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Pre-Test Analysis of the MEGAPIE Spallation Source Target Cooling Loop Using the TRAC/AAA Code

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Abstract – *A pilot project is being undertaken at the Paul Scherrer Institute in Switzerland to test the feasibility of installing a Lead-Bismuth Eutectic (LBE) spallation target in the SINQ facility. Efforts are coordinated under the MEGAPIE project, the main objectives of which are to design, build, operate and decommission a 1 MW spallation neutron source. The technology and experience of building and operating a high power spallation target are of general interest in the design of an Accelerator Driven System (ADS) and in this context MEGAPIE is one of the key experiments. The target cooling is one of the important aspects of the target system design that needs to be studied in detail. Calculations were performed previously using the RELAP5/Mod 3.2.2 and ATHLET codes, but in order to verify the previous code results and to provide another capability to model LBE systems, a similar study of the MEGAPIE target cooling system has been conducted with the TRAC/AAA code. In this paper a comparison is presented for the steady-state results obtained using the above codes. Analysis of transients, such as unregulated cooling of the target, loss of heat sink, the main electro-magnetic pump trip of the LBE loop and unprotected proton beam trip, were studied with TRAC/AAA and compared to those obtained earlier using RELAP5/Mod 3.2.2. This work extends the existing validation data-base of TRAC/AAA to heavy liquid metal systems and comprises the first part of the TRAC/AAA code validation study for LBE systems based on data from the MEGAPIE test facility and corresponding inter-code comparisons.*

I. INTRODUCTION

MEGAPIE (**Mega**watt **Pi**lot Target **E**xperiment) is an initiative [1] launched by Commisariat à l’Energie Atomique, Cadarache (France) and Forschungszentrum Karlsruhe (Germany) in collaboration with Paul Scherrer Institut (PSI), to demonstrate, in an international collaboration (scientific groups from Belgium, France, Germany, Italy, Japan, South Korea, Switzerland and USA are partners in the study), the feasibility of a liquid lead bismuth target for spallation facilities at a beam power level of 1 MW. Such a target is under consideration for various concepts of accelerator driven systems (ADS) to be used in the transmutation of nuclear waste and other applications. The MEGAPIE experiment will be an important ingredient in defining and initiating the next step, a dedicated ADS-quality accelerator plus irradiation oriented target plus (at a later sub-stage) a low power, subcritical blanket. It is the goal of this experiment to explore the conditions under which such a target system can be licensed, to accrue a design data base for liquid lead-bismuth targets and to gain experience in operating such a system under the conditions of present day accelerator performance. Furthermore, design validation by extensive monitoring of its operational behavior and post irradiation examination of its components are integral parts of the project.

The ring cyclotron at PSI [2] with a 590 MeV proton energy and a continuous current of ~2.0 mA is used for a large range of scientific research projects, the most prominent one being the spallation neutron source (SINQ) with its large number of different user facilities. SINQ is designed [2] as a neutron source mainly for research with extracted beams of thermal and cold neutrons and except for its different process of releasing the neutrons from matter, it resembles closely a medium flux research reactor,

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since the neutron beams are extracted from a 2 m diameter heavy water moderator tank surrounding the target.

Target cooling is one of the important aspects of the target system design that needs to be studied in detail. The target is divided into two main parts: the upper target consisting of two submerged Electro-Magnetic Pumps (EMPs) and a Target Heat Exchanger (THX); the lower target consisting of the downcomer, beam window, riser and central rod. The target cooling system is described as a triple-loop, three-fluid system. A thorough study [3] of the MEGAPIE target cooling system has been conducted using the RELAP5/Mod 3.2.2 and ATHLET codes, but to verify the previous code results and to obtain an additional capability to model LBE systems, a similar study of the MEGAPIE target cooling system has been conducted with the TRAC/AAA code. In this paper a comparison is presented for the steady-state results obtained using the above mentioned codes. Several transients, such as an unregulated cooling of the target, loss of heat sink, trip of the main EMP of the LBE loop and an unprotected proton beam trip were studied with the TRAC/AAA code and compared to those obtained earlier using RELAP5/Mod 3.2.2.

II. THE TRAC/AAA CODE

Pre-test calculations/analysis of the possible transients for the MEGAPIE facility performed and presented in this paper were performed with the TRAC/AAA code [4], which is based upon a special version of the TRAC-M code developed initially at the Los-Alamos National Laboratory (USA) to simulate the transient behavior of fast-spectrum reactor systems cooled by liquid metal and gas. The fast-reactor aspects of the code were further enhanced at PSI [5]. The TRAC/AAA code, which is part of the PSI FAST code system [6] has in-built physical properties of LBE and the fluid Diphyl THT, fluids that were chosen as the primary and the secondary coolants in the MEGAPIE facility. In addition to the extensive validation and benchmarking of the original TRAC code, TRAC/AAA has recently been validated for application to LBE systems through the analysis of a range of transients performed in the TALL facility [7].

III. DESCRIPTION OF THE TARGET AND THE TARGET COOLING SYSTEM

Target cooling is one of the important aspects of the target system design. It has gone through elaborated conceptual design studies where many different options have been considered. The target design is presented in Fig. 1 [3]. The target is divided into two main parts, namely the upper and the lower target. The upper target consists of two submerged electro-magnetic pumps and a 12-pin target heat exchanger. The two pumps are the main EMP that provides the main flow for the target cooling, and the bypass EMP that provides the bypass jet for beam window cooling. The lower target consists of the downcomer, beam window, riser and a central rod. The downcomer guides the colder fluid from the exit of THX to the beam window. Once the flow passes the beam window, it turns upward into the riser. The proton beam penetrates into the liquid LBE to a depth of 250 mm. The region heated by the proton beam is called the active zone. The downcomer and the riser are separated by an un-insulated, thin wall main flow guide tube. A substantial amount of heat (i.e. ~ 100kW) is transfered from the riser to the downcomer, which heats up the LBE in the downcomer before it reaches the beam window.

