**CEFDA05-1368**
**TW5-TSS-SEA3.5**

# Task Title: IN VESSEL SAFETY: DEVELOPMENT OF A DUST EXPLOSION COMPUTER MODEL

## INTRODUCTION

Besides the $H_2$ risk issue studied previously, another threat that could endanger the ITER containment is the (Be, W and C) dust issue [1]. Three aspects of the issue are:
(1) the mobilization of deposited dust in the case of air or steam ingress, (2) dust explosion (air – dust), or (3) combined hydrogen-dust explosion in the event of steam ingress, where hydrogen is produced by the reaction between the Be dust and the steam.

On the first issue, the task aimed at establishing the modeling basis for the simulation of dust mobilization in a representative accident, reviewing the analytical and experimental data-base to identify verification and validation test cases, and finally, to evaluate the selected models for the chosen test case was completed in January 2007.
Part of this work was performed in collaboration with FZK.

## 2006 ACTIVITIES

Three steps were defined for this task. The first two steps were jointly performed by CEA and FZK, with the description of dust mobilization models both in CAST3M (CEA) and GASFLOW (FZK) codes and a review of analytical and experimental test cases for the validation of the models. Two joint deliverables were produced. The third step of this activity was the application of the codes (CAST3M in the case of CEA) to numerical benchmarks proposed in the matrix of benchmark test cases defined in the second deliverable, and with the numerical models described in the first deliverable. The third deliverable is the last of this year (completed in January 2007).

### REVIEW AND DEFINITION OF 3D DUST MOBILIZATION EQUATIONS: GASFLOW AND CAST3M MODELS

In this first step, the description of the two different codes for modeling gas and particle mixtures are presented. They use two different approaches, the Lagrangian (Gasflow code) and the Eulerian (CAST3M code) approaches. The CEA CAST3M model includes, apart from gravitational forces, interfacial friction (by means of a drag force) and heat transfer between the phases. When particle interaction is important and has to be taken into account, more complex models are needed, and the concept of the solid stress modulus or intergranular pressure (depending on the author) is introduced. Therefore two-approaches have been developed, one for high dilute flows and other for heavy-laden mixtures, considering in all cases the solid as incompressible. The first one is the most interesting for the study of mobilization problem in ITER as those are the kind of mixtures expected to be present inside the vacuum vessel. In this first deliverable for CEA part, the numerical schemes and the physical models implemented in the CEA code CAST3M for the analysis of high dilute dust and gas mixtures are presented.

### REVIEW OF ANALYTICAL AND EXPERIMENTAL TEST CASES FOR DUST MOBILIZATION MODELING

In terms of the numerical models about particle mobilization described in the first step (Deliverable D1 report), a matrix of benchmark test cases including analytical solutions and numerical simulations are reviewed and proposed.
Some fundamental benchmark test cases for particle mobilization are reviewed:

- #1. Particle trajectory in a uniformed flow

- #2. Particle trajectory in a uniformed flow with gravity

- #3. Particle diffusion from a point source

- #4. Particle diffusion in a uniformed flow

- #5. Particle transport in a curved duct

These 5 test cases are a key step to verify whether a computer code can be further used for more realistic applications. These benchmark test cases include: reproducing an analytical particle trajectory in a uniformed flow field; simulating the particle trajectory with the effect of gravitational terms to demonstrate particle settling; comparisons of numerical particle distributions with enhanced diffusion coefficients to analytical solutions when particles diffuses from a point source in 1D, 2D and/or 3D configurations; further studies of particle diffusion in a straight duct containing uniformed flow by using different particle properties; benchmark of particle mobilization in a 180º curved duct.

The other part of these numerical benchmarks involving gas and particle mixtures is reviewed in test cases 6 to 14 definition. They essentially involve dust mobilization processes induced by shock or rarefaction waves and correspond to several numerical and experimental problems proposed in the existing literature. Some experimental results obtained in the FZK dust dispersion tube experiment, the STARDUST facility and the TAKASE experiment are proposed in order to validate in the near future the numerical codes GASFLOW.

- #6. 1D shock tube test in high dilute mixtures

- #7. Stardust problem

- #8. 1D Dust mobilization problem provoked by rarefaction waves

- #9. Shock-induced fluidization particle bed

- #10. Shock tube problems with dense mixtures

- #10.1. First problem: Shock tube with zero velocities

- #10.2. Shock tube with opposite velocities

- #11. 2D planar section and/or 3D dust dispersion tube with air injection (FZK)

- #12. TAKASE experiment

- #13. Gas-solid particle flows in a 90º bend

- #14. Other tests found in the existing literature like a study on the interaction of a shock of Mach 1.7 in a 2D geometry reservoir in which there is a layer of particles (14.1) or a dusty gas mixture flowing through a 2D nozzle (14.2 &14.3).

All these 14 test cases constitute a pool of benchmark studies. The case matrix based on the physical phenomena involved in the test cases is shown in Table 1.

*Table 1: Matrix of benchmark test cases*

| Physical phenomenon | | Particle transport | | Turbulence diffusion | Particle entrainment | Particle deposition /rebound |
|---|---|---|---|---|---|---|
| | | Low speed flow | High speed flow | | | |
| Benchmark test cases | 1 | X | | | | |
| | 2 | X | | | | X |
| | 3 | | | X | | |
| | 4 | X | | X | | |
| | 5 | X | | X | X | X |
| | 6 | | X | X | | |
| | 7 | X | | X | X | X |
| | 8 | | X | X | | |
| | 9 | | X | X | | |
| | 10.1 | | X | X | | |
| | 10.2 | | X | X | | |
| | 11 | X | | X | X | X |
| | 12 | X | | X | X | X |
| | 13 | X | | X | X | |
| | 14.1 | X | | X | X | |
| | 14.2 | X | | X | X | |
| | 14.3 | X | | X | X | |

## VALIDATION OF SOLVERS FOR DUST MOBILISATION MODELLING WITH CAST3M

The last work combines the test case matrix previously defined and calculations with the CAST3M code considering the actual implemented models. As mentioned below, two different models have been studied, one for dense flows and another for high dilute mixtures. A finite volume approach for multidimensional problems on unstructured grids has been used, and several numerical schemes have been extended to analyse this type of mixtures. The AUSM+up scheme has been extended to dense mixtures and in the case of high dilute mixtures it has only been applied to the gas phase. The Rusanov scheme and a modified version of the AUSM+ have been proposed for the solid phase for high dilute mixtures. Different numerical benchmarks have shown that the schemes behave quite well in the the presence of flows containing discontinuities.

