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APPLICATION OF PACTITER V3.3 CODE TO THE ACPS ASSESSMENT OF ITER NEUTRAL BEAM INJECTORS PRIMARY HEAT TRANSFER SYSTEM

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I. INTRODUCTION

Neutron activation reactions will generate Activated Corrosion Products (ACPs) in ITER divertor, first wall/blanket (FW/BLK) and vacuum vessel (VV) cooling loops, as well as in any other auxiliary cooling systems, dedicated, as for example, to Test Blanket Modules (TBMs), Neutral Beam Injector or diagnostic equipments. Taking into account the experience gained in operating the fission nuclear power plants, where ACPs are responsible for about 90% of the Occupational Radiation Exposure (ORE) of personnel during inspections and maintenances[1], the prediction and minimization of ACPs inventory has been recognized as an important factor in both the ITER safety approach and the licensing process.

Computer code calculation of the ACPs inventory deposited onto the inner walls of the Primary Heat Transfer System (PHTS) cooling loops can provide an estimation of the resulting doses to personnel during the inspection and maintenance activities for both ORE assessment and ALARA processes (Refs. 2-3). Moreover, the ACPs inventory prediction in the PHTS cooling loops is needed for accidental analyses. For accidents not involving the in-vessel source terms, ACP may be the significant source term; e.g. for ex-vessel loss of coolant from first wall, divertor and Vacuum Vessel (Ref. 1). As documented in the Generic Site Safety Report (GSSR), (Ref. 4), and in the ITER Preliminary Safety Report (RPrS), (Ref. 5), the ITER Organization has included PACTITER as reference computer code for the prediction of the formation, activation, migration, deposition and removal of ACPs in the primary cooling loops. In the past the European fusion programs have defined safety related R&D for ITER and for future fusion plants. In this frame, EFDA and later on F4E, has co-financed Grant Agreements for the development of PACTITER computer code. The overall objective of the last Task Agreement launched in this field was the verification and validation of the PACTITER v3.3 code. As a side activity, it was foreseen an independent testing of the code, to be applied to an ITER PHTS cooling loop (Ref. 2).

II. BRIEF DESCRIPTION OF PACTITER V3.3

PACTITER code derived from the PACTOLE series of codes developed by the CEA (Commissariat à l'Energie Atomique) for predicting ACPs in Pressurized Water Reactor (PWR) primary circuits. The main modifications done to PACTOLE for PACTITER are:

- Addition of Cu element with the corresponding solubility data and nuclear reactions, as Cu alloys are used for ITER divertor plasma facing components (PFCs) and in some NBI components;
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The formation process of ACPs is very complex in an ITER PHTS loop like in a PWR one (Ref. 6), involving different mechanisms reacting among each other. The first one is the uniform and generalized corrosion of metallic alloys. For stainless steel, that leads to the generation of a dual oxide layer: an inner compact layer (chromite) and an outer porous layer (ferrite). The former is a passive oxide layer limiting ion exchanges between metallic alloys and primary coolant but does not eliminate them: ions are released in the primary coolant. The quantities of released materials are small (~ few mg/dm²/month) and do not alter component soundness. The primary coolant carries ions generated by the corrosion-release phenomenon or by oxide dissolution. When the coolant becomes supersaturated in corrosion products (CPs), ions can precipitate on the walls or in the bulk of the fluid to form particles. These are also generated by erosion processes and, if transported by the primary coolant, are deposited onto the circuit inner walls or can agglomerate. Dissolution and precipitation depend on the corrosion product equilibrium concentrations, which depend on coolant chemical treatment (pH, H_2 concentration or Redox potential, temperature). Two types of radioactive corrosion product formation coexist. On one hand, the activation of CPs occurs when they are deposited onto surfaces under neutron flux. On the other hand, the corrosion of structural materials under neutron flux is accompanied by a release of radioactive corrosion products. The PACTITER v3.3 code is based on a control volume approach, the primary circuit is represented by an arrangement of several volumes in which transient mass balance equations are solved. Seven different media are taken into account in a control volume as shown in Fig. 1. More details on PACTITER models are given in Ref. 6.

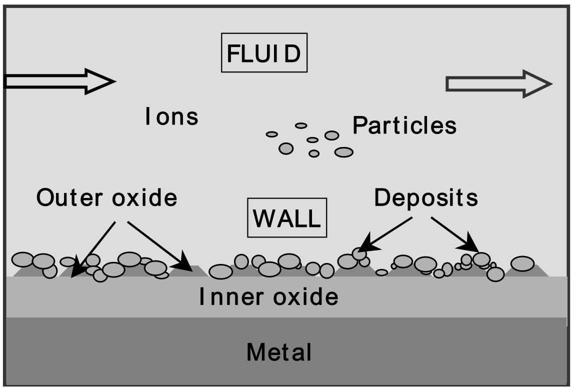

Fig. 1. Media in a PACTITER control volume

III. ITER NBI-PHTS LOOP MODELING

III.A. Description of the ITER NBI-PHTS loop

The function of the NBI-PHTS is to provide cooling water to the low voltage (LV) and high voltage (HV) components of both the heating and diagnostic neutral beams (HNB, DNB) injectors that are located in the neutral beam cell. Neutral Beam Injectors are used to shoot uncharged high-energy particles into the plasma where, by way of collision, they transfer their energy to the plasma particles. Before injection, deuterium (D) atoms must be accelerated outside of the Tokamak to a kinetic energy of 1 MeV. Only atoms with a charge (positive or negative) can be accelerated by an electric field. In Neutral Beam Injection systems, D ions (D-) will be accelerated, then, before injection, they will pass through a cell containing gas (Neutralizer) where they will lose their electron. Residual ions will be dumped by an electric field in the Residual Ion Dump, subsequently the beam of fast neutrals will be injected into the plasma. The NBI-PHTS is designed to cool down two HNBs and one DNB. Heat loads to be removed from individual NBI components vary depending on operational modes of the NBI. The NBI-PHTS is designed to provide several separate cooling water supplies to the NBI components which are under n-flux: LV-grounded grid; LV-Calorimeter; LV-Residual Ion Dump (RID); LV-Neutralizer; LV-Active Correction and Compensation Coils (ACCCs); HV-extractor and accelerator; HV-ion source; HV-plasma grid. The cooling water passes through the primary side (tubes side) of the main heat exchanger (HX) where it is cooled to ~35 °C to satisfy the chemistry requirements for all components. Temperature control is achieved using flow control valves on the main and bypass lines of the main HX.

III.B. Modeling of the NBI-PHTS for PACTITER simulation

The modeling of the NBI-PHTS loop has dealt with the description of the related geometric, thermo-fluido-dynamic, material features. The neutron activation of the HNBs and DNB cooled regions was done in a rough way, as validated data were not available. As preliminary guess, it was assumed a set of reaction rates for the main 13 activation reactions, relative to the most exposed region to n-flux; i.e. the exit scraper, equal to 1/10 of the values adopted in previous analyses by PACTITER on the DIV/LIM loop for the most exposed region to n-flux; i.e. the port limiter. The reaction rates for the other under flux regions of the HNBs and DNB were calculated by scaling down the reaction rates for the exit scraper by a factor between 0.05 and 0.8, depending from their distance from the plasma and position inside the HNBs or DNB. The geometric modeling implied a schematization and simplification of the complex architecture of the NBI-PHTS loop. The following basic-criteria were used to set-up the model: the total coolant inventory, wet surface and mass flow rate of the PACTITER model are the same as the real one; inlet coolant temperature of each injector component is 35 °C. The resulting geometric model of the NBI-PHTS, shown in Fig. 2, is composed of 44 regions.

