FUSION TECHNOLOGY

Annual Report of the Association EURATOM/CEA 2000

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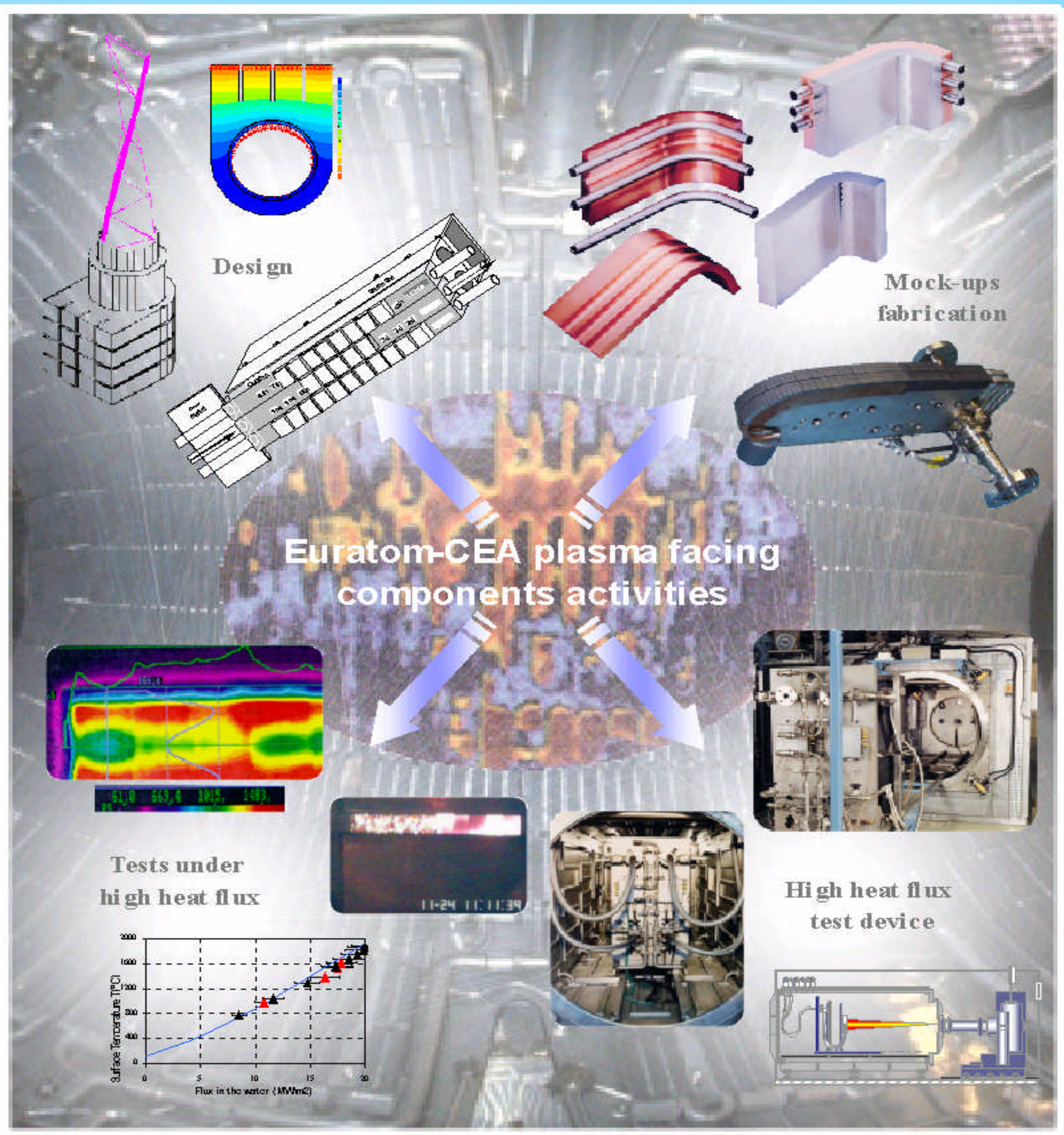

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Task Title : RADIATION TOLERANCE ASSESSMENT OF STANDARD COMPONENTS FOR REMOTE HANDLING AND PROCESS INSTRUMENTATION

INTRODUCTION

The previous results obtained on basic electronic or optoelectronic components have shown real opportunities to use them under total dose up to 10MGy and very high temperature. Year 2000 was mainly devoted to continue characterization of components in order to confirm first results. For a same basic function, some parameters like technology and manufacturers were particularly followed.

This paper reports activities connected with simple logic functions, power transistors, DAC, operational amplifiers and voltage references.

