2: Parameters of TC-1 at various power levels

Beam current, mA	0.2	0.5	0.75	1.0
Thermal power removed in heat exchanger, kW	130	261	391	522
Coolant temperature, ^{o}C				
target inlet	209	217	224	232
target outlet	213	261	290	310
Cooling water temperature, ^{o}C				
heat exchanger inlet	200	200	200	200
heat exchanger outlet	205	209	213	218

Transient, Normal and Emergency Operation Modes

The major efforts were concentrated on analysis of the modes with beam trips. In the framework of comparatively simple model temperature dynamics in the window was computed [6]. Simultaneously effects of the beam pulse structure were estimated (the beam of LANSCE accelerator is a series of trapezoidal impulses with frequency ~100 Hz, amplitude ~20 mA and duration 0.625 ms at ~1 MW power). Analysis revealed that pulse structure caused window temperature oscillation with amplitude ~1% of average value. In the whole dynamics effects of the beam pulse structure are weak and accelerator operation on constant power level may be considered as quasi-stationary operation with continuous current.

Beam trip is rather important factor causing significant oscillations of temperatures and thermal cyclic loads on the target window and other components of TC-1. Special dynamics codes were developed for calculation of temperature changes in different points of TC-1 in transient modes and under accidents. Calculations of transient modes in the loop revealed, in particular, that coolant temperature became approximately equal to that of cooling water in 50-60 sec after beam disappeared. This means that inlet temperature of cooling water should be higher than coolant melting point (125^{o}C), otherwise coolant freezing will take place in the loop under beam trips.

MHD-pump or/and cooling water pump failures were mainly considered. Study of coolant temperature changes in the different points of the loop under MHD-pump failure and the beam keeping has showed that the coolant temperature at the target outlet reaches maximum value of ~1000^{o}C on 17-th second and then drops down to ~600^{o}C on 28-th second because of development of natural convection. In the whole conclusion was made that protection system should remove the beam from the target in several seconds after MHD-pump failure to eliminate undesirable overheating.

On the basis of emergency calculations set points were specified for activation of scram protection system.

STRENGTH CALCULATIONS

Strength calculations were made for the most strained elements of the target: window, inlet and outlet branch pipe , welds of the target body and diffuser plate [6]. The following components of TC-1 were considered: HX, VC, DT, coolant, water and gas pipelines.

The main loads are temperature influence, coolant pressure, weight loads and reactive force under stationary operation modes. Static strength calculations were performed according to the procedure accepted in Russian atomic industry. Calculations demonstrated that static strength of all target elements and TC-1 components are provided under chosen thickness and geometry dimensions of structural materials in all steady state operation modes including hydraulic tests. All requirements of static strength are met.

A lot of efforts was devoted to analysis of fatigue (cyclic) strength related to thermal cyclic loads on the target elements and TC-1 components under transient modes (beam trips) and accidents. The most strained elements proved the target window and HE inlet pipe.

Principal issue in the problem of fatigue strength is ductility decrease (embrittlement) of steel EP-823 as a result of irradiation. According to the available experience after in-pile irradiation up to ~80 dpa residual ductility of EP-823 steel was not less than 3%. Nevertheless, accelerator beam irradiation causes high accumulation of helium (10 to 100 times higher than that in the reactor) and it was assumed in conservative approach that in these conditions EP-823 steel could get zero ductility in the end of TC-1 lifetime.

The total number of cycles caused by beam trips, start and transient modes was estimated equal to $8{\cdot}10^{3}$. It was demonstrated that the window cyclic strength was provided even in the case of the steel zero ductility after irradiation. Effects of the beam pulse structure on the window stress are weak (there are stress oscillations with amplitude ~1% of average value).

Analysis of cyclic loads on the target outlet pipe resulted in arrangement inside of it a special screen in order to reduce temperature jumps and loads on the pipe walls. In the analysis of fatigue strength of TC-1 loop components, in addition to beam trips, transient modes and acidents were considered. It was demonstrated that fatigue (cyclic) strength of TC-1 components was provided.