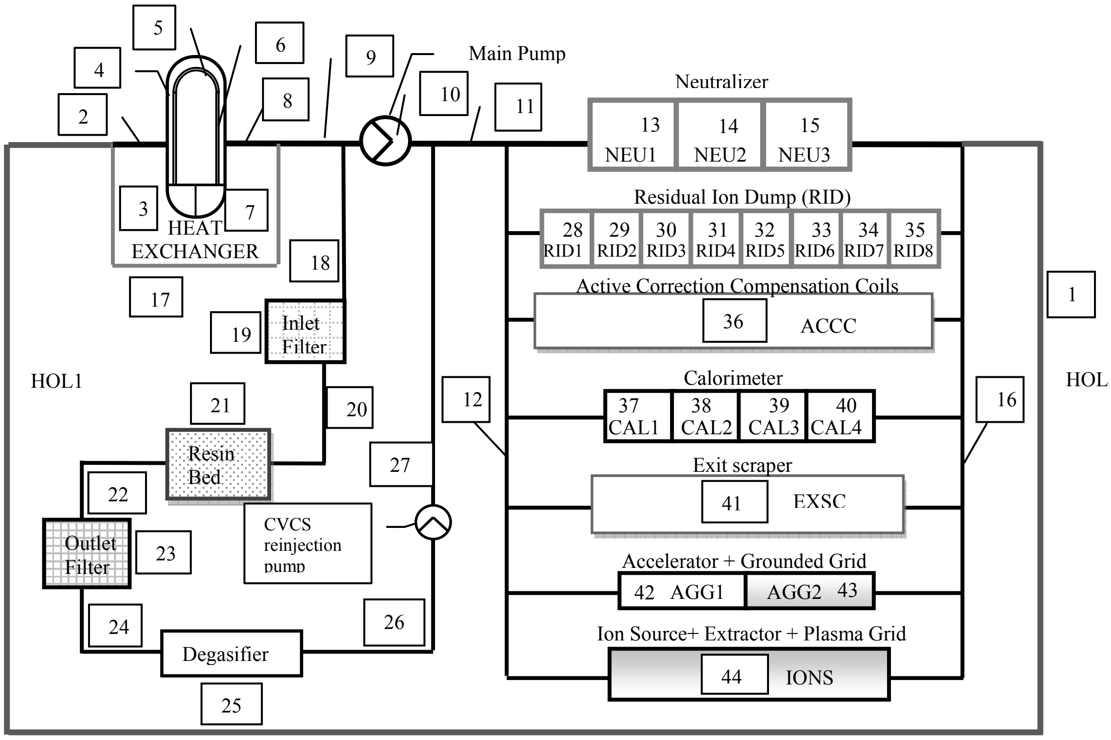

Fig. 2. NBI-PHTS geometric model for PACTITERv3.3 calculations

Regions from 1 up to 16 represent the main loop, all the others (17–44) the six bypasses serving the LV and HV components, the Chemical and Volume Control System (CVCS) and the HX bypass. The main geometric simplification made was to group similar zones of the cooling loop as unique pipe, keeping the value of wet surface and coolant volume. The pipe diameter is then given by the hydraulic diameter D_h of the lumped zones, which is obtained dividing the total coolant volume, multiplied by 4, by the total wet surface W_S, i.e.:

$$D_h = \frac{4 \cdot V}{W_S} \qquad (1)$$

TABLE I shows the total coolant volume and mass plus wet surfaces of the model, grouped for the in-vessel regions (under n-flux) and ex-vessel ones (out-of n-flux).

TABLE I. Total wet surface and coolant volume grouped in under n-flux and out-of n-flux regions

		Total
In-vessel wet surface (m^2)	4103.6	7448.0
Ex-vessel wet surface (m^2)	3344.4	
In-vessel volume (m^3)	10.4	82.1
Ex-vessel volume (m^3)	71.7	
In-vessel coolant mass (kg) *	10287.3	81491.9
Ex-vessel coolant mass (kg) *	71204.6	

* This is a mean value as the coolant density depends on its temperature

TABLE II shows the total wet surface of the four materials composing the NBI-PHTS and the related coolant volume. As one can see the largest wet surface is due to the pure copper or the Oxygen-free high thermal conductivity (OFHC) copper (mostly in the ACCCs). The outlet temperature of each in-vessel component was calculated by the AFT FathomTM code, for such analysis it was assumed the same scheme used in the Process Flow Diagram (PFD), specifying thermal-hydraulics properties such as: Heat Load, Flow Rate, and Pressure Drops for each component.

TABLE II. Total wet surface and coolant volume grouped according to the material in contact with the coolant

	W_S (m^2)	V (m^3)	W_S share	V share
CuCrZr Alloy	103.6	0.3	1.4%	0.4%
OFHC Cu & Cu	3879.5	7.9	52.1%	9.6%
SS 316 L	2736.0	23.5	36.7%	28.7%
SS 304 L	728.9	50.3	9.8%	61.3%
TOTAL	7448.0	82.1	100.0%	100.0%

OFHC = Oxygen-free high thermal conductivity Cu

IV. ITER NBI-PHTS LOOP ACP ASSESSMENT

IV.A. PACTITER input data definition

It was necessary to define an operational scenario and water chemistry parameters in addition to the geometric, thermo-fluido-dynamic, and material data (see Section

III). The detailed information to prepare the input deck was taken from the code user manual (Ref. 7). The operational scenario was derived from one of those presented by ITER which is based on 3 plasma operation 8-h shifts/day, divided in 14.4 h of Mean Up (or Operation) Time (MUT) and 9.6 h of Not-Scheduled Mean Down Time (MDT_{NS}). The operational cycle is organized in 2-week period with 11 Operation Days and 3 Routine Maintenance Days or Mean Down Time Scheduled (MDTs). The 2-week operational cycle is repeated 35 times in 16 months (experimental campaign) followed from 8-month major reactor shutdown. The experimental campaign (490 days) was schematized for PACTITER simulation considering the following split:

- MUT 231 days (~7.5 months)
- MDT_{NS} 154 days (~5 months)
- MDT_S 105 days (~3.5 months)

It was necessary to further divide the operation time or MUT in the basic operational phases of the NBI system; injecting and dwell/decay (between plasma pulses). It was also considered the beam source conditioning, operation required to set up the beam source optimal parameters before plasma operation. Conditioning was allotted with the phase named "idle" to the MDTs time. The MDT_{NS} time was defined as "maintenance". In order to reduce the computational time, the 490-day scenario was further reduced to 1/10th so having the simulation scenario of 49 days. The computing time required to simulate the 49-day scenario is ~ 2 hours. The 49-day scenario was organised in 23 steps alternating the various operational phases as summarised in TABLE III.