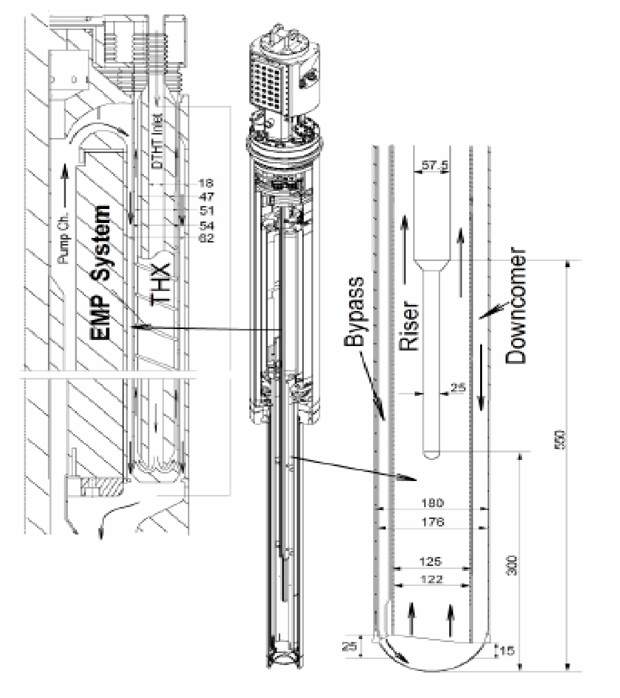

Fig. 1. The MEGAPIE liquid metal target.

The second circulation loop within the target is the bypass flow for beam window cooling. The bypass EMP takes in the colder LBE from the exit of THX and pumps it upwards through an annulus of the pump channel. Then through a collector mounted on top of the pump, the flow is turned downward and is distributed into three triangular ducts that fit tightly in the gaps of the magnetic core of the EMP. Before exiting the EMP housing, the triangular ducts converge into a single bypass tube, through which the LBE is guided all the way to the bottom of the target and injected through a nozzle onto the inner surface of the beam window. The bypass nozzle is mounted at the end of the main flow guide and aligned tangentially with curvature of the beam window.

The important component for target heat removal is the THX. It is a 12-pin design arranged in two semi-circles, and each pin is inserted in a cylindrical channel bored into the thick wall upper liquid metal container. On the primary side, LBE enters from the top and flows downward through the annulus (see the left side of Fig. 1). On the secondary side, Diphyl THT oil enters also from the top into the central tubes, and is turned upward at the bottom of the cooling pin into a spiraling path in the outer annulus (see Fig. 1). It is a counter current flow heat exchanger. The flows patterns are rather simple in this region and the heat transfer characteristics are well known.

The target cooling system is described as a triple-loop, three-fluid system. A simplified schematic of the cooling system is presented in Fig. 2 [3].

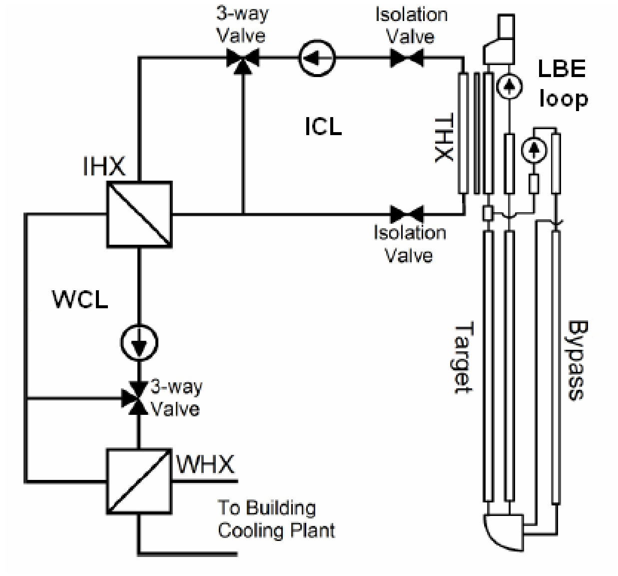

Fig. 2. A schematic of the MEGAPIE cooling system.

The primary loop is the LBE loop, which is often referred to as the target (see Fig. 1.). The Intermediate Cooling Loop (ICL) is connected thermally to the target through the secondary side of the THX. This loop is filled with Diphyl THT. This industrial organic coolant was chosen because of its stability over pyrolysis and radiolysis, and its operating temperature range (i.e. 0÷341 °C) fits within the design specifications of the cooling system. Furthermore, the operating temperature of the ICL is relatively high (i.e. 130÷240 °C). The high boiling and low vapor pressure are also the positive aspects of using the Diphyl instead of water. A Water Cooling Loop (WCL) serves as the buffer between the ICL and the main cooling plant of the SINQ building. The ICL and WCL are connected thermally through the Intermediate Heat eXchanger (IHX). Should any leak develop in the IHX, it will not contaminate the water in the main cooling circuit of the building.