Works done on photodiodes with results on bandwidth have been also reported.

2000 ACTIVITIES

WORK PERFORMED ON ELECTRONIC COMPONENTS

Power transistors

In order to reduce the size of umbilics, the in-service of electronic power supply and motor control components of power systems are especially pertinent. Irradiation and high level of temperature logically affect them.

The basic element and the most critical of any such system is the power switch. Advances in switching technology have led to replacement of bipolar power transistors with MOS (metal oxide semiconductor) and IGBT (Insulated Gate Bipolar Transistor) devices. Previous studies of dose effects on IGBTs were done with significant results [1] [2] and confirmed under ITER conditions.

Nevertheless, the well known “three states” decreases of Vgs is such as to render these devices only suitable with a special gate driver.

The advent of a new technology could change this situation. CoolMOS™ technology is described by its designers as revolutionary, which is why it seemed interesting to evaluate its radiation response. Irradiation have been done [3] and shown that the new technology is potentially suitable for use in a gamma radiation environment.

In the present study, an IGBT *IRG4PH50KD* and a CoolMOS™ *SPP03N60S5* transistors were characterized under usual irradiation conditions at SCK-CEN facilities (dose rate around 26kGy/h for nominal temperature of 70°C.

Like for all other power nMOS, on-line parameter followed was voltage threshold Vgs for different Ids current. Applying few volts to Vgs allows transistor to easy switch from blocking to passing state.

Common irradiation effects on Vgs behaviour usually observed are briefly summarized. As the same way between MOS and IGBT transistors, trapping charges issued of Gamma rays interaction are predominant in the insolent. Particularly, the holes stay in a zone relatively close to their trapping sites. Trapped electrons are rapidly evacuated. Therefore, we will get a rise of positive charge. To put the component in a blocking state, Vgs must be lower than previously and drift toward negative values. Then, a very short recovery phenomenon appears and will reach rapidly saturation states. Finally, trapping charges will take place again with predominant effect. Threshold will drift again toward important negative values. At the same time, there is still formation of new interface state with partial recombination. Both effects will reach a definitive stabilisation of threshold however absorbed dose.

Tests conducted under ITER constraints validate such approach by throwing out total dose acceptance of MOS and IGBT transistors.

Depending of the bias conditions; combined effects of irradiation and temperature increase drift of threshold, shortly for best bias conditions (negative, 0V and dynamic, 2 samples by bias), more deeply for worse conditions (positive). In any case, components were always operational.

Concerning figure 1, the irradiation have been done up to 28MGy without any problems. Permanent state is smoothly moving. This explains the temporary viewing of curve for bias condition of +10V. The test bed is not able to drive thresholds below approximately 20V. This confirms a good homogeneity for such components with no important difference between lots, references and manufacturers.

During this campaign, an unstable period has started just after stopping irradiation. The beginning of an immediate recovery has been generated before cutting supply on the test bed for one day.

Then, after keeping temperature near 100°C, supply have been set again followed one day later by irradiation (same conditions).

Figure 1 shows an interesting phenomenon. Components are still working, but an important drift affect threshold of transistors biased at 0V and -5V (best conditions), more than bias +10V (worst case).

Little recovery can be observed. Post-irradiation measurements done with parameter analyser will confirm this state.

Two actions have taken place in the same time. No significant explanation has been found to explain which of the two, or the two, is involved in this damage. It is obvious that stopping irradiation and supply should be a potential condition for real use; for example, remote handling during a day-mission followed by a rest time (with possibility of lower radiation and/or unsupplied engines).

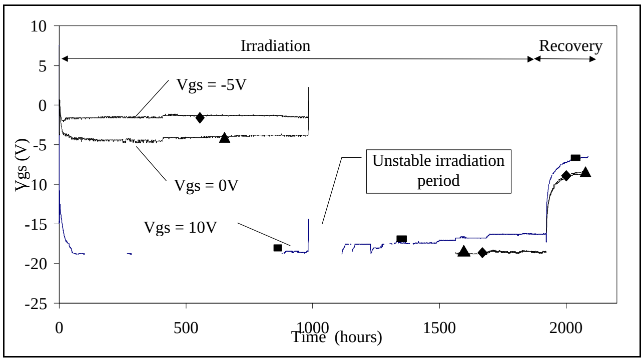

Figure 1 : Data from IGBT IRG4PH50KD

Concerning figure 2, irradiation of CoolMOS™ *SPP03N60S5* has been the same like for IGBT *IRG4PH50KD*. Behaviour during irradiation period does not show very significant differences. Worst and best bias conditions do not change at all.

