Analyses of Transients for 400MWth-Class EFIT Accelerator Driven Transmuter with the SIMMER-III Code

P. Liu [1*], X.-N. Chen [1], F. Gabrielli [1], M. Flad [1], W. Maschek [1], A. Rineiski [1*], S. Wang [1], K. Morita [2], M. M. Rahman [2], Y. Ege [2]

[1] Forschungszentrum Karlsruhe, Institute for Nuclear and Energy Technologies, P. O. Box 3640, D-76021 Karlsruhe, Germany
[2] Department of Applied Quantum Physics & Nuclear Engineering, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, JAPAN

Email contact of main author: * ping.liu@iket.fzk.de, Andrei.Rineiski@iket.fzk.de

Abstract. European R&D for ADS development is driven in the 6th FP of the EU by the EUROTRANS Programme. In EUROTRANS, two ADS design routes are followed, the XT-ADS and the EFIT. The EUROTRANS Design Domain has developed a conceptual reference design of the EFIT, a 400 MWth ADT, loaded with a CERCER U-free fuel with an MgO matrix. For the clad, 9Cr1MoVNb T91 steel has been chosen. The core coolant is pure lead with inlet and outlet temperatures of 400 and 480 °C. EFIT design is to be optimized towards: a good transmutation efficiency, high burn-up, low reactivity swing, low power peaking, adequate subcriticality, reasonable beam requirements and a high level of safety. In the current paper, safety analyses performed with SIMMER-III are reported and discussed. Basically two different safety areas have been analyzed. Firstly, protected and unprotected transients which are initiated by a mismatch of power-to-flow or resulting from a beam disturbance or overpower situation. Secondly a steam generator tube rupture (SGTR) accident has been investigated with its potential impact on the active core. From the safety point of view all ADTs with a high load of Minor Actinides are characterized with a 'zero' Doppler fuel feedback, a high void worth for lead and a very small beta-effective. In addition the massive Helium production from the transmutation process leads to high pressure potentials in the plena. Although the boiling point of Pb is high, voiding may take place via two routes: gas release from the plena after pin failure or steam entering into the core after a SGTR accident. Severe of the transient scenarios analyzed are unprotected with beam-on: unprotected transient overpower, unprotected loss of flow and unprotected blockage accident (UBA). Beam trip scenarios are also analyzed. As the transient behavior of the MgO based fuel and the T91 clad has large uncertainties, the unprotected accidents with the potential of fuel failure and gas release deserve special attention. Extensive investigations have been performed for UBA as it represents a route into pin failure. A summary of all transient cases will be presented while more details reported concerning ULOF.

1. Introduction

European R&D for Accelerator Driven System (ADS) design and fuel development in the 6th EC Framework Programme is driven by the Integrated Project EUROTRANS [1]. In EUROTRANS two ADS design routes are followed, the XT-ADS and the EFIT. The XT-ADS is designed to demonstrate the feasibility of the ADS concept that is a subcritical core combined with an accelerator. The longer-term EFIT development (European Facility for Industrial Transmutation) aims at a generic conceptual design of an industrial-scale transmuter. The main goal of the EFIT design is to achieve effective transmutation of the Minor Actinides (MAs) while respecting important operational requirements as e.g. a low reactivity swing, a low power peaking, reasonable beam requirements and guaranteeing a high safety level. In order to have a sufficient safety level, EFIT design is postulated to have a k-eff near 0.97. A so-called 42-0 approach [2, 3] for fuel composition is proposed by ENEA and adopted in the EFIT core design. With this 42-0 strategy, the EFIT core should be able to transmute about 42 kg/TWh_{th} of MAs and keep near zero the net mass balance of Pu.

The current EFIT core is loaded with a CERCER U-free fuel with MgO as the matrix. The 9Cr1MoVNb (T91) steel is used for the clad, which has a maximum temperature limitation of

550 °C at the normal full power operation condition. Lead is used as the core coolant. It has an inlet temperature of 400 °C and an outlet temperature of 480 °C [4]. The temperature of 400 °C at core inlet provides a margin to avoid lead freezing, and the temperature of only of 480 °C at the core outlet offers many advantages in terms of reduced structure corrosion rates, improvement of the mechanical characteristics (making negligible creep of the structures), and reduces thermal shocks at transient conditions. Moreover at this 480 °C nominal average core outlet temperature, the fuel clad temperature can be maintained below the limit of 550 °C during the normal operation condition. Some core design data will be presented before going to transient analyses.