TABLE III. Main operation scenario data

Operational phase	Time [d]	H_2 [ppm]	T_{mh} [°C]
Idle (MDT_S)	6.9	0.06	35
Conditioning (MDT_S)	3.6	2	55
Injecting (MUT)	5.15	2	61
Decay/dwell (MUT)	18.0	0.06	45
Maintenance (MDT_{NS})	15.35	0.06	35

T_{mh} = Mean temperature of the primary fluid in the under flux regions

IV.B. PACTITER results and discussion

In order to scan the different parameters affecting the ACPs inventory results, some code runs were performed (see TABLE IV). The exact corrosion rates for CuCrZr and pure Cu, mentioned in TABLE IV, are shown in TABLE V. The corrosion and release rates for stainless steels (SS316L and SS304L) were calculated by the code and not given as input data as for pure Cu and Cu alloy. During injecting and conditioning, when neutrons are generated, the water chemistry was a reducing one, during the other phases it was assumed oxidizing ($H_2 \approx 0$ ppm, see TABLE III). It was also considered an initial CPs deposit and outer oxide mass equal to ~2.5 kg, corresponding to an average value of ~ 0.3 g/m^2. Results of the ACP mass inventory are shown in Fig. 3.

TABLE IV. Main PACTITER calculation parameters

Run #	Pure Cu & CuCrZr C_R	ACCCs Ws [m^2]	Resin effic.	Scenario duration	Flow rate to CVCS [kg/s]
3	Values 1	3798	0.98	49 days	30.5
4	Values 1	3798	0.98	98 days	30.5
5	Values 1	1899	0.98	49 days	30.5
6	Values 1	0	0.98	49 days	30.5
7	Values 1	3798	0.99	49 days	30.5
8	Values 1	0	0.98	49 days	30.5
9	Values 2	3798	0.98	49 days	30.5
10	Values 2	3798	0.98	49 days	61.0
11	Values 3	3798	0.98	49 days	30.5
12	Values 3	1899	0.98	49 days	30.5

C_R= Corrosion Rate; Runs #1 & #2 performed to set up the input deck

TABLE V. CuCrZr and Cu corrosion rates

CuCrZr & Cu Corrosion Rate	Reducing conditions [μm/y]	Oxidizing conditions [μm/y]
Values 1	1.50	5.00
Values 2	1.00	3.00
Values 3	0.73	2.19

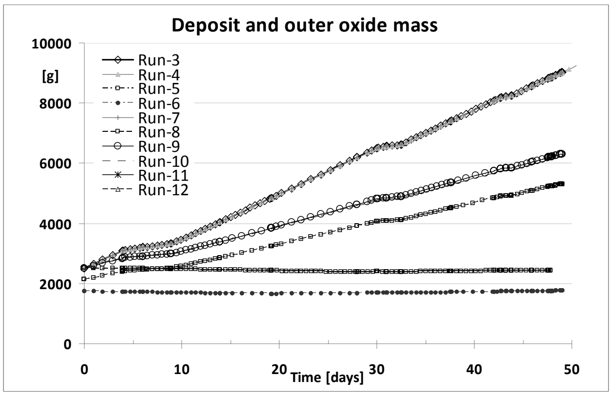

Fig. 3. PACTITER ACP mass for the different code runs

The most important parameter governing the build-up of the ACPs inventory is the Cu and Cu alloy corrosion rate, as shown in Fig. 4. The influence of CVCS flow rate (FR) and filter efficiency is relatively scarce, as no appreciable reduction in the ACP mass was assessed. It was also investigated the possibility to separate the LV-Active Correction and Compensation Coils (ACCCs) from the NBI-PHTS by a dedicated cooling loop. The impact of this choice would be remarkable in terms of ACP mass reduction (factor ~3.7; see Fig. 5 Run-8). That is explained by the large wet surface (Ws) of ACCCs (3798 m^2 which is ~50% of the total loop Ws) made of Cu and affected by a larger corrosion and release rates with respect to stainless steel regions. Another way to reduce the ACCCs Ws of a factor 2 is by doubling the pancake piping diameter from 8 to 16 mm. That would cause a drop of ~40% of the ACP mass (see Fig. 5 Run-5).

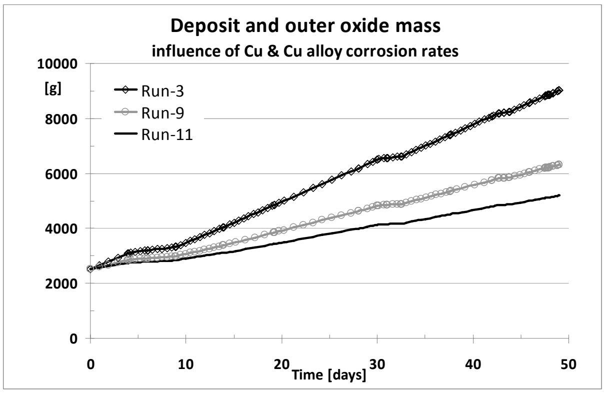

Fig. 4. ACPs mass for CuCrZr and pure Cu corrosion rate Values 1 (Run-3), Values 2 (Run-9), Values 3 (Run-11)

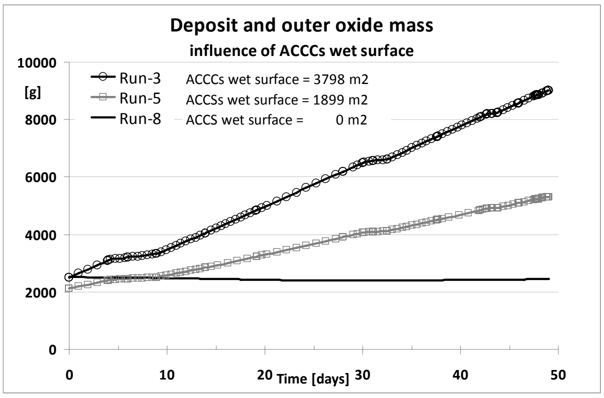

Fig. 5. Impact of the ACCCs Ws on the ACP assessment (Run-3: full Ws, Run-5: ½ Ws, Run-8: no ACCCs)

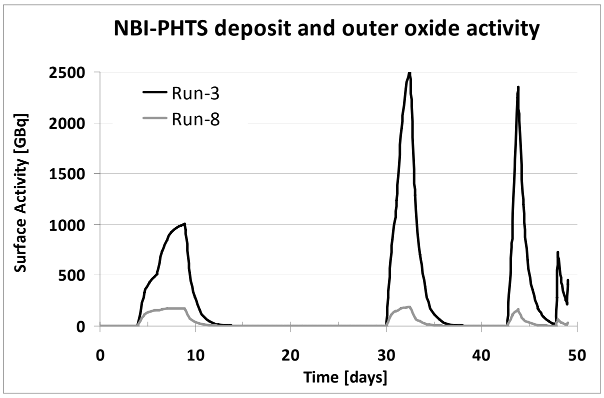

Fig. 6. ACP surface activity in NBI-PHTS with ACCCs (Run-3) and without ACCCs (Run-8)

One can argue that splitting the NBI-PHTS loop in two parts would not reduce the overall ACP mass which would be transferred to the dedicated ACCCs cooling loop. The actual advantage is the reduction of ACPs radioactive inventory (see Fig. 6). The larger ACP mass inventory of ACCCs would be contained in a dedicated loop which will be much less activated considering their position from the plasma and with respect to the neutrons line of sight, while remaining in the NBI-PHTS this large ACP inventory would be activated at higher level when transported to regions where the neutron flux is larger.