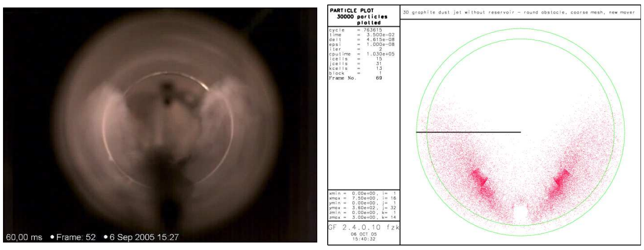


*Figure 1: Dust dispersion tube geometry with air injection (FZK)*

As illustration, figure 1 shows the numerical results obtained for the FZK dust dispersion tube with air injection (case #11) (figure 1), 2D planar section and/or 3D dust dispersion tube with air injection (FZK) (figures 2 and 3) This experiment addressed the dust mobilization provoked by air injected through the holes of a cylindrical tube situated at the bottom of a larger tube, where a dust layer was deposited. Figure 4 shows the 3D calculations results of particles concentration evolution.

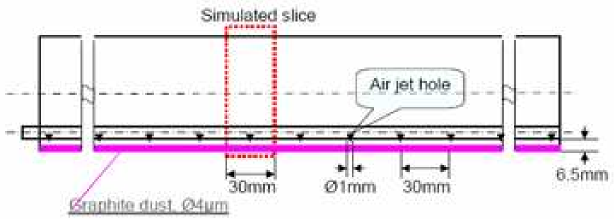


*Figure 2: Dust dispersion tube geometry with air injection*

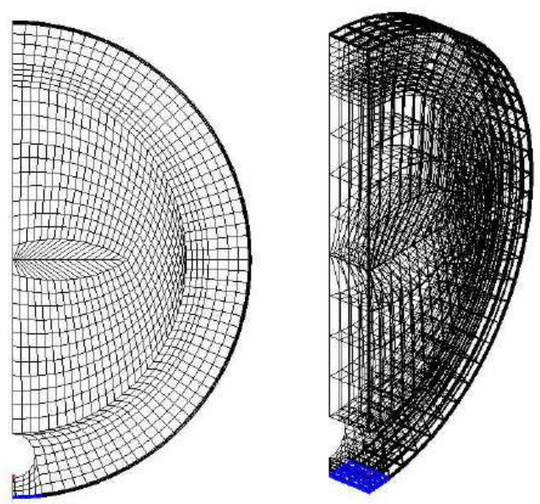

*Figure 3: Dust dispersion problem meshes (2D and 3D)*

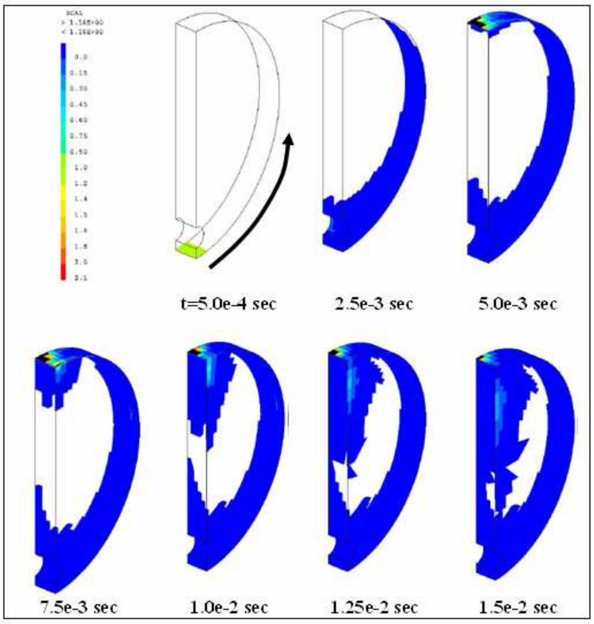


*Figure 4: Particle concentration distribution inside the test section at different times, $t = (0, 2.5, 5, 7.5, 10, 12.5, 15) \cdot 10^{-3}$ s*

Another illustration is the TAKASE test case. In this study the air ingress through breaches in a reservoir (#12) is simulated.

The problem specifications are quite similar to those one may expect inside the vacuum vessel of the ITER in case of a loss-of-vacuum accident. The experimental facility was built for this purpose. Meshes are presented in figure 5.

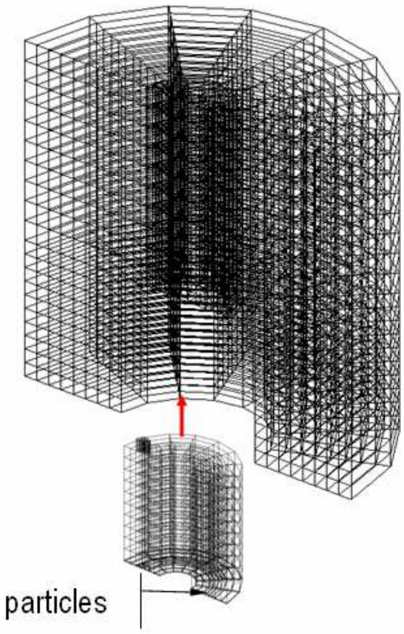


*Figure 5: Meshes modelled with CAST3M. Top: outer reservoir, bottom: inner reservoir*