For EFIT safety studies, the defence-in-depth concept has been applied [5]. The demonstration of the adequacy of the design with the safety objectives is structured along three basic conditions: (1) The Design Basis Conditions (DBC - structured into four categories); (2) Design Extension Conditions (DEC - limiting events, complex sequences and severe accidents); (3) Residual Risk situations. The design of the plant results essentially from the analyses of the DBC events. It must be shown that their consequences are very limited and, in any case, the risk of a whole core accident initiated by these events is very low. DEC are evaluated for licensing purposes independently of their occurrence frequency. The consequences of these accidents are analyzed and their impacts on the environment have to be demonstrated to be lower than the limiting release targets. The consequences of Residual Risk situations are not analyzed since they are postulated to be unacceptable. The prevention measures regarding their occurrence have to be demonstrated to be sufficient.

The safety principles and safety guidelines have been elaborated For EFIT within EUROTRANS and a comprehensive and representative list of transients' analyses has been carried out to test the safety behavior of the reactor plant. For innovative reactors such as EFIT, cliff-edge effects should be identified and excluded. For safety analyses, fuel parameter limits related to the different accidental categories have been determined on the basis of recent experimental evidences. Due to existing uncertainties, fuel melting or disintegration may only be allowed in the DEC category.

Various protected and unprotected transients have been analyzed e.g., protected and unprotected loss of flow (PLOF/ULOF), beam trip transients, over power transients and especially unprotected blockage accidents (UBAs). Unprotected transients set upper safety limits and play an important role in the overall safety assessment, and transient behaviors of MgO based fuel and T91 cladding in the high temperature range are still connected with large uncertainties, therefore, unprotected accidents with a potential of fuel failure and gas release deserve special attention. In this paper, transient results will be presented while more discussions will be concentrated on ULOF and UBA.

All analyses presented in this paper has been performed with SIMMER-III [6, 7], which is a two-dimensional, multi-velocity-field, multi-phase, multi-component, Eulerian, fluid-dynamics code system coupled with a structure model including fuel-pins, hexcans etc., and a space-, time- and energy-dependent transport theory neutron dynamics model. The overall fluid-dynamics solution algorithm is based on a time-factorization approach, in which intra-cell interfacial area source terms, heat and mass transfers, and the momentum exchange functions are determined separately from inter-cell fluid convection. In addition, an analytical equation-of-state (EOS) model is available to close and complete the fluid-dynamics conservation equations. The code has originally been allocated in the severe accident domain of fast sodium cooled reactors. However, the philosophy behind the SIMMER development was to generate a versatile and flexible tool, applicable for the safety analysis of various reactor types with different neutron spectra and coolants, up to the new accelerator driven systems for waste transmutation.

2. Core Design of the 400MWTH-Class EFIT Accelerator Driven System

As the EFIT core design has already been presented in other publications [2, 3, 8], this paper will only give a short introduction. The EFIT core has been established as shown in Fig. 1. The core includes three fuel zones with 42 (inner), 66 (intermediate) and 72 (outer) Fuel Assemblies (FAs), respectively. Each FA has 168 fuel pins and one steel pin at its center. In order to flatten the power distribution, the inert matrix volume fractions and the pin sizes differ in different zones. The inner fuel zone has the same fuel pin as the intermediate zone while the outer zone has a larger fuel pin. In Fig. 1, only one FA has been labelled as Hot FA in each zone, while due to symmetry of the core, there are 6 Hot FAs in each zone. The 42-0 strategy determines that in all the three zones the TRU fuel contains 45.7 wt% Pu in order to keep the reactivity almost constant during reactor operation. In the inner zone, the volume fraction of MgO in the fuel pellet is 57% while in other zones it is 50%, the lowest possible limit for the matrix in the inert matrix fuel.

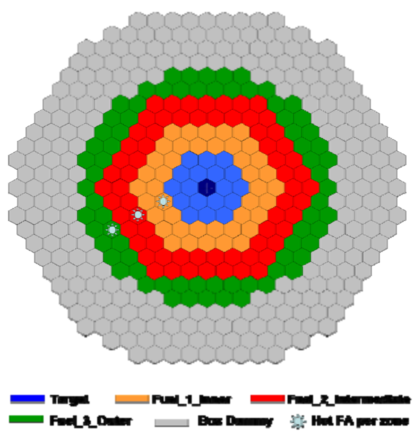

FIG. 1. Layout of the 384MWth Three Zone Core.