Short cutting (one hour) of supply have produced a brief recovery as usual, possibly more important for worst case.

At the end of the experiment, supply has been suppressed during few days. Recovery phenomenon seems to be better for this component than for IGBT.

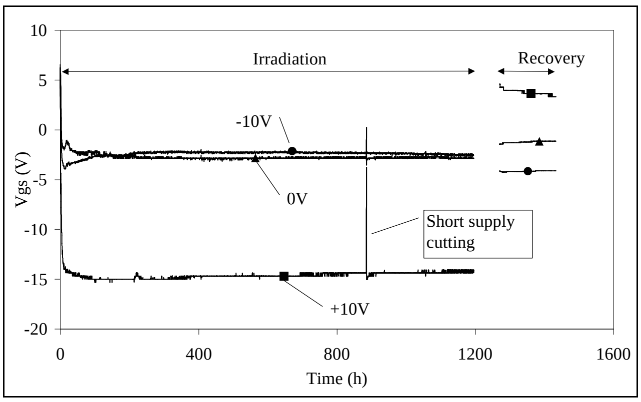

Figure 2 : Data from SPP03N60S5 CoolMOS™

Logic circuits

Results obtained on logic components for bipolar and CMOS technologies have been confirmed by the evaluation of the most recent, ALVC (0.35µm).

Technologies of many manufacturers have been irradiated in order to compare the effect of the design and the fabrication processes. Data given by such parameters are influent for hardness assurance in order to guaranty a better availability for a component.

Unlike for previous campaigns, the simplest common function founded was buses drivers which are now the first components realised with all emerging technologies.

Like for invertors, the tracked parameter is Vout. Slopes (-0,5V -> 2,8V and 2,8V -> -0,5V) are applied for Vin during tests. This parameter is currently used to characterise such components. During radiation, different bias are applied to Vin (0V, 5V (3,3V), slopes). Because the number of wires is reduced between control room and the container, it was necessary to limit on-line investigations. In that way, dynamic bias was chosen.

The others bias were controlled before and after irradiation. Results given on figure 3 to figure 4 have been obtained during this campaign. To permit an easy comparison of the influence of irradiation on all these technologies, the curves represent input voltage necessary to have output voltage equal to Vcc/2 (2,5V/2), intermediate voltage obtained during switching state.

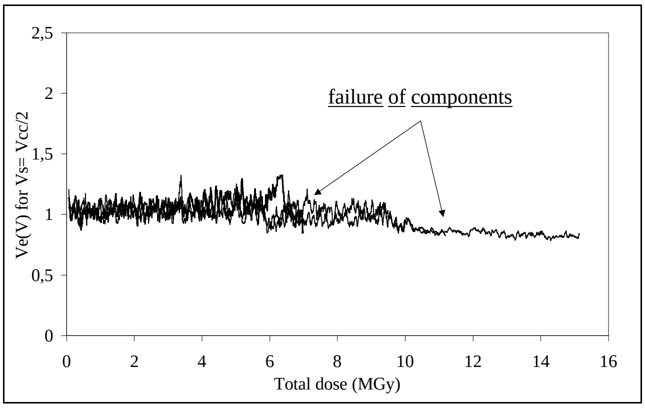

Figure 3 : Response of ALVC 16244 bus drivers (70°C)

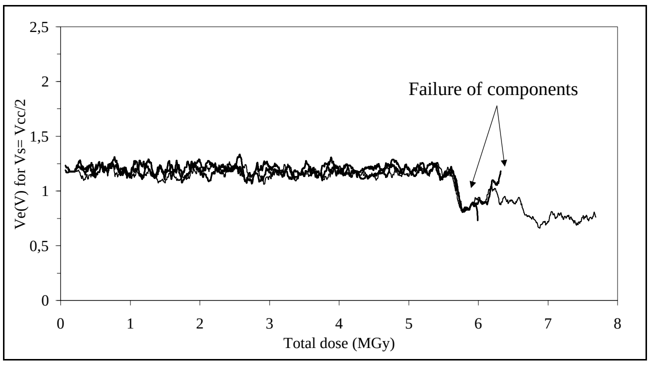

Figure 4 : Response of ALVC 16244 bus drivers (150°C)

Clearly, some failures have put some components in a non functional state after a few MGy of total dose. But most of the components were still in a working state at the end of the irradiation. More, the combined effect of temperature and dose have no important effect. The higher average level of the curves should be explained by a small increase of supply voltage during irradiation necessary to limit the important electric noise created by the components during their switching time. Unfortunately, during this test, many short-circuits have damaged one of the two cards and destroyed the components. Presence of acid gas (chlore) was the main reason. In any case, post-irradiation tests have shown that the components were able to work again. The parametric measures allowed to know the state of each driver.