COOROSION RESISTANCE OF TC-1 MATERIALS

Lead-bismuth eutectic alloy is used in TC-1 simultaneously as spallation target material and heat exchanger coolant medium. That is why the validation of corrosion resistance of equipment and window structure materials is important. Composition of lead-bismuth eutectic used in TC-1 is as follows: lead (44.5±0.5 wt %) and bismuth (55.5 ±0.5 wt %) with impurities (within 0.02 wt %). Helium is used as cover gas in lead-bismuth circuit.

Corrosion resistance of the membrane and perforated plate and stability of thermal and hydraulic characteristics of the coolant circuit with TC-1 irradiated by protons are provided owing to:

- proper choice of thermal and hydraulic parameters of coolant system, for which corrosion resistance of austenitic steel of X18H10T type and ferritic-martensitic steel EP-823 in lead-bismuth coolant has been proved by the duration testing of them in material test facilities and special reactor loops;
- maintaining purity of coolant circuit and gas system in the course of their manufacture and installation;
- maintaining required tightness of coolant circuit in all stages of TC-1 manufacture and maintaining excess pressure of the cover gas during its operation in all modes.

As a result of such a comprehensive approach the corrosion resistance of target circuit equipment materials is substantiated up to working temperatures 350-370^{o}C, while that related to the window material – up to 600^{o}C

RADIATION SAFETY

Calculations were made to estimate thickness of external radiation shielding that should be realized above TC-1 lid at LANL to decrease penetrating radiation (neutron, photons) levels to acceptable values under TC-1 testing in the proton beam [5, 6, 7].

Calculations of the external shielding were performed in 2 phase. On the first phase hadrons (neutrons, protons, and pions) distribution was calculated on the container lid. In this calculations the inner shielding and the TC-1 components arranged between the target and the lid were correctly considered. Radiation transport through the external concrete shielding was calculated by discrete ordinate method. Particle distribution on the lid calculated on the first phase was used as a source. It was assumed that personnel might work near external shielding during 2,000 hours per year with irradiation dose 50 mZv.

As a result of calculation it was determined that necessary thickness of the external shielding made of concrete with density of 2.35 t/m^3 must be ~6m in vertical direction and ~2m in lateral direction from the well edge. The total volume of the external shielding was estimated as ~40m^3.

Activity formation in the cover gas system was calculated. Total activity deposited on the surfaces of the gas system is: on polonium nuclides ~4.5·10^7 Bq, on mercury nuclides ~9·10^{13} Bq. Total gaseous activity is 6.2·10^{12} Bq and it is caused by Kr and Xe nuclides. Under normal operation conditions and possible leaks in the cover gas system (0.1% gas volume per day) and in the container (1% volume per day) equilibrium concentration of all nuclides released into the central hall is sufficiently lower than permissible concentrations specified for personnel by the USA Federal Register. The highest concentration is observed for the nuclides Xe-127 and Xe-129, namely, ~3% of permissible value. In the event of window rupture and leakage of 1% air volume per day from the container activity release into the vented containment is accounted for by radioactive noble gas nuclides and is equal to ~2 10^{10} Bq per day.

TC-1 PERFORMANCE

First TC-1 thermal tests in isothermal mode without simulation of energy generation caused by proton beam and without water supply to the heat exchanger was a final phase of work implementation in Russia [5, 6]. Special test facility was designed and manufactured at the special site of IPPE for TC-1 testing. The main purpose of the tests was to check performance of TC-1 components (electric heating system, MHD-pump and gas system under coolant forcing-over conditions) as well as confirmation of TC-1 main characteristics.

TC-1 testing included 5 phases:

- TC-1 heating from cold state to 200^{o}C (the main and reserve system of electric heating were checked).

- Filling of TC-1 loop from DT.
- Coolant circulation using the MHD-pump
- Coolant forcing over from TC-1 circuit into DT.
- Natural cooling of TC-1 and its transfer to cold (initial) conditions.