3. SIMMER-III Model of the EFIT Core and the Steady-state Results

In SIMMER-III simulations, the fuel assemblies have been subdivided into 6 fuel rings in the core, with each zone including two fuel rings. Fig. 2 shows the geometrical model of the EFIT core adopted in the SIMMER-III simulation. The first three radial meshes are used to represent the target region. Fuel rings are located at the radial meshes 5, 7, 9, 11, 13, and 15. Narrow coolant channels are modelled by the radial meshes 4, 6, 10, 12, and 14 in order to take into account the inter-wrapper flow and the radial heat transfer between FAs. The core is surrounded by outer dummy and absorber assemblies. The pump head transient behaviour can be taken into account in the simulation by a newly implemented in SIMMER-III pump model [9]. The heat exchanger has been taken into account in the SIMMER-III model by simulating a proper heat sink in the heat exchanger region to assure that in the closed coolant flow circle, the coolant temperature at the core inlet is 400 °C.

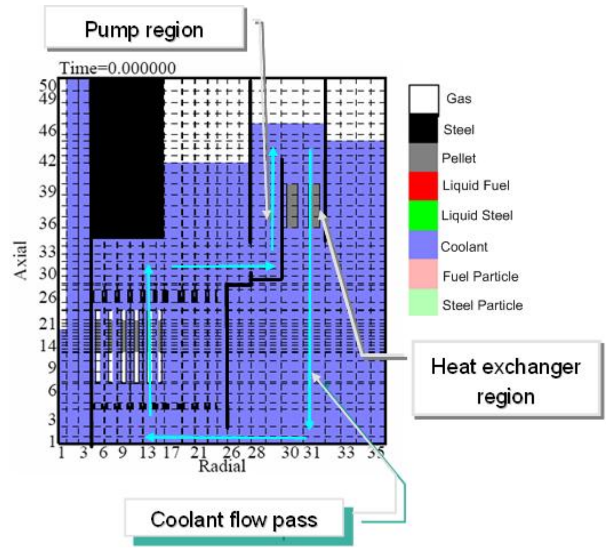

FIG. 2. Geometrical Model of the EFIT Core in SIMMER-III.

Table I shows some key steady-state parameters calculated by SIMMER-III together with their corresponding ENEA design values obtained by ERANOS/MCNPX [10]. From this table, we can see that the SIMMER-III simulation of (total) power distribution, effective delayed neutron fraction, Doppler effect at the steady-state condition is in a good agreement with the respective values from the ENEA design calculations [3, 10]. Some difference exists in the whole active-core void worth as SIMMER has a 500 pcm larger active core void worth comparing to the MCNPX results. SIMMER-III simulated peak fuel temperature is 1340 °C while the peak clad temperature is 520 °C. The design limit for the peak fuel temperature (1380 °C) and the peak clad temperature (550 °C) at the steady operation condition are well respected.

TABLE I: COMPARISON OF STEADY-STATE PARAMETERS.

Parameter		**Inner zone**	**Middle zone**	**Outer zone**	**Reflector-dummy + by-pass**	**Total**
Nominal temperature	°C	400°C (inlet), 480°C (outlet)			-	
Power (SIMMER-III)	MW	94.65	143.26	142.57	-	380.48
Power (ENEA Design)	MW	95.98	142.31	140.48	-	378.77
Pb mass flow rate (SIMMER-III)	kg/s	7854.1	12248.7	12036.8	1176.5	33326.1
β-eff	pcm	159 (SIMMER-III), 148 (MCNPX)				
Whole active-core void worth	pcm	7169 (SIMMER-III), 6670 (MCNPX)				
Doppler constant	-	near zero (SIMMER-III and ERANOS)				
K-eff	-	0.975 (SIMMER-III)				

4. Transient Analyses

The structural material in the EFIT is ferritic-martensitic steel T91. For the EFIT clad and structural materials a protecting aluminization treatment with a GESA type technique is foreseen, so no thermal conductivity reducing oxidation layers have to be taken into account on the cladding surface [11]. Before going to discuss the transient cases, the clad limit temperature adopted in the SIMMER-III simulations is shown in Table II. As a 10-bar pressure in the gas plenum is assumed in all transient cases, the clad limit temperature of 1007

°C for one second failure time is adopted in the simulations, which leads to gas blow-out from the pin.