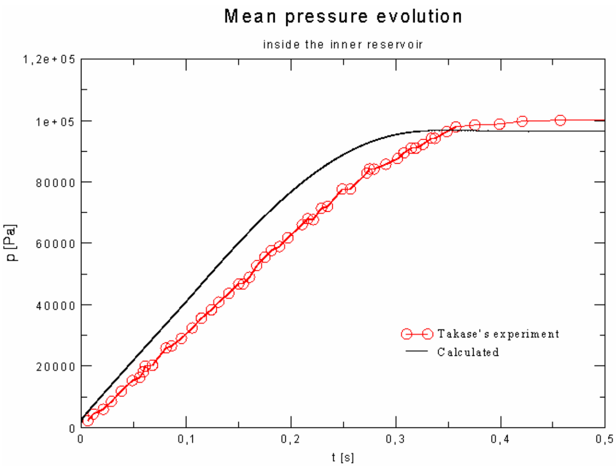


*Figure 6: TAKASE test, evolution of the average pressure inside the vacuum vessel*

Figure 6 gives comparison between the calculated pressures with the experimental one, average values have been considered in both cases. Regarding the particle mobilisation, all the particles are mobilised when the atmospheric pressure is reached inside the reservoir.

The last example shows an application to ITER-like geometry, with a 2D cross section (figures 7 and 8). The air ingress induces a rise of pressure from 5Pa to outside pressure of $10^5$ Pa, the diameter of the breach is 0.1m. The carbon dust is mobilized from a dust layer of 1cm in the bottom of the vessel.

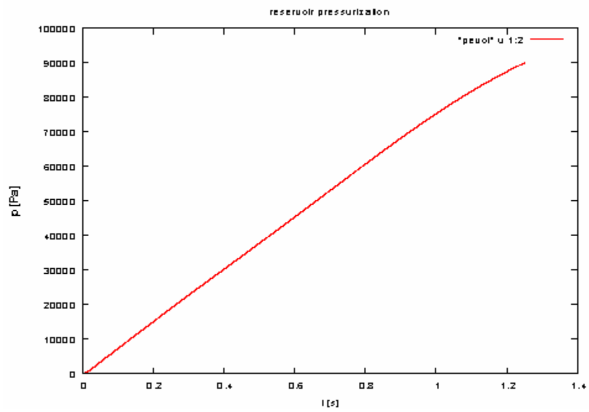


*Figure 7: Evolution of the pressure in the vacuum vessel*

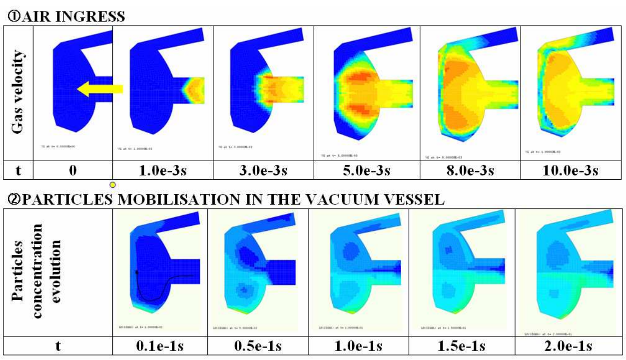


*Figure 8: Sequences of ① air ingress, here gas velocity and ② graphite particles mobilisation inside the vacuum vessel*

## CONCLUSIONS

Despite the fact that most of the tests are numerical tests which originally lack of some specification parameters, they have provided a good assessment of the capabilities of the numerical schemes proposed and qualitatively demonstrate their good behaviour in the characterisation of discontinuities and their easy adaptability to different flow models. The foregoing work has been carried out in the context of the ITER project. In order to validate it suitably, new experiments are being performed and new experimental data will be available in the near future. The addition of more realistic closure laws will also complete the model (i.e. turbulence, lift forces, adhesion-entrainment models and so on).

The next steps are:
(1) Improvement of the closure laws for the transport of dust particles,
(2) Validation on new experimental data,
(3) Development of a reactive source terms to describe the dust explosion or the combined $H_2$-dust explosion,
(4) Validation of the combustion model on experiments.

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# TW5-TSS-SEA5.6

## Task Title: ENHANCEMENT OF THE PACTITER COMPUTER CODE AND RELATED FUSION SPECIFIC EXPERIMENTS

## INTRODUCTION

In fusion devices such as the International Thermonuclear Experimental Reactor, ITER, neutron activation would also produce Activated Corrosion Products in the divertor, blanket and vacuum-vessel cooling loops, as well as in any other auxiliary cooling system. In operating nuclear (fission) power plants, ACP could be responsible for about 90 % of the Occupational Radiation Exposure (ORE) of personnel during the reactor operation, inspection and maintenance [1]. By consequences, the precise determination of ACP inventories and the estimation of the resulting doses to personnel is thus an important safety task. The computer code PACTITER has been used for the calculation of generation and transport of ACP in the various Primary Heat Transfer System (PHTS) or Tokamak Water Cooling System (TCWS). Presently, PACTITER code, is an adaptation of the PACTOLE code developed for Pressure Water Reactor. CORELE Tests facility devoted to the measurement of the release of industrial tube section belongs to the PACTITER validation tools. A first test campaign was performed into CORELE Test facility to determine the SS316L(N)IG stainless steel (industrial tubes used in the first wall/shield blanket) mass release rates under similar operating conditions of the TCWS [2]. Of course, the release of Cu alloy (as CuCrZr) is equally a key point and for that reason, a feasibility study has been launched in 2005 in order to assess the capability of the CORELE loop to provide relevant experimental data as input or validation of PACTITER [4].

## 2006 ACTIVITIES

2006 activities were dedicated to the PACTITER code development and to the experimental characterization of the copper release from CuCrZr alloy under ITER representative conditions. The PACTITER code development consisted in the implementation of the Cu thermodynamic data base. Experimental measurements for CuFeZr and a PhreeqCEA calculation for Cu solubility were successfully compared [5] [6].