IV. TRAC/AAA MODEL DESCRIPTION

The nodalization scheme of the MEGAPIE cooling system used in the TRAC/AAA calculations is shown in Fig. 3. This model was developed from the original RELAP5 model [3] used in the previous MEGAPIE cooling system analysis.

As can be seen from Fig. 3, the TRAC/AAA model of the MEGAPIE cooling system includes the primary LBE loop, the intermediate (Diphyl THT) loop and the water loop together with the building cooling plant connection.

The primary (LBE) loop can be divided into two, namely the main circuit for target cooling and the bypass for beam window cooling. The main circuit components are listed in Table I.

TABLE I

The main LBE loop components

Component	Description
505	collector
507	downcomer
509	beam window
513, 515	riser
517	pump entrance
888	main EMP
503, 520	piping
550	gap behind the EMP housing

The bypass circuit is an open loop because it takes in coolant from the collector and discharges it at the beam window. It consists of the bypass intake (522), the bypass EMP (889), pump outlet (523), down flow collector pipes (525) and the bypass guide (527), which ends with a nozzle. The LBE expansion tank is modeled with components 602 and 600. Heat structure 5031 simulating the THX is a connection element between the LBE loop and the ICL.

The main function of the intermediate (Diphyl THT) loop is to transport the heat from the LBE loop to the WCL. The main ICL components are listed in Table II.

TABLE II

The main ICL loop components

Component	Description
739, 742	isolation valve
743	check valve
110, 740, 741	ICL-TWV
887	pump
107, 112	tee
149, 150	expansion tank (ET)
100, 101, 103, 104, 105, 106, 108, 111, 113, 114, 115, 116, 118, 119, 120, 171, 173, 174, 176	piping

Diphyl THT pump (887) is installed on the hot leg (upstream of the IHX) in order to provide a higher pressure in the IHX (htstr 3031) compared to the THX (htstr 5031) for safety reasons (i.e. to avoid the ingression either of the water or the LBE in case of an accident). Heat structure 5031 simulating THX is a connection element between the LBE loop and the ICL, while heat structure 3031 simulating the IHX is a connection element between the ICL and the WCL. ICL-TWV installed upstream of the IHX, distributes the flow between IHX and the by-pass line (120) during normal, part-load operation and during transients, in order to control the LBE cold leg temperature at a constant value of 230°C.

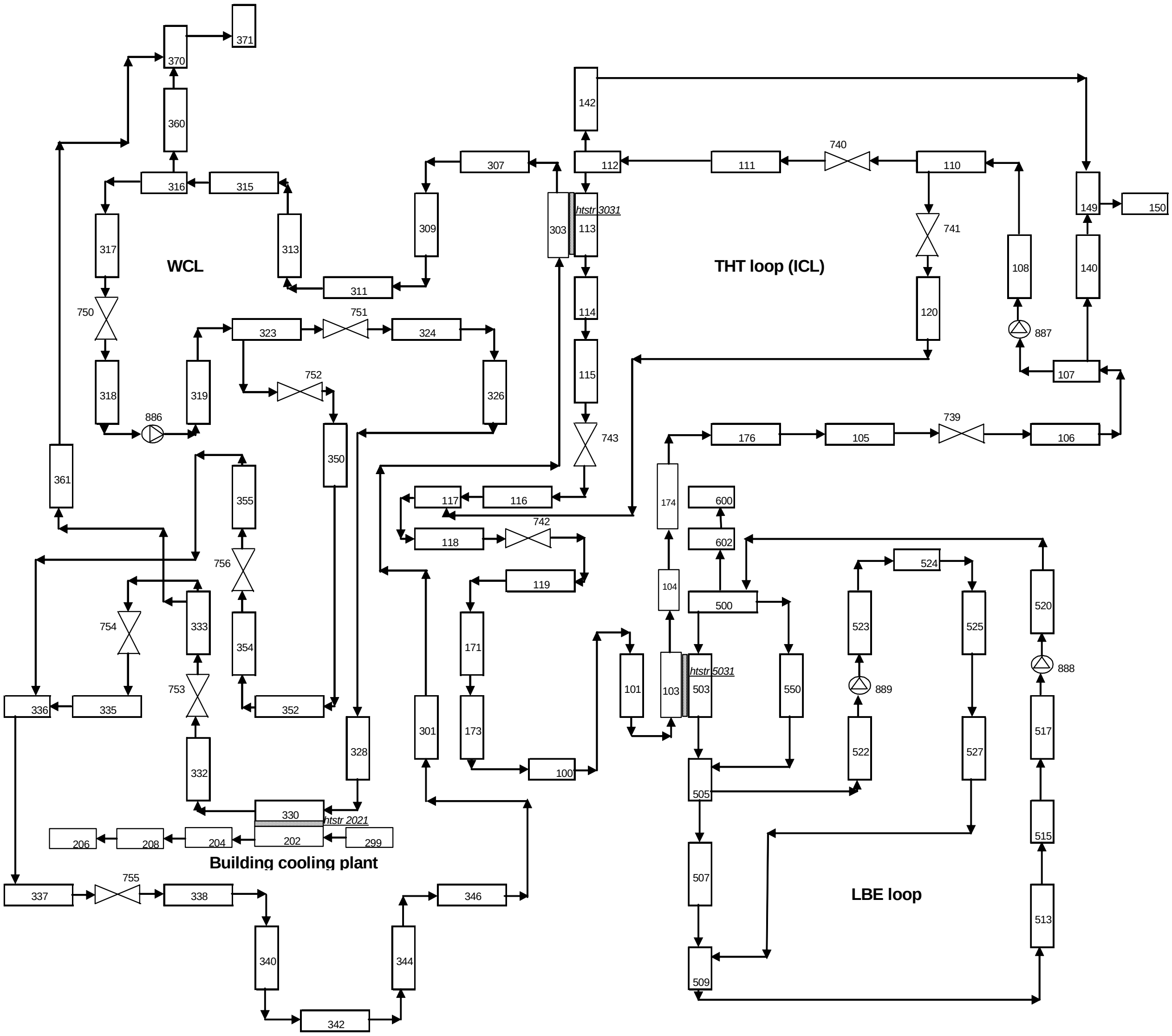

Fig. 3. A schematic of the MEGAPIE cooling system.