TABLE II: CREEP FAILURE TEMPERATURE LIMITS FOR T91 STEEL

Pressure in the plenum	**Temperature limits at corresponding failure time [°C]**					
	0.1 s	1 s	10 s	2 min	30 min	10 hour
10 bar	1069	1007	950	894	838	783
50 bar	1042	981	925	870	815	761
100 bar	1009	949	894	841	788	735

In Table III, transient cases which have been analyzed with the SIMMER-III code, and their relevant boundary conditions are specified. These SIMMER-III calculated cases mainly comprise transients caused by beam variations, reactivity changes and coolant blockages, namely, the beam trip (BT), the protected and unprotected transient overpower (PTOP and UTOP), the protected and unprotected loss of flow (PLOF and ULOF), the protected and unprotected coolant flow blockage accident (PBA and UBA), the beam overpower and the HX Tube Rupture Accident. 'Unprotected' is synonymous with a 'beam-on' condition during the accident sequences while "protected" means a "beam-off" condition.

TABLE III: DEFINITION OF ANALYZED TRANSIENTS

Transient No.	**Transient cases**	**Descriptions**	**Burn-up state**
P-1	PLOF	Source-off after 3 sec of the start of LOF, Pump stops within 1 sec	BOL
P-2	PTOP	500 pcm jump in reactivity, Source-off after 3 sec of the starts of over power	BOL
P-9	Protected blockage with radial heat transfer (PBA)	Source-off after 3 sec. of start of blockage, flow rate of peak FA-ring reduced to less than 10%	BOL
P-10	Spurious beam trips (BT)	Beam trips for 1 and 10 sec intervals	BOL
U-1	ULOF	Complete loss of all forced/enhanced circulations in primary system, pump stops within 1 sec	BOL
U-2	UTOP	500 pcm jump in reactivity	BOL
U-9	Unprotected blockage with radial heat transfer (UBA)	Flow area of peak fuel assembly (FA) ring reduced to less than 10%	BOL
U-10	HX tube rupture	Steam generator tube rupture – 1 tube failure	BOL
U-11	Beam overpower	20% beam increase at hot full power	BOL

4.1. A Summary of All Transient Cases

Postulated severe accident scenarios shown in Table III, starting from steady state conditions, have been investigated. Table IV is a summary of maximal temperatures of clad, fuel and coolant in the different transient cases except for the beam trip cases. For the beam trip cases, the maximal temperature drop instead of the maximal temperatures are labeled in Table IV since in these cases, the temperature drops are of more important concern compared to the temperatures themselves.

As can be seen from Table IV, except for unprotected blockage cases, from the thermal hydraulics point of view, ULOF (U-1) is the most crucial transient case which needs careful attention for insuring safety of the EFIT core. Comparing to UTOP (U-2) and Beam

TABLE IV**:** MAXIMAL TEMPERATURES IN CORRESPONDING TRANSIENT CASES

Transient cases	Clad maximal temp., °C	Fuel maximal temp., °C	Coolant maximal temp., °C
P-1, PLOF	690	1340	686
P-2, PTOP	524	1380	492
P-9, PBA	688	1364	679
P-10, 10s Beam trip	88 (Temp. decrease)	743 (Temp. decrease)	65 (Temp. decrease)
P-10, 1s Beam trip	14 (Temp. decrease)	129 (Temp. decrease)	10 (Temp. decrease)
U-1, ULOF	884 (Overshooting)	1687 (Overshooting)	858 (Overshooting)
	730 (Final stabilized)	1552 (Final stabilized)	685 (Final stabilized)
U-2, UTOP	538	1530	503
U-9, UBA	1430 (clad breaks up close to melting point)	Pin breaks up due to cladding lost	Few local coolant boiling happens
U-11, Beam overpower	545	1597	507

overpower (U-11), ULOF has the highest peak temperatures of clad, fuel and coolant. Luckily, with the current simulation conditions, the peak temperatures in ULOF are still below their corresponding failure limits, therefore, it can be concluded that the current EFIT core can survive a ULOF, UTOP, and beam overpower from the point view of thermal hydraulics.

Concerning the beam trip cases (P-10), although the maximal temperatures are not our concern here, the maximal temperature drop during the beam trip intervals needs very much attention. With a 10-second beam trip, the maximal fuel temperature can drop 743 °C from its initial value while in a one second beam trip case it can still drop 129 °C. These large temperature drops may lead to significant thermal stress in the pellets which, in turn, affect the integrity of the fuel pellets. The beam trip transient results should be taken into account in the mechanical analysis of the fuel pin.