V. CONCLUSIONS

A preliminary assessment of the ACP inside the NBI-PHTS by PACTITER v3.3 was carried out investigating the impact of different corrosion rates of Cu and Cu alloys. The major conclusion of this study is the proposal of separating the cooling of the Active Correction and Compensation Coils (ACCCs) from the NBI-PHTS. A remarkable reduction of the ACP mass inventory and activity was consequently estimated.

ACKNOWLEDGMENTS

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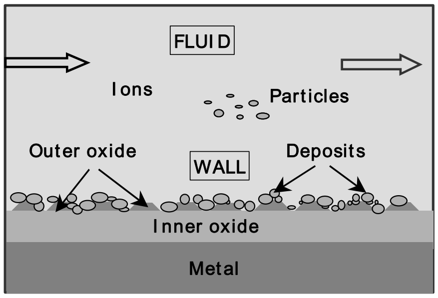

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III. ITER NBI-PHTS LOOP MODELING

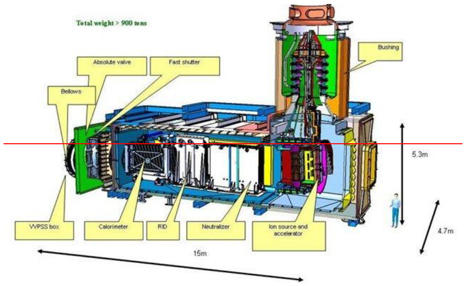
III.A. Description of the ITER NBI-PHTS loop

The function of the NBI-PHTS is to provide cooling water to the low voltage (LV) and high voltage (HV) components of both the heating and diagnostic neutral beams (HNB, DNB) injectors that are located in the neutral beam cell. Neutral Beam Injectors are used to shoot uncharged high-energy particles into the plasma where, by way of collision, they transfer their energy to the plasma particles. Before injection, deuterium (D) atoms must be accelerated outside of the Tokamak to a kinetic energy of 1 MeV. Only atoms with a charge (positive or negative) can be accelerated by an electric field. In Neutral Beam Injection systems, D ions (D-) will be accelerated, then, before injection, they will pass through a cell containing gas (Neutralizer) where they will lose their electron. Residual ions will be dumped by an electric field in the Residual Ion Dump, subsequently the beam of fast neutrals will be injected into the plasma. The NBI-PHTS is designed to cool down two HNBs and one DNB. Heat loads to be removed from individual NBI components vary depending on operational modes of the NBI. The NBI-PHTS is designed to provide several separate cooling water supplies to the NBI components which are under n-flux: LV-grounded grid; LV-Calorimeter; LV-Residual Ion Dump (RID); LV-Neutralizer; LV-Active Correction and Compensation Coils (ACCCs); HV-extractor and accelerator; HV-ion source; HV-plasma grid. The cooling water passes through the primary side (tubes side) of the main heat exchanger (HX) where it is cooled to ~35 °C to satisfy the chemistry requirements for all components. Temperature control is achieved using flow control valves on the main and bypass lines of the main HX.

~~The NBI-PHTS is designed for two HNBs and one DNB. Heat loads to be removed from individual NBI components varies depending on operational modes of the~~

~~NBI. The NBI-PHTS is designed to provide several separate cooling water supplies to the NBI components:~~
~~LV-grounded grid; HV-extractor and accelerator; HV-ion source; HV-plasma grid; LV-Active Correction and Compensation Coils (ACCCs); LV-Calorimeter; LV-Residual Ion Dump (RID);LV-Neutralizer.~~

~~The cooling water passes through the primary side (tubes side) of the main heat exchanger (HX) where it is cooled to approximately 35 C to satisfy the chemistry requirements for all components. Temperature control is achieved using flow control valves on the main and bypass lines of the main HX. Neutral Beam Injectors are used to shoot uncharged high-energy particles into the plasma where, by way of collision, they transfer their energy to the plasma particles. Before injection, Deuterium atoms must be accelerated outside of the Tokamak to a kinetic energy of 1 Mega electron Volt (MeV). Only atoms with a positive or a negative charge can be accelerated by electric field; for this, electrons must be removed from neutral atoms to create a positively-charged ion. In Neutral Beam Injection systems, the ions pass through a cell containing gas where they recover their missing electron and can be injected as fast neutrals into the plasma.~~



~~Fig. 2. Heating Neutral Beam (HNB) Overview~~

III.B. Modeling of the NBI-PHTS for PACTITER simulation

The modeling of the NBI-PHTS has dealt with the geometric, thermo-fluido-dynamic, material description of the loop related features. The neutron activation of the HNBs and DNB cooled regions was done in a rough way, as validated data were not available. As preliminary guess, it was assumed a set of reaction rates for the main 13 activation reactions, relative to the most exposed region to n-flux; i.e. the exit scraper, equal to 1/10 of the values adopted in previous analyses by PACTITER on the DIV/LIM loop for the most exposed region to n-flux; i.e. the port limiter. The reaction rates for the other under flux regions of the HNBs and DNB were calculated by scaling down the reaction rates for the exit scraper by a factor between 0.05 and 0.8, depending from their distance from the plasma and position inside the HNBs or DNB. ~~As preliminary guess, it was assumed reaction rate values for the main activation reactions equal to 1/10 of the values adopted in previous analyses by PACTITER on the DIV/LIM loop.~~ The geometric modeling implied a schematization and simplification of the complex architecture of the NBI-PHTS loop~~, shown in Fig. 3 presenting the Process Flow Diagram (PFD) of main NBI components with the option of placing the 3rd HNB~~.

The following basic-criteria were used to set-up the model: coolant inventory, the total wet surface and the total mass flow rate of the ~~NBI-PHTS~~ PACTITER model are the same as the real one; inlet coolant temperature of each Injectors component is 35 C. The resulting geometric model of the NBI-PHTS, shown in ~~Fig. 4~~Fig. 2, is composed of 44 regions.