Some drifts were appearing on the level of Vin necessary to switch the outputs from high to low and low to high. The influence of bias conditions during irradiation was visible and often explained on papers, particularly the alternative bias [4] [5] [6] but significantly at very lower dose. The most significant is the increase of the minimal voltage Vmin necessary to obtain the functionality of the component. Already used to control working margins of non elementary components, this parameter have also shown a good appreciation of the influence of the total dose effect on CMOS components. It was used few years ago to control irradiated components [7] and introduce as a patent [8] to measure the ability to work during an other irradiation period. The drift of this parameter could be seen as an equivalent of the drift of the threshold voltage for a elementary component.

The average post-irradiation value obtained for this parameter is between 1,8V and 2,4V (pre-irradiation value was between 0,6V and 1,1V). For a nominal voltage of 2,7V, the tolerance is just of 0,3 to 0,9V instead of 1,7 to 2,2V for pre-irradiated ones. So, it is obvious that the components are degraded by irradiation but still operational with a reduced margin. No significant recovery was observed after irradiation. Vmin seems to become a asymptotic value. These observations could be compared with those made on CMOS inverters last year. At that time the asymptotic value of the threshold voltage have been mentioned for different bias conditions.

Analog circuits

In order to develop the basic function of analog to digital converter, it seems important to know the behaviour of the elementary components ever used in any case of conversion. The first stage of such function is a digital to analog converter. The well-known component able to realise this function is DAC 312.

Often used in our designs, it has given significant results on usual nuclear applications. A new test card has been developed to evaluate such component and to follow the linearity response (analog output vs. digital input). Due to the lack of wires, it was not so easy to follow each binary value.

An intermediate solution has been designed. So, during irradiation, a dynamic bias (binary values of 0 / 4095 at 1Hz) have been applied to few digital input pins, the others were connected to binary 1 by design. Control on output has been made for input value of 0, 2047 and 4095. Pre-irradiation control has been made.

Three pairs of components (same manufacturers but different packages) were submitted to irradiation (27kGy/h at around 60°C). Concerning figure 5, the responses under radiation shown an acceptable drift (less than few %) for all bias even if experiment have been stopped before reaching 10MGy. After 150 hours, irradiation has been suppressed during one day. Some of components have produced an immediate and important drift (more than 10% of the value for 4095 bias) then stabilised until irradiation has restarted.

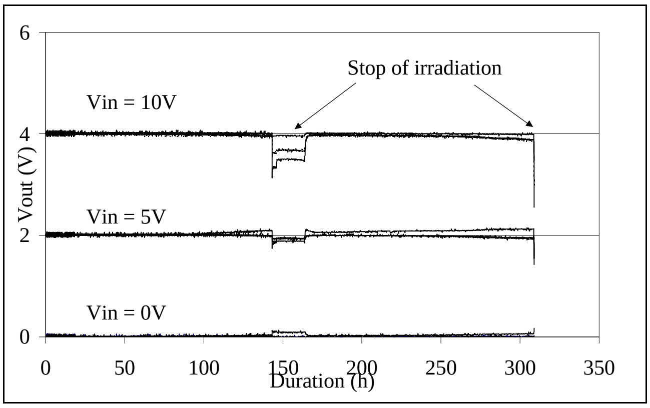

Figure 5 : Response of DAC 312

The same decrease has taken place at the end of the experiment just before cutting supply. These events shown a significant sensitivity to the dose rate, which bring to the creation of intermediate stable states linked with total dose evolution.

The post irradiation control was done few days after end of experiment. Some components were unusable while others confirmed significant damage. The linearity control (see figure 6) gives some information of the new state of the components. Few bits of the digital value affects internal threshold switches and corrupts converted value [9].