### CuCrZr Release rate Evaluation in the CORELE Test Facility

Some previous studies on CuCrZr alloy have shown the formation of a layer of black copper oxides (CuO) on the exposed surface of pipes under high heat flux in the temperature range around 100°C and with a nominal flow velocity of 10 m/s with high hydrogen peroxide content [3]. This surface layer is described as loosely adhesive and detachable by fluid flow effects by the authors. Then the phenomenology of copper release from CuCrZr can be expected to be the consequence of a erosion-corrosion process. Erosion corrosion is a combination of chemical and mechanical wear leading to the destruction of a metal. Normally, a thin film of oxides forms on exposed alloys surfaces. This film provides protection from oxidation of the metal surface. However the formation of this protective layer can be hindered by high flow velocities and, thus, the removal of the material can be accelerated by:

- The chemical dissolution of the metallic oxides and then the occurrence of cationic species in the fluid;
- The mechanical erosion of the oxide layer producing some particles in suspension in the flowing fluid.

The initial principle of the measurement of elementary release rate in the CORELE loop consisted in continuously trapping the cationic copper released from two test sections on mixed bed ion exchange resins (see figure 1). Full rods of copper alloy are inserted in zircalloy test sections. The diameter is adapted in order to adjust the water velocity section for a given flow rate.
In order to satisfy the specified water velocity of 10 m/s with a pressure in the range of 40 to 50 bar in the test section, we had to adapt the configuration of the CORELE loop. The flowrate is regulated at 40 l/h. As shown in figure 1, only one test section has been used because the capacities of the experimental loop did not enable us to reach the specified conditions with two sections. Other adaptation consisted in adding 0.45µ Millipore filters in order to trap eroded oxide particles by the water flow.

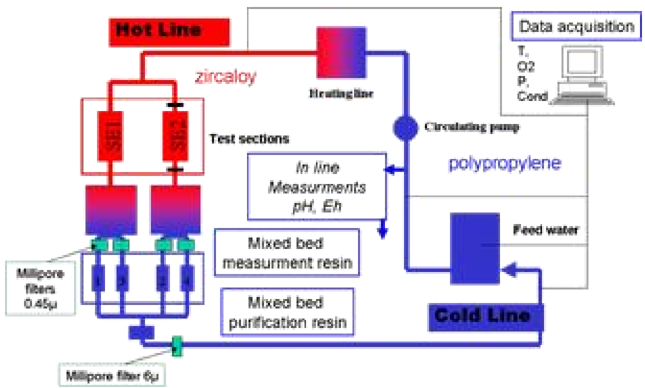


*Figure 1: Schematic view of CORELE loop*

The net release rate R (mg/dm²/month) is then given by:

$$R = \frac{W}{A.t}$$

Where:

W : Mass of copper in measurement resin or in filters (mg),

A : Exchange surface area between test specimen and water (dm²),

T : Time during which the resins and the filters are trapping the released products in the loop (month, assuming 1 month = 30 days).

The first step achieved in 2006 consisted in the validation of the functioning of the adapted CORELE loop in the ITER representative water chemistry (i.e. with an ultra pure water whose conductivity at 25°C is less than 0.1 µS/cm). In these conditions the pH is neutral (between 6.8 and 7.4). The water chemistry is continuously monitored through pH, Eh, $O_2$ and conductivity measurements.
The copper trapped in the filters is dissolved by a 2.5 L, 0.5 M $HNO_3$ solution after a 48h contact time. Acidic elution ($HNO_3$ 1.43 N) of the mixed ion exchange resins bed enables the release of the total copper fixed. Solutions are analysed by ICP-AES spectroscopy.

## RESULTS

The exposed copper surface of the test specimen is covered with a layer of black oxides which is loosely adhesive and even detachable. This description is fully consistent with the observations of Zheng et al. (2006) [3]. The test specimen after 525 hours experiment is shown in figure 2. The black colour of oxides is probably due to the predominance of $CuO_s$.


*Figure 2: Test specimen, CuCrZr rod after 525 hours exposure on 10 m/s water flow during the ITERCU-1 experiment (120°C and 44 to 49 bars)*

In details, figure 2 shows that the black copper oxide deposit is rather homogeneous except on the upstream side were the alloy could be apparent. The figure 3 shows the time evolution of the total amount of copper measured in the resin beds (mg). After 525 hours duration of the ITERCU-1 experiment, a mass of 106 mg of ionic copper was trapped.

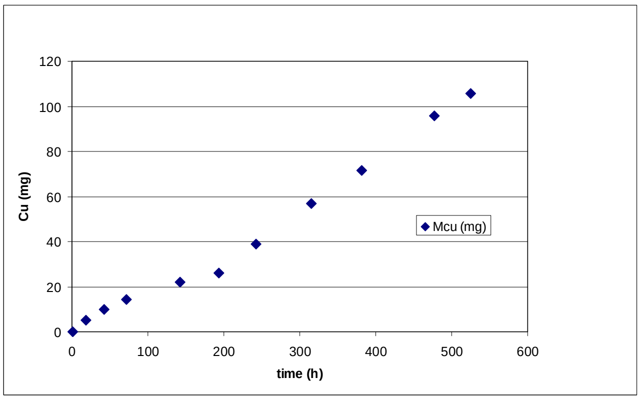


*Figure 3: Total amount of cationic copper trapped in the resin beds (mg) during the 525 hours ITERCU-1 experiment with pure water*

The corresponding release rate R (mg/dm²/month) of cationic copper is displayed in figure 4.