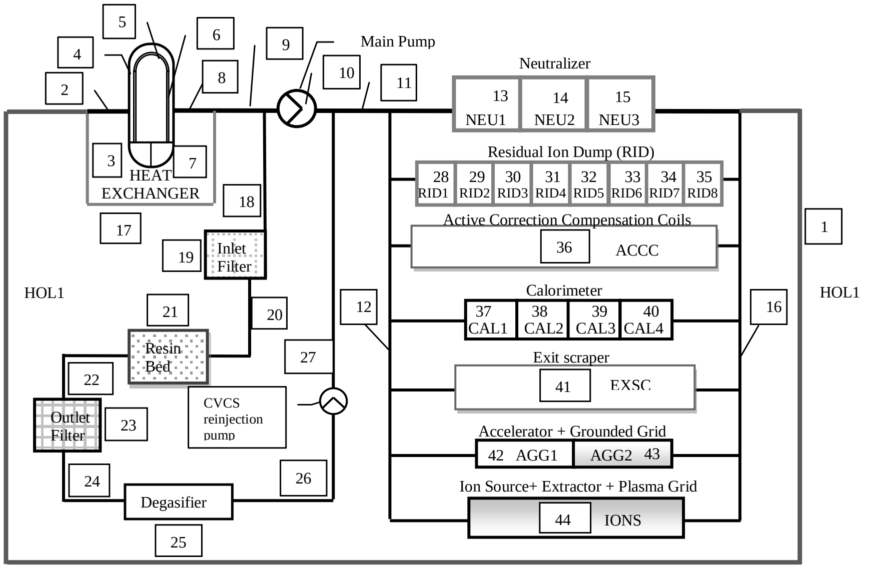
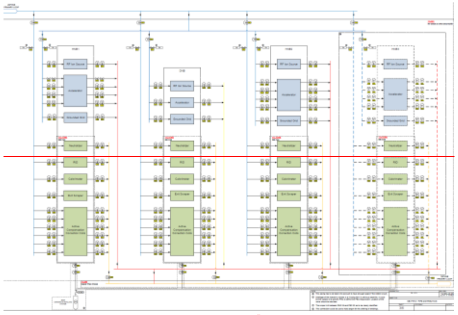


Fig. 2. NBI-PHTS geometric model for PACTITERv3.3

~~The comparison between this scheme and the PFD (Fig. 3) puts in evidence the simplification required by the code to limit the computational time.~~ Regions from 1 up to 16 represent the main loop; all the other (17–44) represent the six bypasses serving the LV and HV components, the the Chemical and Volume Control System (CVCS) and the H~~eat Exchanger~~X bypass. The main geometric simplification made was to group similar zones of the cooling loop as unique pipe, keeping the value of wet surface and coolant volume. The pipe diameter is then the hydraulic diameter D_h, of the lumped zones , which is obtained dividing the total coolant volume, multiplied by 4, by the total wet surface W_S, i.e.:~~obtained dividing the total coolant volume multiplied by 4 by the total wet surface W_S, i.e.:~~

$$D_h = \frac{4 \cdot V}{W_S} \qquad (1)$$



~~Fig. 3. 3HNB+1DNB Process Flow Dyagram (PFD)~~

shows the total coolant volume and mass inventories plus wet surfaces of the model grouped for the in-vessel regions (under n-flux) and ex-vessel ones (out-of n-flux).

TABLE I. Total wet surface and coolant volume grouped in under flux and out-of flux regions

		Total
In-vessel wet surface (m^2)	4103.6	7448.0
Ex-vessel wet surface (m^2)	3344.4	
In-vessel volume (m^3)	10.4	82.1
Ex-vessel volume (m^3)	71.7	
In-vessel coolant mass (kg) *	10308.3	81638.6

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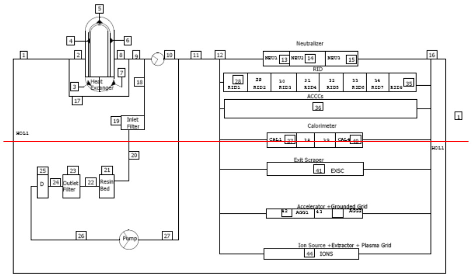
Ex-vessel coolant mass (kg) *	71330.4	

* This value is dependent from the coolant density which depends from the coolant temperature

TABLE II shows the total wet surface of the four materials composing the NBI-PHTS and the related coolant volume. As one can see the largest wet surface is appointed to the pure copper or the Oxygen-free high thermal conductivity (OFHC) copper (mostly concentrated in the ACCCs). The outlet temperature of each in-vessel component was calculated by the AFT Fathom^{TM} code: for such analysis it was assumed the same scheme used in the PFD, specifying thermal-hydraulics properties as: Heat Load, Flow Rate, and Pressure Drops for each component.



~~Fig. 4. NBI-PHTS geometric model for PACTITERv3.3~~

~~**TABLE I.** Total wet surface and coolant volume grouped in under flux and out-of flux regions~~

~~-~~	~~-~~	~~Total~~
~~In-vessel wet surface (m^2)~~	~~4103.6~~	~~7448.0~~
~~Ex-vessel wet surface (m^2)~~	~~3344.4~~	
~~In-vessel volume (m^3)~~	~~10.4~~	~~82.1~~
~~Ex-vessel volume (m^3)~~	~~71.7~~	
~~In-vessel coolant mass (kg) *~~	~~10308.3~~	~~81638.6~~
~~Ex-vessel coolant mass (kg) *~~	~~71330.4~~	

~~* This value is dependent from the coolant density which depends from the coolant temperature~~

TABLE II. Total wet surface and coolant volume grouped according to the material in contact with the coolant

	W_S (m^2)	V (m^3)	W_S share	V share
CuCrZr Alloy	103.6	0.3	1.4%	0.4%
OFHC Cu & Cu	3879.5	7.9	52.1%	9.6%
SS 316 L	2736.0	23.5	36.7%	28.7%
SS 304 L	728.9	50.3	9.8%	61.3%
TOTAL	7448.0	82.1	100.0%	100.0%

OFHC = Oxygen-free high thermal conductivity Cu

IV. ITER NBI-PHTS LOOP ACP ASSESSMENT

IV.A. PACTITER input data definition

~~In order to carry out the ACP assessment, it~~ It was necessary to define an operational scenario and water chemistry parameters in addition to the geometric, thermo-fluido-dynamic, and material data ~~was necessary to define an operational scenario and the water chemistry parameters in addition to the geometric, thermo-fluido-dynamic, and material data~~ (see Section III). The detailed information to prepare the input deck was taken from the code user manual (Ref. 7) The operational scenario was derived from one of those presented by ITER Organization which is based on 3 plasma operation 8-h shifts/~~-~~day, divided in 14.4 h of Mean Up or Operation Time (MUT) and 9.6 h of Not-Scheduled Mean Down Time (MDT_{NS}). The operational cycle is organized in 2-week period with 11 Operation Days and 3 Routine Maintenance Days or Mean Down Time Scheduled (MDTs). The 2-week operational cycle is repeated 35 times in 16 months (experimental campaign) followed from 8-month major shutdown. The experimental campaign (490 days) was schematized for PACTITER simulation considering the following split:

- MUT 231 days (~7.5 months)
- MDT_{NS} 154 days (~5 months)
- MDT_S 105 days (~3.5 months)

It was necessary to further ~~split~~ divide the operation time or MUT in the basic operational phases of the NBI system; injecting and dwell/decay (between plasma pulses). It was also considered the ~~Beam~~ beam source conditioning, operation required to set up the beam source optimal parameters before plasma operation. Conditioning was allotted with the phase named “idle” to the MDTs time. The MDT_{NS} time was defined as “maintenance”.~~It was allotted to the MDTs time together with phase named “idle”. The MDT_{NS} time was defined as “maintenance”~~. In order to reduce the computational time, the 490-day scenario was further reduced to 1/10th so having the simulation scenario of 49 days. The computing time required to simulate the 49-day scenario is ~ 2 hours. The 49-day scenario was organised in 23 steps alternating the various operational phases as summarised in TABLE III.