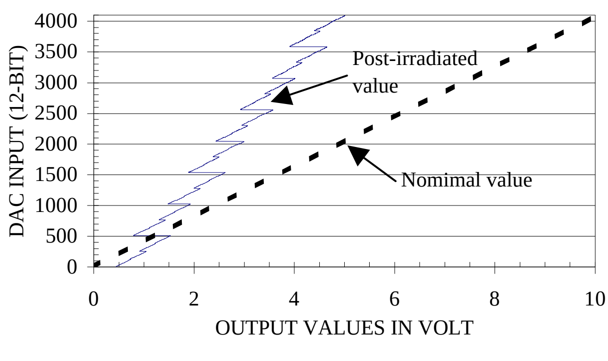

Figure 6 : Response of DAC 312
(pre and post-irradiation)

WORK PERFORMED ON OPTOELECTRONIC COMPONENTS

A new experimental test bed was designed in order to simplify the previous one and increase the measurement precision. The behaviour of the photodiodes has been explored to increase knowledge about the influence of extreme conditions. No publication has reported the effect gamma irradiation on the photodiodes for such integrated dose. However, many studies have been done for CERN activities. The usual parameters used to characterize those components are:

- Sensitivity with P(photoreceiver) = f(total dose). This measurement has been already used. Photodiode is lighted and photoreceiver (Irec) current is red through a resistance while the photodiode is reverse biased at V(rec). P(photorecevіver) = I(rec) * V(rec).

- Static behaviour with I(photoreceivers) = f(Vbias) without lightening. Figure 7 shows the general aspect of the measures with the followed parameter which are blocking direct voltage, limit reverse voltage and dark current mainly introduced by environment (temperature and irradiation).

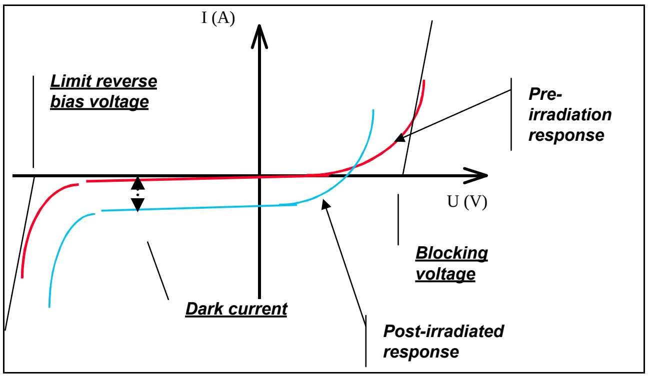

Figure 7 : I(phoreceivers) = f(Vbias)

- Sensitivity to lighting I(photoreceiver) = f(P(ligh)). Figure 8 explains more precisely how the parameter is calculated for a define reverse bias condition. At time control, measures are done for different lighting conditions in order to evaluate the mean straight line.

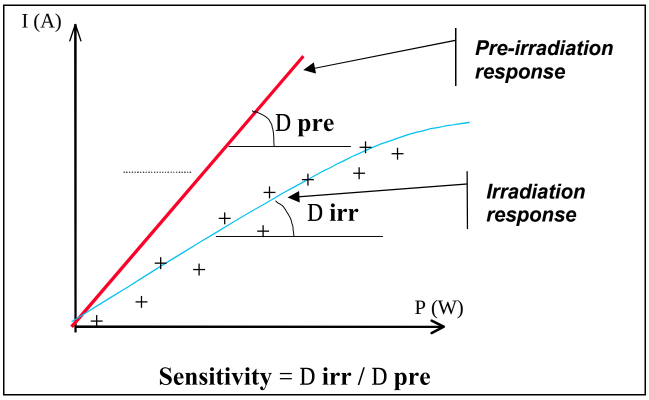

Figure 8 : Sensitivity of the photoreceiver

During the irradiation photodiodes are unsupplied and unlighted. Every half-hour or hour, photodiodes are biased according with their own characteristics. Lightening is sent to the photodiode and the photocurrent is measured through a resistance directly by the PC and the switching board. In the same time, control is done through reference links. Figure 9 helps to understand how the test bed is working.

To validate the test bed, campaigns have been conducted to characterise two types of photodiodes, Si HFD 3013 (monomode 850 nm) from Honeywell and InGaAs FD80FC (multimode 1310 and 1550 nm) from Fermionics.
Main significant results are presented on next figures for monomode HDF3013.

Increase of dark or leakage current has been shown.