A check valve (743) is installed downstream of the IHX to prevent reverse flow through IHX, via the degassing line, with full bypass flow. An expansion tank (149, 150), shaped as a slim cylindrical vessel, is installed on the hot leg upstream of the pump (887) and is also connected to the inlet of the IHX. The arrangement is designed to vent out any trapped gas during filling and gases produced by radiolysis or pyrolysis. It also accommodates the thermal expansion of the coolant (Diphyl THT) during transients. The top of the tank is covered with Ar gas, which is also used for system pressurization. To avoid the ingression either the water or the LBE in case of an accident, the gas space of the expansion tank is set to be at 3.5 bar.

The water loop is an extra loop serving as a buffer between the ICL and the building cooling plant. The reason for such a loop is to eliminate any possibility of the Diphyl THT coolant leaking into the building cooling circuit. The design of the loop is almost like a copy of the ICL. It is a closed loop transferring the heat from the IHX (htstr 3031) to the Water Heat eXchanger (WHX (htstr 2021)), to which building cooling circuit is connected. The size of the main pipe construction is DN80 with the wall thickness of 3.2 mm. The main WCL components are listed in Table III.

TABLE III

The main WCL loop components

Component	Description
316, 333, 336	tee
370, 371	expansion tank
323, 751, 752	WCL-TWV
750, 756, 755	isolation valve
753	shut-off valve
754	check valve
886	pump
301, 303, 307, 309, 311, 313, 315, 317, 318, 319, 324, 326, 328, 330, 332, 335, 337, 338, 340, 342, 344, 346, 350, 352, 354, 355	piping

Heat structure 3031 simulating IHX is a connection element between the ICL and the WCL, while heat structure 2021 simulating WHX is a connection element between the WCL and the building cooling plant. The WCL is pressurized to approximately 4 bar for the nominal operation in SINQ, but can also be pressurized to a higher pressure of 10 bar for some of the test conditions during the Integral Test.

The pump (886) is installed in the hot leg upstream of the WHX (htstr 2021). There is no particular reason for such an arrangement. Based on the design, the cold-leg of is kept to an approximate constant temperature of 40 °C. A three-way valve (simulated by components 323, 751 and 752) is installed upstream of the IHX (htstr 3031) to regulate the bypass flow from the IHX, so that the cold leg temperature can be stabilized for any transient condition.

The Building coolant plant is simulated by fill component 299, pipe components 202 and 208, plenum component 204 and break component 206. Water from the building cooling plant is supplied at ~2.8 bar pressure and a temperature of 30 ^{o}C.

V. CALCULATIONAL RESULTS AND ANALYSIS

The transients simulated using the TRAC/AAA code and described below include: failing of a Three-Way-Valve (TWV) in the ICL and the WCL resulting in an unregulated cooling of the target, loss of the heat sink (ICL and/or WCL), trip of the main EMP of the LBE loop, as well as unprotected (when both TWVs are stuck and are not performing regulation of the LBE temperature) proton beam trip transients. The calculational results are presented together with a comparison to the corresponding RELAP5/Mod 3.2.2 results [3, 8].

V.A. Steady state operating conditions

The comparison of the calculational results of the MEGAPIE cooling system steady state conditions is based on the three system codes: RELAP/Mod 3.2.2, ATHLET-MF and TRAC/AAA. The results for the first two codes were taken from reference [3]. The anticipated steady state operating conditions of the MEGAPIE cooling system are presented in Table IV. These are the expected nominal conditions for SINQ operation.

TABLE IV

The nominal operating conditions of the MEGAPIE cooling system definition for the benchmark study

Target	Proton beam heat deposition on the target	581 kW
	Mass flowrate of the main EMP of the target	40 kg/s
	Mass flowrate of the bypass EMP of the target	2.5 kg/s
	Temperature (regulated) at THX exit	230 ^{o}C
ICL	Mass flowrate	8.0 kg/s
	THX inlet temperature	138 ^{o}C
WCL	Mass flowrate	8.0 kg/s
	IHX inlet temperature	50 ^{o}C

The steady state results obtained from RELAP5/Mod 3.2.2, ATHLET-MF and TRAC/AAA are given in Table V. The RELAP5/Mod 3.2.2 results were taken as the base values in the comparison and the percentage difference of the other two calculations with respect to RELAP5 are given in Table V. This shows that the operating conditions within the target - the predicted LBE temperatures and flow-rates – are within 2% in case of ATHLET-MF and within ~1.1% in case of TRAC/AAA, which is an excellent agreement. It should be noted that the flow through the THX is less than 40 kg/s in the RELAP5 and TRAC/AAA calculations, because a small amount of LBE flows through the EMP gap, which is modeled in RELAP5 and TRAC/AAA but not in ATHLET-MF. Bigger differences in the coolant temperature and flow-rate predictions can be seen for the ICL as predicted by ATHLET and TRAC/AAA. Temperature and coolant flow-rate differences in the ICL can be explained by the different coolant (Diphyl) properties that were used in the RELAP5 [3], ATHLET and TRAC/AAA calculations. This resulted in different flow-rate and temperature values around the circuit. Some differences can be observed also in the temperature and flow-rate predictions for the WCL as calculated by different codes. These differences can be explained by slightly different modeling of the WCL in different codes.