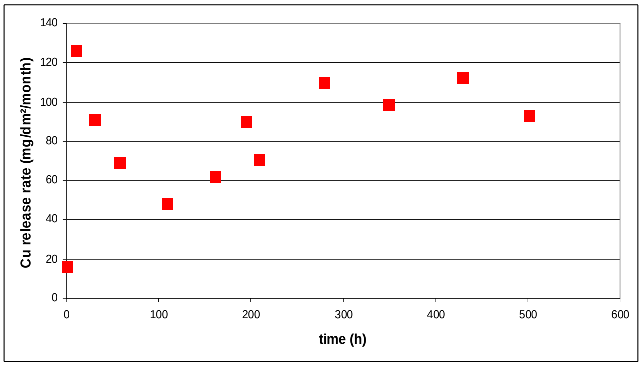


*Figure 4: Cationic copper release rate trapped in the resin beds during the 525 hours ITERCU-1 experiment with pure water*

The total amount of cationic copper trapped in the resin beds ($MCu_c$) is equal to 106 mg. The first value shown by figure 4 corresponds to the amount of cationic copper released during the period needed to increase the temperature in the CORELE loop. So, the operating temperature for this first R value was ranging between 25 and 120°C. Then release rates obtained at 120°C operating temperature show a maximum initial value, followed by a continuous decrease until a minimum value around 100 h and then, a regular increase until a rather constant value around 100 mg/dm²/month. The mean R value over the 525 hours duration of the experiment is equal to 89.6 mg/dm²/month. This value is in a very good agreement with those considered by Schindler and Blet (2006) [2]. The total amount of Copper obtained from the analysis of the 0.45 µ Millipore filters ($MCu_p$) is equal to 85.0 mg.

## CONCLUSIONS

After several adaptations on the experimental device, this first ITERCU-1 experiment allowed us to validate the capacity of the CORELE loop to perform some release rate measurements on CuCrZr rods under specific conditions of ultrapure water (i.e. with a conductivity < 0.1 µS/cm) with a water velocity of 10 m/s a 120 °C temperature and a pressure ranging between 45 to 49 bars. The quantitative analysis of copper trapped on the resins and on the filters provided an evaluation of the total quantity released during the 525 hours experiment, MCu = 191 mg. The total average release rate is the following: R = 86 mg/dm²/month. This value is consistent with the results of former studies.

The results give clear evidence that two processes are involved in the copper release, by dissolution of copper oxide film on the surface of the CuCrZr alloy and by mechanical erosion of oxide particles due to the water flow. This conclusion differs from the results obtained on stainless steel by former experiments on the CORELE loop [7], [8]. This key point lead us to adapt the loop in order to allow the regular sampling of particles trapped on 0.45µ Millipore filters during the next experiments involving $H_2O_2$ in order to investigate the water radiolysis effect on the alloy copper erosion-corrosion.

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**TW6-TSL-004**

# Task Title: COLLECTION OF DATA RELATED TO TORE SUPRA OPERATION EXPERIENCE ON COMPONENT FAILURE

## INTRODUCTION

The overall objective of this task is to include data coming from Tore Supra operating experience (e.g. component failure rate database or more generally function failure) in the “Fusion Component Failure Rate Database”.
This task refers exclusively to the systems of Tore Supra that are relevant to ITER and not present in other tokamaks:
- Cryo-plant, including Toroidal Magnet and its safety system (quench detection, energy dumping,…).
- PFC cooling system (including auxiliaries, e.g. power supply, compressed air, leak detection/localization,…).

A functional analysis, categorisation and compilation of maintenance/failure rate statistics has to be performed.

## 2006 ACTIVITIES

A kick-off meeting has been held at Cadarache on December the 4th, 2006. During this meeting it has been asked, by the EFDA contact person, to analyse also the causes of in-vessel water leaks that occurred in Tore Supra during its whole life. This point had been previously excluded from the contract. It was agreed to add it to the task. The various analyses are being completed by the responsible officers in charge of the operation of the systems of interest.

During the end of 2006 a qualitative analysis has been performed, aiming, first, to checked the availability of the data needed to fulfil the task. A description of the operation conditions and maintenance strategy of each system of interest associated with a breakdown to main functions and components has been started.

It has been checked that the available electronic data stored in the command-control database allows to reconstruct very accurately the working time and the number of solicitations of the main components, at least for the three and half last years. For older periods these data will be inferred from statistics related to log books and to the plasma shot database that are both available since the beginning of the Tore Supra operation (1988).

The Tore Supra failure database available, since 1997, has been analyzed to extract failures related to the specific components that are under the scope of the task. Despite the very large number of components assembled in these systems, a low number of failures or malfunctions have been recorded. This shows a good availability of these systems. It is thus important to link the failure rate to the preventive maintenance strategy used at Tore Supra and which leads to this result.

The impact of these failures on the global availability of Tore Supra, are also being analyzed.
With the availability of above mentioned data, it appears that statistics regarding the different types of failure rates can be produced.

A second meeting has been scheduled by the mid of March, with the EFDA contact person and with the manager of the “Fusion Component Failure Rate Database” to check the availability of the first quantitative results and their compatibility with the format of this database.

## CONCLUSIONS

It has been found that the various electronic Tore Supra Databases and log books contain the data needed to complete this task.
Analyses and statistics are currently being produced.
It is important to associate the failure rates to the preventive maintenance strategy and to the cost associated to reach a given availability rate.

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**TW6-TSS-SEA5.1**

# Task Title: IN VACUUM VESSEL DUST MEASUREMENT AND REMOVAL TECHNIQUES

## INTRODUCTION

During ITER lifetime, dusts will be produced due to the interaction of all types of plasmas (including conditioning procedures) with the Plasma Facing Components (PFCs). These dusts will be activated, tritiated and potentially chemically toxic (presence of beryllium). ITER has fixed a set of safety limits to manage the potential hazards which might be caused by these dusts. The aim of the EFDA task TW6-TSS-SEA5.1 is to assess techniques that could be used during ITER lifetime to control dust inventories within the vacuum vessel and to be able to recover the dusts when the safety limits are reached.
An interim report [1] has been issued in December 2006 to:
- Summarise the work already performed by G. Counsell et al. within the EU Task DV7A-T438 and by the Japanese home team,
- List some other potential techniques,
- Propose future work to be performed within the task to explore selected approaches more in details.