TABLE III. Main operation scenario data

Operational phase	Time [d]	H_2 [ppm]	T_{mh} [°C]
Idle (MDT_S)	6.9	0.06	35
Conditioning (MDT_S)	3.6	2	55
Injecting (MUT)	5.15	2	61
Decay/dwell (MUT)	18.0	0.06	45
Maintenance (MDT_{NS})	15.35	0.06	35
Operational phase	Time [d]	H2 [ppm]	Tmh [C]
Idle (MDT_S)	6.9	0.06	35

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Conditioning (MDT$_S$)~~Beam conditioning~~	3.6	2	55
Injecting (MUT)	5.15	2	61
Decay/dwell (MUT)	18	0.06	45
Maintenance	15.35	0.06	35

T_{mh} = Mean temperature of the primary fluid in the under flux regions

~~Tmh = Average T of the primary fluid in under flux regions~~

IV.B. PACTITER results and discussion

In order to scan the different parameters affecting the ACPs inventory results, the following code calculations were performed (see TABLE IV). The exact corrosion rates for CuCrZr and pure Cu, mentioned in TABLE IV, are shown in TABLE V. The corrosion and release rates for stainless steels (SS316L and SS304L) were calculated by the code and not given as input data as the case of pure Cu and Cu alloy.

During injecting and conditioning, when neutron are generated, the water chemistry was a reducing one, during the other phases it was assumed slightly oxidizing ($H2 \approx 0$ ppm, see TABLE III). It was also considered an initial CP deposit and outer oxide mass equal to ~2.5 kg, corresponding to an average value of ~ 0.3 g/m^2. Results of the ACP mass inventory are shown in Fig. 3.

TABLE IV. Main calculation parameters

Run	Pure Cu & CuCrZr C_R	ACCCs Ws [m^2]	Resin effic.	Scenario	Flow rate to CVCS [kg/s]
3	Values 1	3798	0.98	49 days	30.5
4	Values 1	3798	0.98	98 days	30.5
5	Values 1	1899	0.98	49 days	30.5
6	Values 1	0	0.98	49 days	30.5
7	Values 1	3798	0.99	49 days	30.5
8	Values 1	0	0.98	49 days	30.5
9	Values 2	3798	0.98	49 days	30.5
10	Values 2	3798	0.98	49 days	61.0
11	Values 3	3798	0.98	49 days	30.5
12	Values 3	1899	0.98	49 days	30.5

C_R= Corrosion Rate; Runs #1 & #2 performed to set up the input deck

~~The exact corrosion rates for CuCrZr and pure Cu, mentioned in TABLE IV, are shown in TABLE V. The corrosion and release rates for stainless steels (SS316L and SS304L) were calculated by the code and not given as input data as the case of pure Cu and Cu alloy.~~

TABLE V. Cu and CuCrZr corrosion rate values adopted for PACTITER ACPs assessment

CuCrZr & Cu corrosion rate	reducing conditions [μm/y]	oxidizing conditions [μm/y]
Values 1	1.50	5.00
Values 2	1.00	3.00
Values 3	0.73	2.19

~~During injecting and conditioning, when neutron are generated, the water chemistry was a reducing one, during the other phases it was assumed slightly oxidizing (H2 ≈ 0 ppm, see TABLE III). It was also considered an initial CP deposit and outer oxide mass equal to ~2.5 kg, corresponding to an average value of ~ 0.3 g/m^2. Results of the ACP mass inventory are shown in Fig. 5.~~

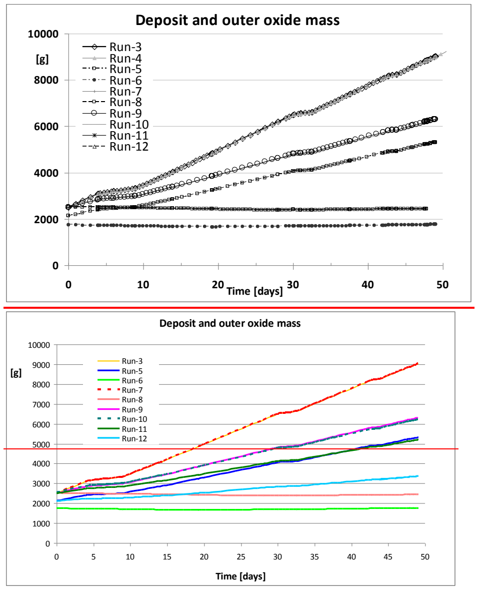
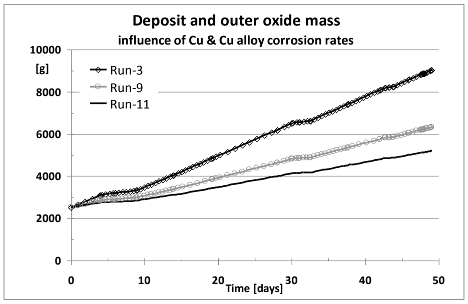


Fig. ~~5~~3. PACTITER ACP mass for the different runs

The most important parameter governing the build-up of the ACPs inventory is the Cu and Cu alloy corrosion rate, as shown in Fig. 4~~. Fig. 6 shows clearly this dependence~~.

The influence of CVCS flow rate (FR) and filter efficiency is relatively scarce, , as no appreciable reduction in the ACP mass was assessed. It was also investigated the chance to separate the LV-Active Correction and Compensation Coils (ACCCs) from the NBI-PHTS by a dedicated cooling loop. The impact of this choice would be remarkable in terms of ACP mass reduction (see Fig. 5 Run-8). That is explained by the large wet surface (Ws), of ACCCs (3798 m^2 which is ~50% of the total Ws) made of Cu and affected by a larger corrosion and release rates with respect to stainless steels. Another way to reduce the ACCCs Ws of a factor 2 is by doubling the pancake piping diameter from 8 to 16 mm. That would cause a drop of ~40% of the ACP mass (see Fig. 5 Run-5).