TABLE V

Steady state operating conditions of the MEGAPIE; comparison of different code results

			RELAP5	ATHLET-MF	Percentage difference	TRAC/AAA	Percentage difference
Target	Flowrate, kg/s	Main circuit	39.5	40.0	1.3	39.56	0.2
		Bypass circuit	2.5	2.5	0.0	2.5	0.0
	Temperature, °C	THX inlet	329.5	326.6	-0.9	325.8	-1.1
		THX outlet	230.0	226.1	-1.7	230.6	0.3
		End of downcomer	250.2	245.3	-2.0	251.5	0.5
		Top of active zone	344.7	339.5	-1.5	347.9	0.9
	Heat transfer through, kW	MFG	114.3	92.2	-19.3	116.3	1.7
		Bypass tube	1.05	1.5	42.9	1.00	-4.8
ICL	Flowrate, kg/s	Through THX	7.91	7.9	-0.1	7.91	0.0
		Through IHX	4.64	4.621	-0.4	4.05	-12.7
		Through bypass	3.27	3.276	0.2	3.86	18.0
	Temperature, °C	THX inlet	136.5	147.0	7.7	139.9	2.5
		THX outlet	174.5	175.7	0.7	168.7	-3.3
		IHX inlet	175.2	175.8	0.3	168.7	-3.7
		IHX outlet	110.4	124.8	13.0	108.5	-1.7
WCL	Flowrate, kg/s	Through IHX	7.96	8.0	0.5	7.98	0.3
		Through WHX	6.46	6.616	2.4	6.45	-0.2
		Through bypass	1.54	1.384	-10.1	1.54	0.0
	Temperature, °C	IHX inlet	50.5	52.0	3.0	53.0	5.0
		IHX outlet	68.9	69.7	1.2	70.6	2.5
		WHX inlet	69.6	69.8	0.3	70.8	1.7
		WHX outlet	46.7	48.3	3.4	48.7	4.3

V.B. Unprotected proton beam trip

For the code transient benchmarking, the first case selected was the unprotected proton beam trip transient. Codes that were used in this exercise were RELAP5/Mod 3.2.2 [3] and TRAC/AAA.

Although SINQ is a continuous spallation neutron source the proton beam does not run continuously without interruption because all the ultra-sensitive detectors deployed in the injector and along the beam lines can trigger a shut down of the beam instantly whenever a fault signal is detected. There are two different types of interruptions, namely the beam trip and the beam interrupt. Beam trip is a short interruption of the beam when the beam is shut-off instantly, followed by a 10 s shut-off time, and switched back to full power in a 20 s period. This event happens quite frequently; roughly 50 times a day. For a beam interrupt, the proton beam is shut off instantly but without a recovery for an extended time period (i.e. > 30 s). The duration of this beam shut-off can last from several minutes to a few days. This type of interruption happens less frequently; approximately one or two times per week.

This section of the paper presents the results of the first type of beam interruption – the beam trip. The case that was simulated using RELAP5 [3] and TRAC/AAA is the unprotected beam trip transient. The scenario of the transient is as follows: the proton beam is shut off (tripped) instantly at time 1000 s, followed by a 10 s down time, and switched back to full power in a 20 s ramp. In this case, both of the three-way valves (ICL-TWV and WCL-TWV) remained in their steady-state operational positions during the whole transient.

The resultant temperatures at the inlet and outlet of the THX as predicted by RELAP5 [3] and TRAC/AAA during the unprotected beam trip transient are presented in Fig. 4. From Fig. 4, one can see that at the start of the beam trip, with a small delay, the LBE temperature at the THX inlet quickly drops down by ~ 70 °C, but after the restart of the beam, it goes up and stabilizes at its initial value. The LBE temperature at the THX outlet at the same time falls down to 212 °C (217°C in case of RELAP5) at the start of the beam trip, but later it recovers to its original value of 230 ^{o}C. Very slight differences can be seen in the behavior of the LBE temperature at the outlet of the THX in the initial stage of the transient as predicted by TRAC/AAA and RELAP5. These differences probably result from the slightly different TRAC/AAA and RELAP5 models of the MEGAPIE cooling system and the different ICL physical properties both of which will produce small differences in the heat exchanger (THX) characteristics.

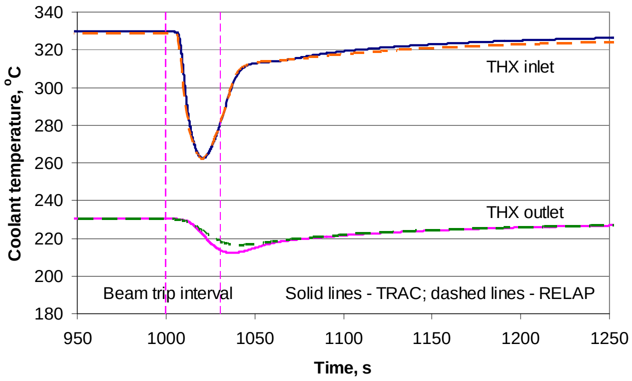

Fig. 4. The LBE temperatures at the inlet and the outlet of the THX during the unprotected beam trip transient.