## 2006ACTIVITIES

### DUST PRODUCTION PROCESSES

Different dust formation processes occur in a Tokamak. They can take place in steady state phase (normal operation), off-normal operation modes or during maintenance.

During the steady state phase, the dust formation is closely linked to erosion of PFC materials. The eroded materials tend to re-deposit in layers in cold areas. These layers are made of stratified mixed materials (Be, W, C and metallic impurities) coming from the plasma facing components during the different operating modes. Due to weak adherence of these layers and important mechanical and thermal stresses inside the layers, they can flake once they have reached a certain thickness. Then they can produce dusts of different sizes depending on the stress levels and local deposit structure (typically from some ten µm to few mm).
The growth of small particles in the edge of fusion plasmas (with low Te (<5 eV), low ne (~ $10^{17}m^{-3}$) and high neutral density) from atomic or molecular precursors which are released by physical or chemical erosion can also lead to dust creation. The particles have a so-called cauliflower shape. This mechanism starts with particle size of about 10-50 nm and may nucleate and grow up to quasi spherical species with diameters exceeding 1 µm.

Off-normal plasma events such as Edge Localised Modes (ELMs), Vertical Displacement Events (VDEs) or disruptions produce high heat load and since the thermal conduction into the layer of the PFC is insufficient, the surface temperature can reach the boiling or sublimation point of the material. Dust particles are then created by either condensation and growth of the vaporized material, or pressure-driven ejection of melt layer material or explosive brittle destruction by heating of gas bubbles. In this case, significant amounts of small dust particles (< 1 µm) are produced and can agglomerate into larger structures.

Unipolar arcs can also produce large particles and droplets of molten metals. In this case, a large amount of energy is deposited at the metal surface leading to melting and vaporization of the material. The dust particles are comparatively large, spherical and composed of a single material.

The wall conditioning procedures involving dc-glow discharge in He or in reactive gases (carbonization, boronization, siliconization) purposefully generates surface films, which are subject to the same degradation as the a-C:H films and are thus potential source of dust particles.

At last, during maintenance activities, large particles can arise from mechanical abrasion during component replacement.

The whole dusts are mainly foreseen on or under the divertor, at the bottom of the vacuum vessel, behind the PFCs, in tile gaps/castellations or between tiles and at the horizontal ports.

### ITER CONSTRAINTS

For ITER safety, inventory guidelines have been set:
- To limit the mobile activation product inventory inside the vacuum vessel: the mobilisable dust limit inside the vacuum vessel has been set to 100 kg of W, 100 kg of Be and 200 kg of C,
- To ensure that chemical reactivity is adequately controlled: dusts on the “hot” surfaces of the divertor must be limited to 6 kg of Be, 6 kg of W and 6 kg of C in order to produce less than 2.5 kg of $H_2$,
- To avoid the hazard of dust explosions (not yet explicitly considered).

Calculations have been made in order to determine when these limits could be reached. The administrative guideline of 100 kg for tungsten dust could be reached in about 500 plasma pulses. This reveals that the administrative guideline is reached before the assumed replacement of the divertor. Dust diagnostics and removal methods are thus highly required.

Based on the data currently available, the techniques to be developed for dust monitoring and removal should be able to deal with the following conditions:
- Dust size between 10 nm and 100 µm with various shapes,
- Composition: Be, C, W and metallic impurities,
- Localisation: bottom of the machine but also in shadowed areas (behind tiles or in gaps/castellations),
- Tokamak conditions: vacuum environment with magnetic and radiation fields and at temperatures up to 240°C,
- In order to limit the impact on operation, preference will be given to non-intrusive techniques.

## ASSESSMENT OF DIAGNOSTICS FOR DUST MONITORING

### Introduction

For the general limits inside the vacuum vessel, one can set the total amount of eroded material as an envelop value for dust creation assuming 100% conversion of the eroded material to dust. This value could be used for the safety approach to demonstrate that the general limits inside the vacuum vessel are fulfilled. However, this value could be too conservative and could constrain too much the operation time requiring dust removal more frequently than necessary.

In order to reduce the margins, the quantity of deposited materials could also be assessed. In this case margins are reduced compared to erosion quantity and are maybe not so much conservative since some authors have noticed that even if these layers are still adhering when they are under vacuum, they may peel off due to external shocks applied by changes of environments and/or ambience (tokamak venting or water leaks).

Finally and ideally, we should be able to monitor dust which could be mobilisable in case of an accident. But in this case, mobilization can be different depending on the conditions which are considered, from mobilization by loss of vacuum up to mobilization by explosion. Even in the case of the “loss of vacuum” event, pressurization rates and positions of leaks may be very different. It would be thus quite difficult to assess the quantity of dust that can be mobilisable from a local measurement in given conditions.

### Review of techniques that could be used

Three categories of diagnostics have been considered:
- Optical systems: spectroscopic, laser or imaging techniques
- Sampling systems: sample extraction for external analysis
- Gravimetric systems: measure the weight of accumulating materials

The following diagnostics have been assessed:

*Optical systems:*
- Detection of the dust motion (movement and oscillations) with high speed, high resolution CCD cameras or speckle interferometry at the interface of the plasma and the surrounding walls (plasma sheath).
- Implantation of trace impurity species (figure 1) with a clear spectroscopic signature at different depths throughout sample plasma facing components for monitoring local erosion phenomena.

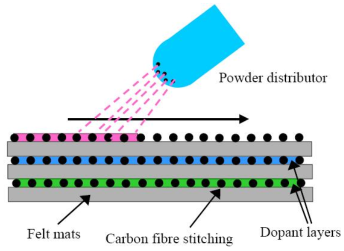


*Figure 1: PFC dopant principle*

- LADAR (Laser Distance and Ranging): distances are measured via time-of-flight measurements for the reflection of ultra-short laser pulses from a surface.
- Laser Induced Breakdown Spectroscopy (LIBS): the plasma generated by the material ablation is analysed.