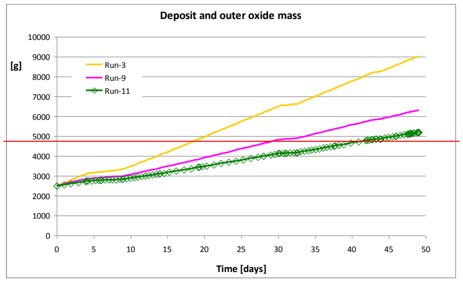
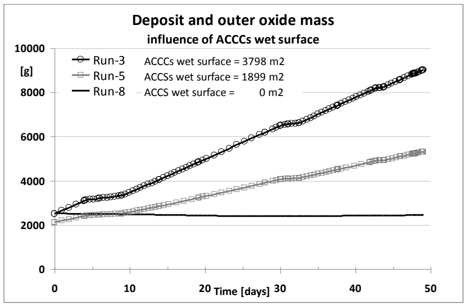


Fig. ~~6~~4. ACPs mass for CuCrZr and pure Cu corrosion rate Values 1 (Run-3), Values 2 (Run-9) Values 3 (Run-11)

~~The influence of CVCS flow rate (FR) and filter efficiency is relatively scarce, as no appreciable reduction in the ACP mass was assessed (see Fig. 5: Run 3 vs. Run 7 for resin efficiency and Run-9 vs. Run-10 for CVCS FR impact). It was also investigated the chance to separate the LV Active Correction and Compensation Coils (ACCCs) from the NBI-PHTS by a dedicated cooling loop. The impact of this choice would be remarkable in terms of ACP mass reduction (see Fig. 7 Run-8). That is due to the large wet surface (Ws), of ACCCs (3798 m^2 which is ~50% of the total Ws) made of Cu and affected by a larger corrosion and release rates with respect to stainless steels. Another chance to reduce the ACCCs Ws of a factor 2 is by doubling the piping diameter of the pancake from 8 to 16 mm. That would cause a drop of ~40% of the ACP mass (see Fig. 7 Run-5).~~



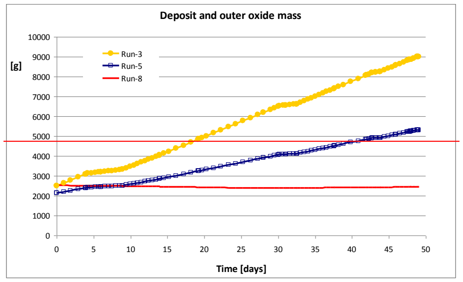


Fig. ~~7~~5. Impact of the ACCCs Ws on the ACP assessment (Run-3: full Ws, Run-5: ½ Ws, Run-8: no ACCCs)

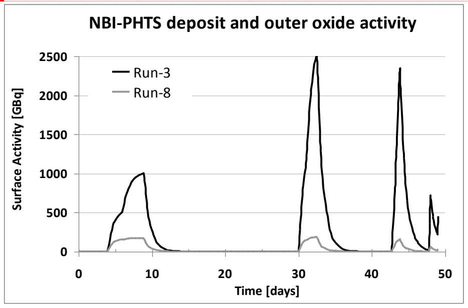


Fig. 6. ACP under flux activity in NBI-PHTS with ACCCs (Run-3) and without ACCCs (Run-8)

One can argue that splitting the NBI-PHTS loop in two parts would not reduce the overall ACP mass which would be transferred to the dedicated ACCCs cooling loop. The actual advantage is the reduction of ACPs radioactive inventory (see Fig. 6). The larger ACP mass inventory of ACCCs would be contained in a dedicated loop which will be much less activated considering their position from the plasma and with respect to the neutrons line of sight, while remaining in the NBI-PHTS this large ACP inventory would be activated at higher level when transported to regions where the neutron flux is larger

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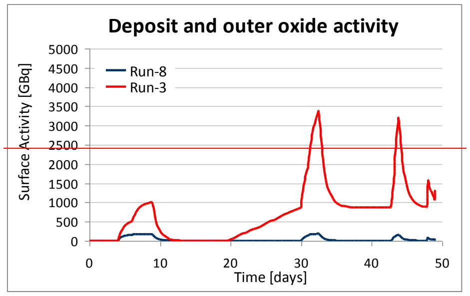
~~One can argue that splitting the NBI-PHTS loop in two parts would not solve the problem of reducing the overall ACP mass which would be transferred to the dedicated ACCCs cooling loop. The actual advantage is the reduction of ACPs radioactive inventory (see Fig. 8).~~



~~Fig. 8. ACP under flux activity in NBI-PHTS with ACCCs (Run-3) and without ACCCs (Run-8)~~

~~The larger ACP mass inventory of ACCCs would be contained in a dedicated loop and hence much less activated considering the position of these coils with respect to the line of sight of neutrons, while the large ACP inventory due to of ACCCs inside the NBI-PHTS would cause its larger activation when transported to regions where the neutron flux is higher.~~

V. CONCLUSIONS

A preliminary assessment of the ACP inside the NBI-PHTS by PACTITER v3.3 was carried out investigating the impact of different corrosion rates of Cu and Cu alloys. The major conclusion of this study is the proposal of separating the cooling of the Active Correction and Compensation Coils (ACCCs) from the NBI-PHTS A remarkable reduction of the ACP mass inventory and activity was estimated.

ACKNOWLEDGMENTS

This work, supported by the European Communities under the contract of Association with EURATOM ENEA, was carried out within the framework and the supervision of the Fusion for Energy (F4E) which is the European Union’s Joint Undertaking for ITER and the Development of Fusion Energy. The views expressed in this publication are the sole responsibility of the author and do not necessarily reflect the views of Fusion for Energy. Neither ~~Fusion for Energy~~F4E nor any person acting on behalf of ~~Fusion for Energy~~ F4Eis responsible for the use which might be made of the information in this publication.

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1. M. T. PORFIRI~~,~~ and L. DI PACE, “Influence of the CVCS adoption on the ACP inventory of the ITER VV PHTS loop”; *EFDA Final Report Task TW5-TSS-SEA5.5* (2008~~)~~).
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3. W. GULDEN, L. PERNA, J. FURLAN, “EU Safety Activities for ITER licensing”; *Proceeding of the 23rd Symposium on Fusion Engineering*, May 31 – June 5, San Diego, California (2009).
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5. ~~J. ELBEZ-UZAN,~~ “ITER Preliminary Safety Report”, ~~Volumes~~ Vol. I-II, (2010).
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7. F. DACQUAIT, F. HERBELET, M. MONIN-BAROILLE, “Elements of validation of the PACTITER V3.3 code” Technical report CEA DEN/DTN/SMTM/LMTR/2008-46 Ind 0 (2008)

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Answers to the reviewers' comments

Reviewer #1

Q1.Section II. Regarding the main modifications done in PACTOLE, it could be expected an extension to consider the enhanced corrosion due to high magnetic fields. Why it is not implemented? It seems an essential feature (not included in PWRs codes) for a corrosion code in fusion magnetic devices.
A1: The issue of the influence of the magnetic field on the behaviour of ACPs was analyzed in a previous study carried out to set up the model for ACPs predictions for the STARFIRE Project [Ref. C. Baker, et al., "STARFIRE, Appendix G - Corrosion Products in the Primary Coolant Loop," ANL/FPP-80-1, 1980]. In particular it was summarized in paragraph "G.2.6 Conclusions on Magnetic Effects" as it follows: "*The main concerns of magnetic interaction are the increased deposition of particles in very low flow areas and alteration of the microstructure of the oxide film. The advantages of a magnetic filter may provide incentive to maximize the magnetization potential of coolant particles. This suggests an advantage to having* Fe_3O_4 *rather than* Fe_2O_3 *as the stable phase (the chemical, hence magnetic, form of the coolant is controllable by water chemistry conditions)*"
Considering the limitation allotted to the paper (5 pages) and the different topics to be treated, it was decided to skip this issue, even though it should be acknowledged the need to implement a model to describe the effects of magnetic field in future developments of PACTITER and to validate this model by dedicated experiments.