In the course of TC-1 tests operation of sensors and devices of instrumentation system was demonstrated, as well as operation of monitoring, control and safety system, and its components. In the whole, double testing of TC-1 carried out in Russia (2001) and in the US (2005) without proton beam demonstrated that TC-1 components monitoring, control and scram system reliably provided all technical parameters to be necessary for full scale testing of TC-1 under accelerator proton beam irradiation.

PROBLEMS OF MOLTEN METAL TARGET DEVELOPMENT

The experience gained in the course of TC-1 development gave an opportunity for better comprehension of the key issues of molten metal target realization in ADS. In this view, below noted are some problems [8, 9].

Assurance of the target window reliability is one of urgent tasks. The principle challenge is deterioration of mechanical properties of window material under proton-neutron radiation. This problem needs furthermore studies. Under proton beam radiation high accumulation of helium is observed. This accumulation is 10 to 100 times higher than that under radiation in nuclear reactors. For the window reliability it is necessary to provide its proper cooling and strength-ability under irradiation and thermal cyclic loads caused, mainly, by beam trips. In principle the molten metal target gives an opportunity of beam insertion without a window cooled with liquid metal. However, in this case the problem appears of coolant flow stability on the free surface and that related to evaporation of radioactive spallation products from coolant to the ion guide. In the whole, a windowless target, to our mind, requires additional R&D efforts.

Due to spallation and fission reactions the high specific activity formed in the coolant is as much as 100 times higher than that formed in lead-bismuth cooled reactors [6]. Due to gaseous (Kr, Xe) and volatile (Hg, Cs, I, Br, Rb) nuclides the gas activity in the cover gas system is approximately 10^5 times higher than that in the reactor under normal operation. At the same time rather high activity of mercury nuclides is observed (~30,000 Ci for TC-1) in the coolant of the target loop. About ~10% of this activity enters the cover gas system to be deposited on the walls. An important factor influencing to radiological safety during repair work or in case of accident with the loop integrity loss is accumulation of Po nuclides. Unlike reactors, where only Po-210 is formed, the long-lived Po-209 and Po-208 are also formed in target loop. Owing to the above factors assurance of radiation safety for target loops is more complicated than that for reactors.

If molten metal target operates for more than 1 year, then an important problem is to assure necessary purity of the coolant and corrosion resistance of structural materials of the circuit. This technology was developed for lead-bismuth as coolant for nuclear reactors. It implies, in particular, formation and maintenance of oxide films on structural materials surfaces to protect them against corrosion as well as reduction of lead oxides by means of insertion of gaseous mixtures with hydrogen. Specific features of the coolant technology for liquid metal target is caused by spallation product accumulation, which can influence physical-chemical processes in the coolant and destroy protective oxide films on structural materials surfaces, as well as high activity of the coolant and the cover gas, that causes high activity of gas mixture removed from the circuit, makes coolant technology loop non-repairable and essentially aggravates analysis of gas compositions.

Beam trips have two major consequences for the target that are not located in subcritical blanket: thermal cycle loads on the target circuit components and necessity to permanently support the temperature of heat exchanger cooling water much higher than coolant melting point (125°C for lead-bismuth), otherwise the coolant may be frozen. The important task is reliable beam removal in the events of target circuit component failure that is why the development of passive techniques for beam removal is urgent.

CONCLUSIONS

Experience of TC-1 development has shown that its reliable and safe operation requires maintaining purity of coolant circuit and gas system, assurance of tightness of coolant circuit and maintaining excess pressure of the inert cover gas. Besides, it is necessary to provide stable beam (without interruptions) of proton accelerator.

At present the TC-1 is lead-bismuth loop operating at UNLV at the temperatures up to ~300°C. Future use of TC-1 can be related to setting up technical and educational base for carrying out studies on the properties of lead-bismuth coolant within the above temperature range.

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