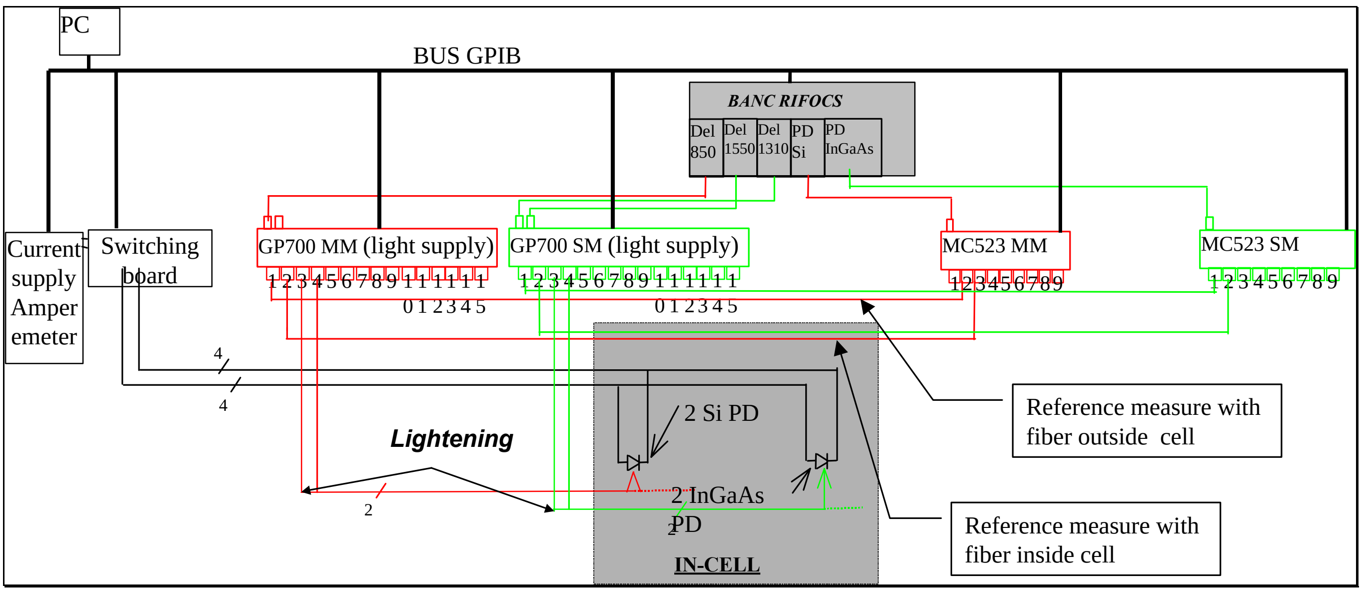

Figure 9 : Test bed for photodiodes

After an important drift due to the adaptation to temperature and irradiation environment, a quasi linearity is observed with the absorbed dose [10]. Recovery is visible during the stopping of the irradiation. It has disappeared with the return of irradiation and slid down to an asymptotic state after the final stop. Unfortunately, failures (components, cables or testbed ?) have involved some results after the 40th day (second period of recovery). But, it seems possible to say that the evolution of dark current is very similar for the two types of photodiodes (Si and InGaAs technologies). These results extend the experiment made by CERN [11] with similar experimental conditions.

Reverse blocking voltage (or avalanche breakdown) has not significantly affected by radiation. The same failures than previously have created a lack of stability for some reverse voltages.

Direct blocking voltage have apparently shown an important dispersion for either Si and InGaAs photodiodes. Some components have a common voltage of approximately 0,4V with no significant variation under radiation. Others were rapidly lowered to 0,1V and stabilized. No explanation is clearly identified and mentioned on publications. No link appears with the dark current.

The sensitivity of Si photodiodes have suffered in order comparable to those observed last year. A fast and significant decrease of sensitivity at low total dose from 100% to 30% even less than 10% was followed by a permanent state while a very small recovery could be noticed after each stop of irradiation. This should also allow us to verify a possible contribution of an integrated lens to the measured response degradation, as it was yet suggested in literature [12]. The unusual variation of temperature at day 55 has affected the recovery.

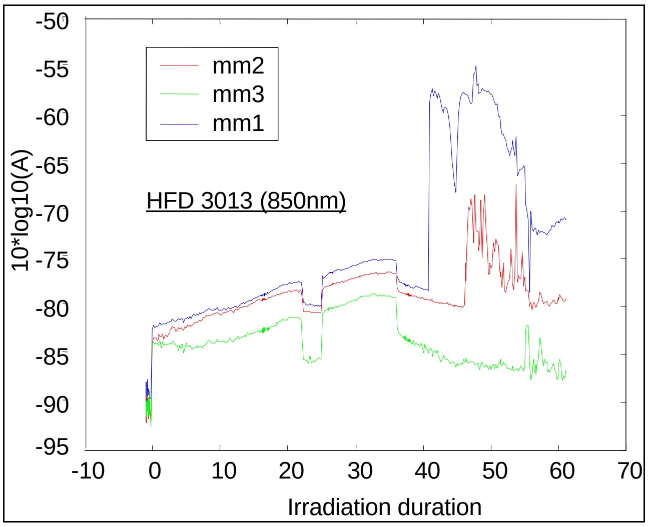

Figure 10 : Dark current for inverse bias voltage of 5V

The sensitivity of InGaAs diode have confirmed those obtained last year. It should be important to notify the very important influence of the temperature drifts due to the thermal effect of radiation. Nevertheless, significant recovery allows the erasing of such damage up to the last state before stopping radiation. Usual recovery could be observed after to reach pre-irradiated state.