Q2.Section III.A. Regarding the list of NBI components, it will be useful to identify those considered as 'under n-flux'
A2: DONE

Q3.Section III.A. NBIs in ITER will accelerate negative ions (-D) so, electrons will be added instead of removed. It is recommended to move the description of the system to the beginning of the Section (style recommendation).
A3: The correction was done, even though it must be reported to ITER Organization that the different technical information cited in the first submission of the paper was taken from the ITER web site accessible to the general public (please check the consistency of what reported in the web page: http://www.iter.org/mach/heating where for the **Neutral Beam Injection** it is written
"Using injection to heat the fuel in the ITER Tokamak is very much like using steam in the household cappuccino machine to heat milk. Neutral Beam Injectors are used to shoot uncharged high-energy particles into the plasma where, by way of collision, they transfer their energy to the plasma particles.
Before injection, Deuterium atoms must be accelerated outside of the Tokamak to a kinetic energy of 1 Mega electron Volt (MeV). Only atoms with a positive or a negative charge can be accelerated by electric field; for this, electrons must be removed from neutral atoms ***to create a positively-charged ion. The process must then be reversed before injection into the fusion plasma; otherwise the electrically-charged ion would be deflected by the magnetic field of the plasma cage. In Neutral Beam Injection systems, the ions pass through a cell containing gas where they recover their missing electron and can be injected as fast neutrals into the plasma***."

Q4. Figures: Increase the font size in Figures 2 and 4. Figure 3 will be impossible to read anyway (remove!). Figures 5, 6, 7 and 8 are not compatible with B&W publication.
A4: Figure 2 and 3 eliminated, Fig. 4 (now Fig. 2) and related characters enlarged, Figs. 5, 6, 7 and 8 (now Figs. 3-6) made in B&W and related characters increased.

Q5. Section III.B. A uniform activation ratio (for all regions) of 1/10 seems too simplistic. Provide justification.
A5: DONE.

Q6. There is no mention in the paper to the possibility of using specific corrosion inhibitor for Cu loops when ACCCs is separated from the rest of the system. Author is invited to consider the feasibility of such an option (not required for acceptation of the paper).
A6: considering that this mention is not required for the paper acceptance and the limited space allotted to the paper the issue was not treated. Furthermore that seems out of the scope of the paper.

Q7. References: the ITER Preliminary Safety Report is an institutional document in which author is not a single person.
A7: DONE (see Ref. 5 of the revised paper).

<u>Reviewer #2</u>
All the comments considered in the revised paper

Cover Letter for the submission of the paper presented at 19th TOFE Las Vegas November 2010

APPLICATION OF PACTITER V3.3 CODE TO THE ACPS ASSESSMENT OF ITER NEUTRAL BEAM INJECTORS PRIMARY HEAT TRANSFER SYSTEM

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Dear Sirs,
Making reference to your e-mail dated 16 Feb 2011 find below my answers to editor's comments and reviewers' comments (in green characters)

From: FST <fst@ans.org>
Sender: em.fst.0.211e09.e448a47e@editorialmanager.com
To: "Luigi Di Pace" <luigi.dipace@enea.it>
Date: 16 Feb 2011 14:27:14 -0500
Subject: FST10-216 Review Results
X-Original Arrival Time: 16 Feb 2011 19:27:14.0090 (UTC) FILETIME=[83C750A0:01CBCE0F]

CC: uckanna@ornl.gov

FST10-216
Application of PACTITER v3.3 to the ACPs assessment of ITER Neutral Beam Injectors Primary Heat Transfer System
by Dr. Luigi Di Pace et al

Dear Dr. Di Pace,
………
Please revise the paper accordingly, provide a point-by-point response to the reviewers, and highlight the revisions; both on a copy of revised manuscript and in your reply letter to me.
Your revision is due by: Mar 02, 2011
Please name your files clearly with reference to the manuscript number given above FST10-216RevisedClean.pdf, FST10-216RevisedMarked.pdf, FST10-216AuthorReply.pdf, etc.] –
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The authors should refer to the following website for paper preparation
http://www.new.ans.org/pubs/journals/fst/tofe19/ and follow the instructions carefully. Specifically note:
*Fix/observe spacing between paper title-author names-text: skip 4 lines (see template & guidelines) **[DONE]**
*Figs. 2-5 are too small to read. **[Fig. 2 & 3 crossed out, Fig. 4 enlarged (now Fig. 2), characters of Fig. 5 enlarged (now Fig. 3)]**

*Figs. 5-7 need the fonts increased. **[DONE, now Figs. 3-5]**
*Figs 5-8 may lose info in b&w. **[DONE, now Figs. 3-5]**
*Fig. 8 data lines could be differentiated by something else rather than color. **[DONE, now Fig. 6]**

Sincerely,

TOFE19 Guest Editors & Nermin A. Uckan
Fusion Science & Technology
http://www.ans.org/pubs/journals/fst/

Reviewers' comments:

REVIEWER #1:
Review Questionnaire:
1. Is the subject of interest to the readership of FS&T? - Yes
2. Is this an original contribution? - Yes, it is.
3. Are title and abstract adequate to the content of the paper? - Yes
4. Does it give adequate credit to earlier work in the field? - It gives enough references to put in context the work.
5. Is it correct and complete? - See list of comments below
6. Is it clearly presented? - Yes
7. Are the figures clear? - Figures are not clear (too small fonts) and must be adapted to black and white in print (color online)
8. Recommend: accept after revisions

Comments:
Several issues have been identified and numbered in the manuscript (attached for an easier follow up - see this link http://fst.edmgr.com/l.asp?i=7926&l=7FYMBHFR).

1.Section II. Regarding the main modifications done in PACTOLE, it could be expected an extension to consider the enhanced corrosion due to high magnetic fields. Why it is not implemented? It seems an essential feature (not included in PWRs codes) for a corrosion code in fusion magnetic devices. **[see detailed answer in the file Answer to reviewers' comments_FST10-216.doc]**

2.Section III.A. Regarding the list of NBI components, it will be useful to identify those considered as 'under n-flux' **[DONE]**

3.Section III.A. NBIs in ITER will accelerate negative ions (-D) so, electrons will be added instead of removed. It is recommended to move the description of the system to the beginning of the Section (style recommendation). **[DONE, see also detailed answer in the file Answer to reviewers' comments_FST10-216.doc]**

4.Figures: Increase the font size in Figures 2 and 4. Figure 3 will be impossible to read anyway (remove!). Figures 5, 6, 7 and 8 are not compatible with B&W publication. **[DONE]**

5.Section III.B. A uniform activation ratio (for all regions) of 1/10 seems too simplistic. Provide justification. **[DONE]**

6.There is no mention in the paper to the possibility of using specific corrosion inhibitor for Cu loops when ACCCs is separated from the rest of the system. Author is invited to consider the feasibility of such an option (not required for acceptation of the paper). **[see detailed answer in the file Answer to reviewers' comments_FST10-216.doc] anyway the reviewer wrote"**not required for acceptation of the paper"
7.References: the ITER Preliminary Safety Report is an institutional document in which author is not a single

person. **[DONE]**

REVIEWER #2:

I recommend publication with minor revisions (see attached at his link http://fst.edmgr.com/l.asp?i=7926&l=7FYMBHFR). **[DONE]**