Despite of the small differences in the calculations, the TRAC/AAA and RELAP5 results for the unprotected beam trip transient are in good mutual agreement.

V.C. Failure of a valve – unregulated cooling

The second transient benchmark case selected was the failure of the ICL-TWV with a simultaneous unprotected proton beam trip or beam interrupt, and the codes used were RELAP5/Mod 3.2.2 [8] and TRAC/AAA.

Since any active component may fail at some point it is a valid question to ask - what if one of them fails. The active components of the MEGAPIE cooling system are: i) the TWVs which bypasses the heat exchanger in the ICL and WCL; ii) the isolation valves in the ICL as a barrier for the active LBE; iii) all the re-circulation pumps in the target and cooling loops (total 4). The failure of one of these components will significantly compromise the system capacity. However, a single component failure does not necessarily mean the end of the irradiation test. If the failed component is located outside the active region (e.g. in the ICL and WCL), there is a good chance that it can be repaired or replaced. Every effort must be made to ensure a component failure does not develop further so that the system has a better chance to be recovered.

For this exercise one component is assumed to fail and that is the ICL-TWV. The TWV in either the ICL or the WCL are the only devices available to regulate the coolant temperature as all the pumps run at a constant speed. Since there is no preset "fail-safe" position, a failing TWV can fail in any position as follows: i) sticking in a position (most likely the nominal position); ii) completely open to the heat exchanger; iii) complete bypass of the heat exchanger. It is clear that the system would not be able to operate in the pre-defined conditions if one of the TWVs fails to response to the control system. In some cases, the target temperature field may not even change, for example there is no effect on the target operation if the WCL-TWV sticks at any position that lets more than 30% of the flow through the WHX. The reason for this is that the target temperature is to a large extent controlled by the ICL-TWV. The ICL has sufficient capacity and flexibility to absorb significant changes in the WCL. In general, the system has less tolerance to a fault in the ICL, because the operating temperatures of the target and ICL are the direct consequence of the ICL-TWV operation.

As was described above, during the steady state operation no critical limit is violated with full beam power on if one of the TWV fails. If the ICL-TWV sticks in the nominal position during a beam trip (see section V.B.), it has little impact on the transient. If the cooling is not regulated in such a short time (i.e. < 30 s), it results in a few additional degrees drop in the LBE temperature which has no impact on the operation of the facility. The only case, which needs to be considered is the beam interrupt or shut off (see section V.B.). This is also simulated to start at a time of 1000 s. If the proton beam heating is switched off, the unregulated cooling is capable of taking out more than half of a MJ per second. Therefore it takes only a short time to cool the LBE down to freezing. The cooling down process after a beam interrupt has been simulated using the two codes. Two cases of unregulated cooling, namely 100% (fully open) and 20% flow through the IHX, are presented in Fig. 5.

For 100% ICL flow through the heat exchanger (ICL-TWV pos. 1.0, Fig. 5) the initial steady-state temperature is ~ 250°C and it takes ~ 210 s for the LBE to freeze. For the second case with 20% of the ICL flow through the heat exchanger the initial LBE temperature is ~360°C and it takes ~ 750 s (~ 850 s in case of RELAP5) for the LBE to freeze. If the valve sticks at the nominal position (i.e. ~ 67% flow through IHX in case of RELAP5 and ~ 46% in case of TRAC/AAA), it takes roughly ~ 300 s to cool down to freezing. To stop the cooling, the only possible action is to switch off the ICL-pump. The beam trip transient for each case is also presented in Fig. 5 and here the restart of the beam quickly restores the LBE to its initial temperature. Note that the curves for the beam interrupt cases are stopped at ~ 130 °C, because the LBE properties modeled in the system code(s) do not extend below the freezing point of the LBE.

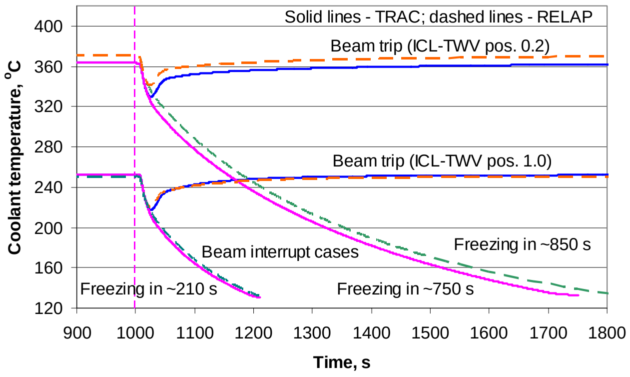

Fig. 5. Average LBE temperature in proton beam transients; violet and green lines are the cool down curve after a beam interrupt and the blue and orange lines are the transient curve during a beam trip.

From Fig. 5 one can see that TRAC/AAA and RELAP5 simulation results are in good mutual agreement for the beam trip and beam interrupt cases with ICL-TWV fully open, but some differences exist between the two calculations for the simulated cases with ICL-TWV open only to 20%. The trends of the LBE temperature behavior are the same in both simulations, the only difference being the LBE temperature level during the transients. This can be explained by the different effect of the 20% open ICL-TWV on the LBE temperature level in the target cooling loop. It should be born in mind that nominal position of the ICL-TWV, under normal operating conditions, differ in RELAP5 (~ 67% flow) and TRAC/AAA (~ 46% flow). In spite of some differences, the agreement between the two codes in predicting the cooling system response to the modeled transients is good.