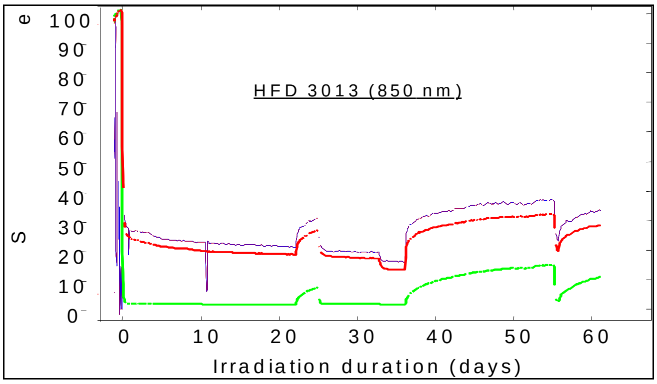

Figure 11 : Sensitivity to the radiation

This phenomenon has not been previously observed [11] and can be acceptable so far as the sensitivity will conserve the ability to detect significant variation of lighting power (ON/OFF state or modulated state).

Measurement of bandwidth have been starting on lots of photodiodes. First results seem to confirm that there is no significant action of radiation. Experiment must continue in order to provide to provide an estimation of the bit error rate (BER).

CONCLUSION

Very large number of components has been studied during these years. Most of them have given a good behaviour under radiation. Few have been destroyed or very affected by radiation or combination of radiation/high temperature.

Some events need to be followed with more attention. Unfortunately, we have observed that presence of rest periods (out of radiation) supplied or not supplied, disturb comportment of components by creating important drifts.

Thus, in order to approach real conditions of remote engines, such periods must be introduced during irradiation campaigns. This will permit to understand recovery phenomena and define best rules to use such components. Depending of the depth of the damages, some compensation should be possible at the level of the control room.

More, complex logic functions need to be evaluated before final design of the ADC demonstrator.

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T329-5

Task Title : IN VESSEL RH DEXTEROUS OPERATIONS Task extension 2

INTRODUCTION

The T329-5 project aims at demonstrating the feasibility of effective remote handling dexterous operations for the Divertor maintenance. A derived goal is the development of the missing technology required to achieve the primary objective.

The main action consists at performing a representative maintenance operation under the so called "blind" conditions (without video feedback) by making full use of a 3D CAD model of the remote workspace. For this purpose, an experimental site (RIS for Remote Intervention System) will be set up inside the DTP (Divertor Test Platform) located at the ENEA Brasimone site.

This test-bed is built around a MAESTRO master-slave hydraulic manipulator driven by a TAO 2000 telerobotics controller [2]. The system is operated through a force-reflecting master arm and a Graphical Supervisor [3] that simplifies the preparation and the supervisory execution [1] of the remote missions.

It will be used to demonstrate under realistic conditions that a maintenance mission possibly leading to some unexpected situations may be successfully realised by current telerobots.

The technological developments of T329-5 deal with the following topics:

- registration of environment objects using points sensed on their surface with a touch probe ; the necessary computations are made by the SCK/CEN BLINE module ;
- long distance teleoperation in order to allow an operator to control an intervention system located several hundred kilometers away ;
- water hydraulic that would better suit the contamination constraints of ITER.

2000 ACTIVITIES

The goal for 2000 was to complete the T329-5 task. As far as CEA/STR was concerned, this implied the following actions:

- prepare the Brasimone mission with the MAESTRO manipulator on the Fontenay-aux-Roses test-bed ;
- terminate the preliminary evaluation of the SCK/CEN BLINE registration module using the Fontenay-aux-Roses resources ;
- develop the Graphical Supervisor software that has been previously specified ;
- ship the MAESTRO arm to Italy and perform the Brasimone mission ;
- realise the long distance teleoperation tests ;
- evaluate the behaviour of the IHA single water hydraulic joint mockup from a control point of view.

Unfortunately, the commissioning of a MAESTRO manipulator in Brasimone has been significantly delayed due first to funding problems related with the acquisition of a RH system dedicated to the Fusion experiments.

It was therefore decided to provisionally send to Italy the CEA/STR prototype system.