*Sampling:*
- Use of the general pumping system in the divertor region to collect airborne dust and analyse them out-vessel.
- Dust sampling using a highly flexible, remote manipulation and sampling system, similar to a medical endoscope. For collection, a local blast of inert gas is used to dislodge the dust, which is then collected by means of a suction tube.

*Gravimetric systems:*
- Capacitance Diaphragm Microbalance (Figure 2): the cumulative weight of dust, flakes or film growth on the surface of a diaphragm is measured by determining the change in capacitance caused by its deflection relative to a fixed plate.

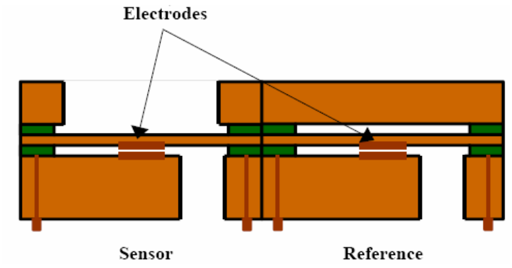


*Figure 2: Capacitance Diaphragm Microbalance*

-Electrostatic detector: when conductive particles land on the energized grid, a transient short circuit occurs and this current pulse can be easily measured.

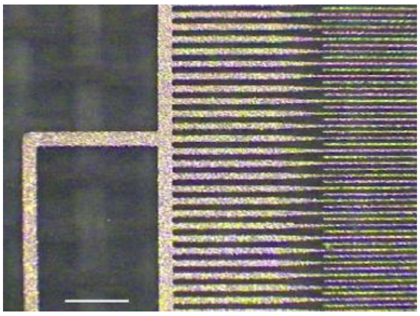

*Figure 3: Electrostatic detector*

**Other techniques to be assessed in 2007**

In order to avoid damage by overheating (> 1000°C) of the Tore Supra neutralisers, a security system has been tested triggered by the thermal radiation measured with optical fibres. The analysis showed that the surface conditions as dust and flakes play an important role.
Based on these observations, one could imagine that near-infrared spectroscopy might allow in-situ global characterisation of layers, dust and flakes. Other techniques dedicated to tile survey, such as pulsed or modulated laser photothermal thermography will be assessed to identify their potential ability as diagnostic/monitoring tools for deposit/dust.
The Speckle technique will be also assessed as a mean to monitor erosion/deposition.
At last, methods to estimate dust in suspension by laser extinction or using the laser from the Thomson scattering system to follow the diffusion of the light by the dusts in suspension will be also assessed.

## ASSESSMENT OF REMOVAL TECHNIQUES

### Introduction

Dust removal may need to be done on a regular basis, perhaps monthly or quarterly, in particular if the diagnostic tools have been proven to be not enough accurate to ensure that the safety limits are respected.
Removal of dust, flakes and deposited films from the vessel is a three stage process:
- Material mobilization: material must be detached from the surface on which it is attached, via inert gas puffing or more abrasive forces,
- Collection of the mobilised material and transport within the vessel,
- Transport outside the vessel.

### Possible methods

*Vibrating conveyor*
This technique, proposed by G. Counsell et al. within the EU Task DV7A-T438, relies on vibration to assist the movement of the material, under gravity, down a slight incline (figure 4). The vibrating conveyor can operate under high magnetic field and under vacuum.

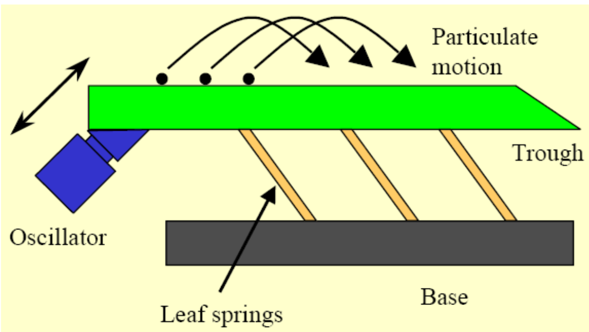


*Figure 4: vibrating conveyor*

The installation of such a conveyor has been proposed in the divertor region for continuous operation.

The preliminary design (figure 5) foresees a toroidal conveyor with a poloidal shape similar to the vacuum vessel, and that could extend up the inner and outer vessel walls to locations at which the local vessel wall slope is greater than the friction angle of the particulate to be collected and transported.

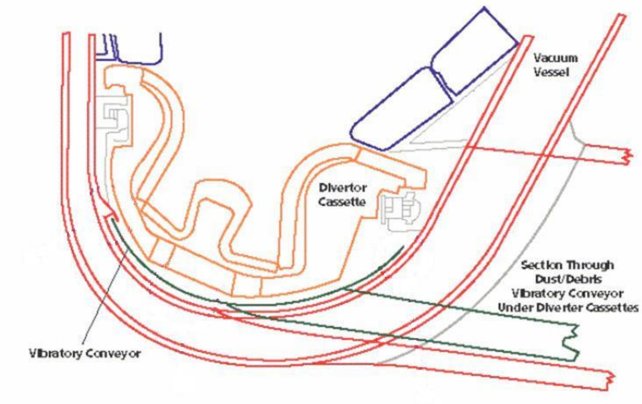


*Figure 5: Poloidal cross section showing location of toroidal vibratory conveyor*

*Electrostatic conveyor*

This technique, proposed by the Japanese home team, is based on the fact that a particle, which is initially grounded to the floor of the vacuum vessel, can be inductively negatively charged by the application of an electric field by a collection electrode. As a matter of fact, when an electric field is applied, the particle is dielectrically polarized. Since the particle is grounded to the floor the positive charge of the ground surface is neutralised so the particle get negatively charged. This particle is then floated by the Coulomb force due to the electric field between the charge and the electric field.
When a non spatially uniform electric field is applied, a gradient force is produced and the particle can travel according to the non-uniform travelling wave, so called “electric curtain” (figure 6).
Tests have been performed on particules from 10 to 100 µm.