V.D. Failing of a valve – loss of the heat sink

The next benchmark case to be simulated was a loss of heat sink transient and the codes used were RELAP5/Mod 3.2.2 [8] and TRAC/AAA.

The heat exchanger in each loop is the only path to transfer heat through the system (heat losses to the surrounding structures were not taken into account). The valve employed to regulate the cooling or to isolate the active part of the loop can also cut off the heat transfer path. If the flow through the heat exchanger is completely stopped without being detected, the rest of the system can heat up rapidly by the power deposited from the proton beam. The rate of the target heat up depends on the location of the heat transfer cut off. There are three different locations where this can happen: i) the ICL isolation valve(s) shut off the THX on the secondary side; ii) the ICL-TWV bypassing the IHX; iii) the WCL-TWV bypassing the WHX.

There are two isolation valves installed one in the inlet and one in the outlet pipes of the secondary side of the THX. Failing of any one of these two valves is sufficient to shut off the target heat sink. Without any simulation, one can simply determine the target heat up rate. For example the total thermal capacity of the target is ~ 500 kJ/°C (i.e. LBE + EMP system + structures) and with 581 kW of proton beam heating, the temperature of the target will increase by slightly more than 1°C/s.

If the heat flow path cut off point moves out to the ICL-TWV, there are more than a hundred liters of Diphyl THT coolant and all the thermal mass of the steel pipes and structures to add to the target. The total heat capacity of the oil loop is ~ 400 kJ/°C. So that including the thermal inertia of the oil loop, the average LBE temperature rises at a rate of ~ 0.6 °C/s under the full power proton beam conditions. The RELAP5 simulation results for this case (see Fig. 6) give a slightly steeper heat-up slope (i.e. ~ 0.7 °C/s). TRAC/AAA simulation of the same case (Fig. 6.) gives the LBE temperature rise equal to ~ 0.6 °C/s implying a slightly larger total LBE and ICL thermal capacity. It should be noticed as well, that in the initial phase of the transient, both codes predict similar behavior of the temperatures in Fig. 6, but only later some differences in the temperature increase slope begin to be obvious for the LBE, target structures and the main EMP.

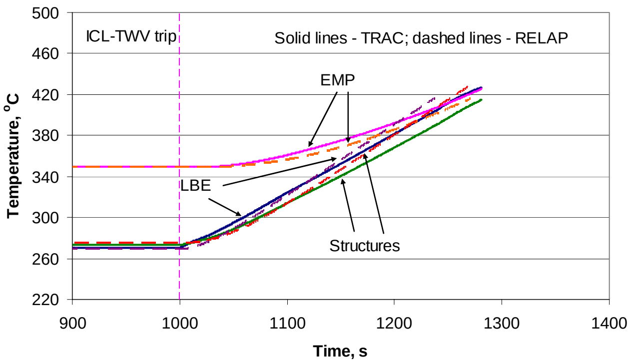

Fig. 6. The rising of average temperatures of LBE, target structures, and main EMP in the case when IHX is bypassed.

The behavior of the LBE temperature propagates to the temperature behavior of the EMP and the target structures. So the differences in the LBE temperature behavior as predicted by the TRAC/AAA and RELAP5 codes are also evident in the temperature behavior of the EMP and the target structures. Since the target is heated up homogeneously and gradually, thermal stress in the structures is not expected to be high. Also if the flow over the beam window region is not disturbed, the beam window temperature increase should not result in any extra stress. Thus, the determining factor of response time is on the temperature limit of Diphyl THT, but this time period should be sufficient for the operator to shut down the system in a duly way.

For the case when the heat transfer cut off point moves further out to the WCL-TWV, it is obvious that the heat up is much slower than in the previous cases due to the fact that the thermal masses of the ICL and WCL are involved in the transient (see Fig. 7).

A small discrepancy can be seen in the temperature behavior shown in Fig. 7 as predicted by TRAC/AAA and RELAP5, but that can be explained by the slightly different models of the MEGAPIE cooling system. One interesting observation is that it takes ~ 160 s (~80 s in TRAC/AAA case) before the temperature of the LBE responses to the changes in the target cooling system (see Fig. 7).

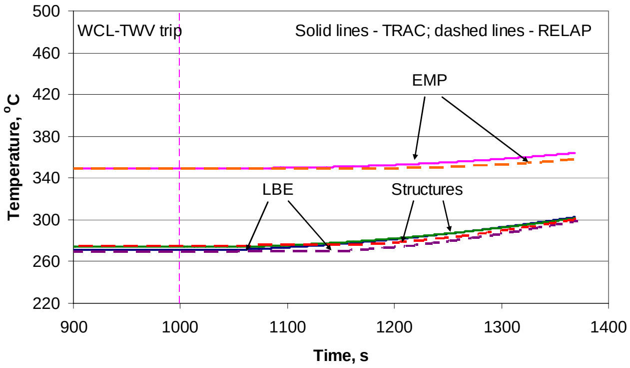

Fig. 7. The rising of average temperatures of LBE, target structures, and main EMP in the case when WHX is bypassed.

The bigger delay in RELAP5 case is due to the ICL-TWV's regulation. In the TRAC/AAA case the ICL-TWV was simulated to be stuck in its normal operating position and was therefore not performing any regulation. It is obvious that ICL-TWV operation does not play a significant role during this transient. The heat up is relatively mild and will not result in any risk of high thermal stress or over-heating of neither the target nor the ICL in a short term. The only critical issue is then the water boiling in the WCL. That condition comes at ~300 s after the WHX is bypassed. In any case, this time period should be sufficient for the operator to shut down the system and in this way to protect the IHX.