Obviously, the blockage transients are the most severe accident cases among all these simulated transient cases. Pin failure happens in the core in a UBA situation. Since the knowledge of the blockage scenario is still very limited and the material properties under high temperatures are unsure, further investigations need to be performed both experimentally and theoretically concerning the material behaviors in a high temperature range as well as the possible blockage phenomena themselves.

Results of all protected transients, namely PLOF (P-1), PTOP (P-2) and PBA (P-9), indicate that if the beam can be shut off in time, all the above unprotected transients including even the blockage cases will not lead to any serious problem in the core. The core can finally arrive at a shut down condition.

The simulation of the SGTR accident (U-10) revealed some moderate ingress of steam into the core. The void volume in the core is in the range of 4 % at maximum, which would correspond to a reactivity contribution of roughly 300-500 pcm. From the current simulation a threat to the core via a massive voiding can not be deduced.

As ULOF and UBA are transient cases which needs more attention, besides the temperatures shown in Table IV, the following sections will further discuss the “overshooting” in the ULOF case, while detailed analysis with different sensitivities of the blockage conditions has been carried out and the results will be reported later in another paper [12].

4.2. ULOF (Primary Pump Head Loss within One Second)

In the ULOF analysis with SIMMER-III, the following boundary conditions are applied. The pressure drop in the whole system is 1.37 bar in a steady-state condition, while the primary pump will stop within one sec for the loss of flow simulation. Fig. 3 shows transients of the pump pressure and the coolant flow rate in the whole core. ULOF starts at 2 sec counting from its initial steady-state. As the pump suddenly stops within one second, there is a very obvious overshooting of the coolant mass flow rate in the core, 30% reversed flow can be seen from Fig. 3 after the pump stops. The pump stop triggers a movement of coolant levels which causes the phenomena described in the following. The undershooting of the coolant mass flow rate leads to the overshooting of temperatures as shown in Fig. 4. The coolant mass flow rate in the core is finally stabilized at 30% due to the natural convection in the system. With the 30% remained coolant heat removing capacity, the fuel, clad, and coolant peak temperatures finally stabilized again at 1552 °C, 730 °C, and 685 °C, respectively. Due to the overshooting, the peak temperature of fuel, clad, and the coolant is 1687 °C, 884 °C and 858 °C, respectively. Therefore, even taking the short time overshooting into account, the clad and coolant temperatures are well below the failure limit and also the fuel peak temperature is well below the limits for melting and disintegration (1877 °C) given by the 'Fuel-Domain' AFTRA of EUROTRANS [13].

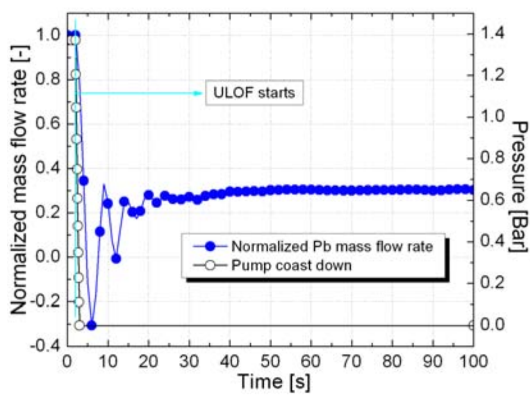

FIG.3. Pressure and Coolant Flow Rate Transients in the ULOF Case

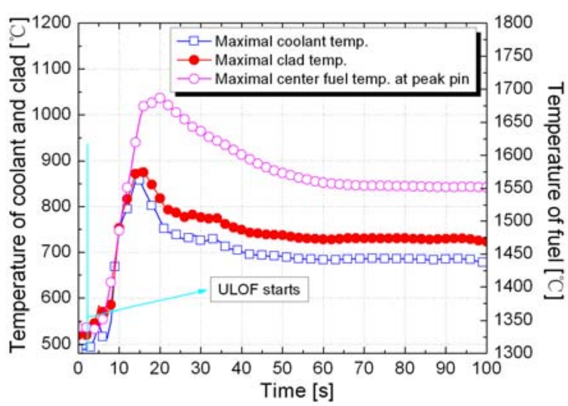

FIG.4. Temperature Transients in the ULOF Case

Fig. 5 shows the reactivity and power transient in the ULOF condition. The power is finally stabilized at around 2% higher than its nominal value. Although the power has increased a little bit more than 8% at the overshooting point, the overshooting temperature shown in Fig. 4 indicates that 8% power increase is acceptable with the current simulation conditions.