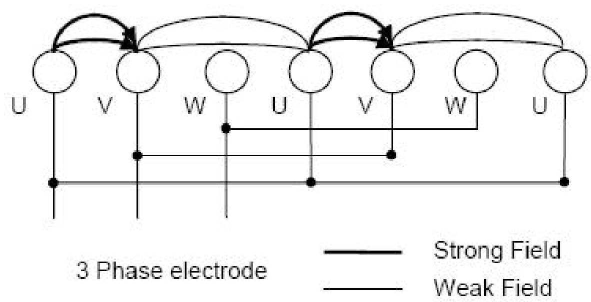


*Figure 6: Principle of electric dust conveyer transportation*

Based on these properties, two types of devices have been proposed:
- A so-called "dust floatation and transport device", which is developed to act like a vacuum cleaner but able to work in a vacuum ambience. Put on a remote handling arm, it can locally remove dusts from the surfaces of the divertor or from horizontal ports (figure 7).

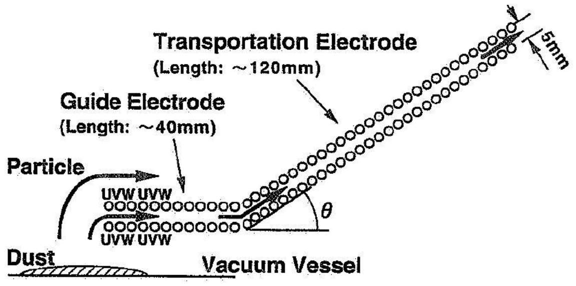


*Figure 7: Example of 2-stage linear-type electrode with a guide electrode for the dust transportation test*

- A continual dust removal device that could be installed under the divertor to allow a continuous operation (figure 8).

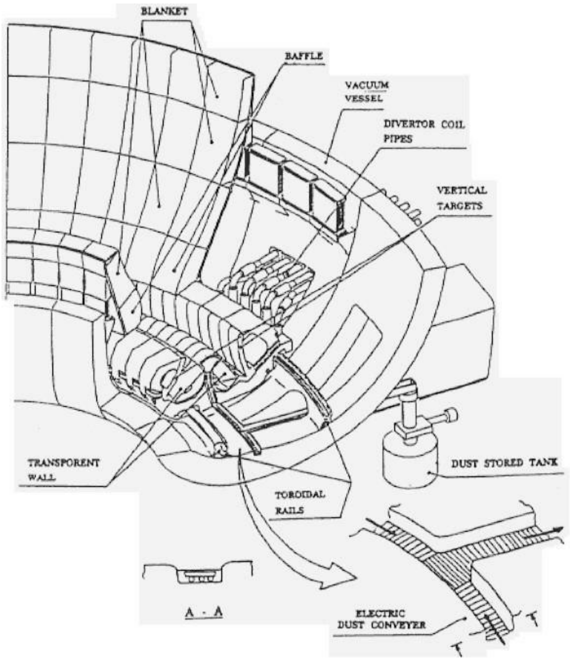


*Figure 8: Concept of continual dust removal system*

*"Dishwasher"*

This integrated technique (allowing material mobilization, collection and transport) is based on the injection of liquid through high pressure jets (strategically placed and allowing to be reciprocated into the vessel during cleaning periods), to remove the dusts from the rear of the PFCs. This proposal seems very surprising but is supported by the fact that this technique is able to reach the rear of the PFCs.
Nevertheless, the application of the technique leads to loose the conditioning so the selection of the “ideal” solution is essential.
Many solutions have been assessed and fluids developed for the replacement of chlorofluorocarbons (CFCs) and chlorinated solvents could be suitable candidates.

*Other techniques*

-Gas blasting: localised puff of inert gas to mobilise loose materials from the surface.
- Pellet blasting: frozen pellets of $CO_2$ are fired at the surface, the ice sublimes and the resulting rapid gas expansion carrying away material.
- Water hammer: regular oscillations of pressure in the coolant circuit supplying each PFC will detach by vibration loose dust and flakes.
- Excimer laser, Xenon light or flash lamp: detachment of the films by selective heating. Molecular bonds in hydrocarbon film deposits are broken by the strong source of UV light.
- Suction.
- Pumping with filter: use of the general pumping system to collect airborne dusts.
- Pumping with electrostatic precipitator: same principle as above except that an electrode is used to stick the dust.
- Wiping out with cloth or swabbing.
- Adhesive tape.

**Other techniques to be assessed in 2007**

This survey has shown that collection and transport techniques for the dusts have been developed (electrostatic or vibrating conveyor). The main issue on which we will focus our work will concern the material mobilization and in particular from the gaps and castellations. Techniques using laser and radiation forces will be studied.
Moreover, the constraints linked to the use of the remote handling tools will be considered during the selection process.

## CONCLUSIONS

Work will continue within this task in order to assess more in details techniques that could be complementary to the already studied ones.
For diagnostics, two approaches will be studied:

- Mapping of the deposited areas based on the thermal behaviour of the dust/layers. This will use techniques developed for security system to follow heating loads on the surfaces: pyrometer, near infrared thermography, lock-in, others.
These techniques don't give a quantitative measurement of the layer thickness and can be disturbed by the reflectivity of metallic surfaces so they will be coupled to:

- Non invasive and local measurements:
-Laser techniques: ablation followed by LIBS, radar, others that could be used as "calibration" for mapping techniques,
- Measure of dust in suspension: extinction, Thomson diffusion, others.

Concerning removal, since collection and transport means have been developed, effort will be focussed on material mobilization and in particular inside gaps/castellations.

Moreover, the constraints linked to the use of the remote handling tools will be considered during the selection process.

## REPORTS AND PUBLICATIONS

[1] 'Interim Report on in-vessel dust measurement and removal techniques', S. Rosanvallon, 22nd Dec 2006

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