V.E. Failure of the main EMP of the LBE loop

The final benchmark case to be simulated is the failure of the main EMP in the LBE loop and the codes used were RELAP5/Mod 3.2.2 [8] and TRAC/AAA.

The design of the MEGAPIE cooling system is based on the use of forced convection loops therefore the failure of a circulation pump could greatly compromise the cooling capability of the system. There are a total of four pumps in the system: the main and bypass EMPs in the target and a normal centrifugal pump in each of the cooling loops (i.e. the ICL and the WCL). In this exercise the consequences of the failure of the main EMP in the target were investigated. The failure was simulated to start at time t=1000 s.

Before the study of this transient was performed, it was thought that the target could not withstand the failure of either of the EMPs, because the target structure might be damaged by the high proton beam heating if the cooling was not effective. However the studies reported in reference [9] demonstrate using CFD and FEM analysis, that the transient stress is not high enough to threaten the integrity of the target.

Following the main EMP trip at time 1000 s, the LBE temperature in the inner target increases rapidly to ~ 470 °C, but after ~70 s it reaches a new steady state value of ~ 440 °C. This can be explained by the fact that immediately after the main EMP trip the LBE flow-rate through the target falls to ~17 kg/s for a short period, but quickly (in ~10 s) natural circulation is established in the target, which stabilizes the temperature. Finally, the target LBE flow-rate settles to a new value of 21.4 kg/s which is approximately half the LBE flowrate during the normal operation of the main EMP. The average temperature of LBE in both the hot and cold legs of the target is shown in Fig. 8.

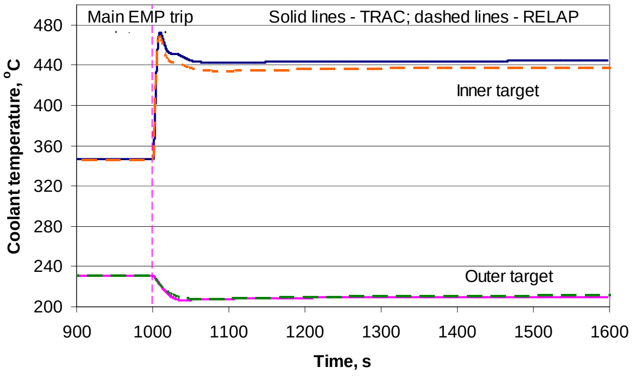

Fig. 8. The average LBE temperature of inner and outer target during the main EMP trip.

The close agreement of the final temperatures calculated by TRAC/AAA and RELAP5 shows that they both predict similar levels of natural circulation flow in LBE systems. The RELAP5 simulation gives slightly lower LBE temperatures in the inner target than the equivalent TRAC/AAA calculation.

VI. CONCLUSIONS

In the paper, the results of pre-test calculations of possible transients for the MEGAPIE test facility are presented using the TRAC/AAA code and compared with earlier calculations performed using the RELAP5/Mod 3.2.2 and ATHLET codes. In the paper a comparison is given for the steady-state results obtained using the above codes. In addition the analysis of several transients such as: failure of a TWV in the ICL and the WCL resulting in an unregulated cooling of the target, loss of heat sink, the trip of the main EMP in the LBE loop, as well as unprotected proton beam trip were analysed with TRAC/AAA and compared to the results of previous calculations using RELAP5/Mod 3.2.2. After the comparison of the calculation results the following conclusions were derived:

i) The comparison of the TRAC/AAA and RELAP5 calculational results for all the transients shows excellent agreement for the primary loop (LBE) parameters. Good agreement between the calculational results obtained by both codes for the primary loop of the MEGAPIE cooling system was demonstrated over a wide range of different transients. This is especially important, because the main aim of this comparison was a benchmarking of the codes through an inter-code comparison for LBE systems.

ii) The transient behavior of the LBE temperatures, especially at the inlet and the outlet of the THX, as well as at other locations of the LBE loop during the transients is in a good agreement between the two codes. Slight differences in the behavior of the LBE temperature during the transients as simulated by both codes can be explained by the coolant property differences particularly that of the ICL coolant Diphyl, as well as by slightly different models of the MEGAPIE cooling system as modeled in different codes. These differences have an impact on the heat transfer characteristics of the two heat exchangers.

iii) This is the first phase of the TRAC/AAA code benchmark and validation for LBE systems based on information available from the MEGAPIE test facility and continues the previous work for LBE systems based on the TALL facility. This work will continue in the second phase, when experimental data becomes available from the experiments in the MEGAPIE test facility.

iv) Application of the TRAC/AAA code to the analysis of the MEGAPIE target cooling system and its on-going validation provides access for the MEGAPIE team to an "in-house" system code capability for modeling LBE systems.

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NOMENCLATURE

ADS - Accelerator Driven Systems
EMP - Electro-Magnetic Pump
ICL - Intermediate Cooling Loop
IHX - Intermediate Heat eXchanger
LBE - Lead-Bismuth Eutectic
MEGAPIE - **Mega**watt **Pi**lot Target **E**xperiment
PSI - Paul Scherrer Institut
SINQ - Swiss Spallation Neutron Source
THX - Target Heat Exchanger
TWV - Three-Way-Valve
WCL - Water Cooling Loop
WHX - Water Heat eXchanger

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