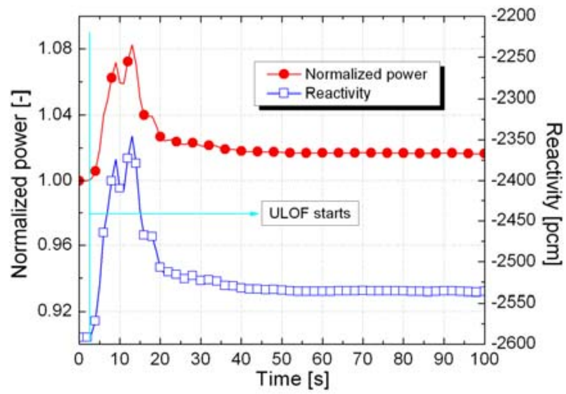

FIG.5. *Power and Reactivity Transients in the ULOF Case*

5. Conclusion

Different protected and unprotected transient scenarios have been analyzed for the EFIT core. Among all these scenarios, ULOF and UBA are the most severe transients. Under the current simulation conditions, except for the unprotected blockage case, the EFIT core can survive under all these transient conditions including the ULOF. UBA transients will lead to pin failures in the core. Because the knowledge of the blockage scenario is very limited and the material properties under high temperatures are unsure, further investigations need to be performed both experimentally and theoretically concerning the material behaviors in a high temperature range as well as the possible blockage phenomena themselves.

Acknowledgments

The authors appreciate the efforts and support of all the scientists and institutions involved in IP EUROTRANS, as well as the financial support of the European Commission through the contract FI6W-CT-2004-51652.

References

[1] KNEBEL, J. U., and FAZIO, C., "European research programme for the pransmutaion of high level nuclear waste in an accelerator driven system EUROTRANS", Jahrestagung Kerntechnik 2007, Karlsruhe, Germany, May 22-24 (2007).

[2] ARTIOLI, C., et al., "Optimization of the Minor Actinides transmutation in ADS: the European Facility for Industrial Transmutation-EFIT-Pb Concept", ACCAPP'07, Pocatello, U.S.A, July 30 – Aug. 2 (2007).

[3] ARTIOLI, C., et al., "Minor actinide transmutation in ADS: the EFIT core design," Int. Conf. on the Physics of Reactors "Nuclear Power: A Sustainable Resource", Interlaken, Switzerland, Sept. 14-19 (2008)

[4] CORSINI, G., et al., "Main components functional sizing of EFIT," EUROTRANS-DM1-WP1.2 Deliverable D1.24 (2007).

[5] EHSTER, S., "Approach and acceptance criteria for safety design of EFIT", EUROTRANS-DM1-WP1.5 Deliverable D1.21 (2007).

[6] MASCHEK, W., et al., "SIMMER-III and SIMMER-IV safety code development for reactors with transmutation capability", M&C 2005, Avignon, France, Sept.12-15 (2005).

[7] YAMANO, H., et al., “SIMMER-III: a coupled neutronics-thermohydraulics computer code for safety analysis”, 15th Int. Conf. on Nucl. Eng., Nagoya, Japan, April 22-26 (2007).
[8] LIU, P., et al., “First safety analysis for the EFIT core design”, Jahrestagung Kerntechnik 2008, Hamburg, Germany, May 27-29 (2008).
[9] Wang, S., Private communication, 2008.
[10] SAROTTO, M., et al., “Specification for the EFIT core and fuel element”, EUROTRANS-DM1-WP1.2 Deliverable D1.6 (2008)
[11] Müller, G., et al., “Behavior of steels in flowing liquid PbBi eutectic alloy at 420–600 °C after 4000–7200 h,” J. Nucl. Mater. 335, pp.163-168 (2004)
[12] LIU, P., et al., “ULOF and Unprotected Blockage Accident Analyses of the 400MWth-Class EFIT Accelerator Driven Transmuter with the SIMMER-III Code”, The 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-13), Kanazawa, Japan, Sept. 27-Oct. 2, N13P1103 (2009).
[13] LIU, P., et al., “First safety analyses for an EFIT type accelerator driven transmuter”, AccApp’07, Pocatello, U.S.A, July 30 – Aug. 2 (2007).