Unfortunately, a number of defaults were experienced with this system (calibration difficulties, software bugs and mechanical failures) that have precluded the successful preparation of the Brasimone mission.

The problem has been made worse by the total breakdown of one axis in October that has required lengthy repairs, thus interrupting the preparation work.

At the present time, the MAESTRO arm has been put into operation again, but a second calibration is necessary.

The current situation is now the following : the preparation of the Brasimone mission is not yet completed and both the final demonstration in Italy and the long distance testing have been delayed.

Nevertheless, a significant part of the preparation task has been made:

- the complete mission has been executed a number of time with our test-bed (figure 1) ;
- the automatic tool grasping/releasing functions and the tool racks designed to be used inside the DTP have been validated (see figure 2) ;
- the scripts for executing the Brasimone mission have been partly written, tested and validated ;
- the BLINE module has been fully validated prior to its use in Brasimone.

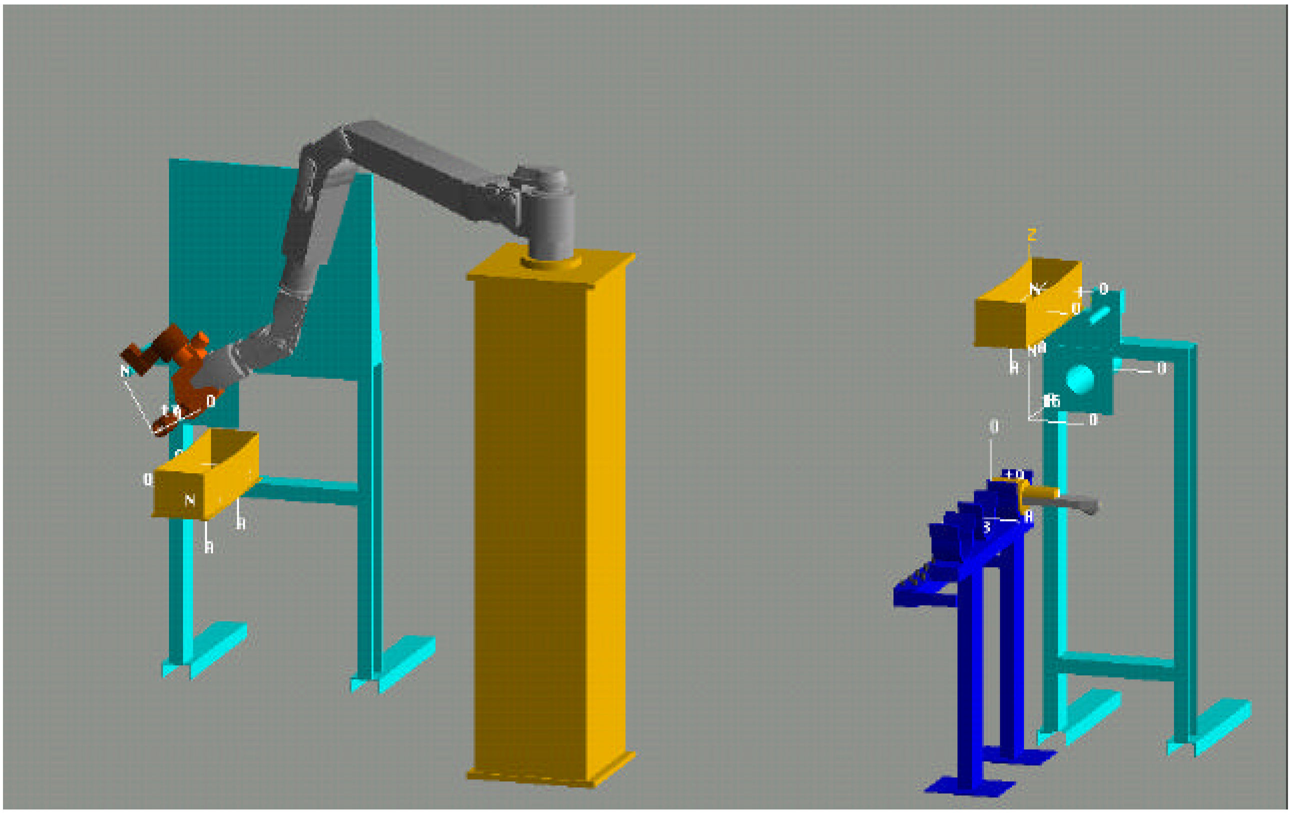

Figure 1 : CAD view of the RIS site set up in Fontenay-aux-Roses CEA facility

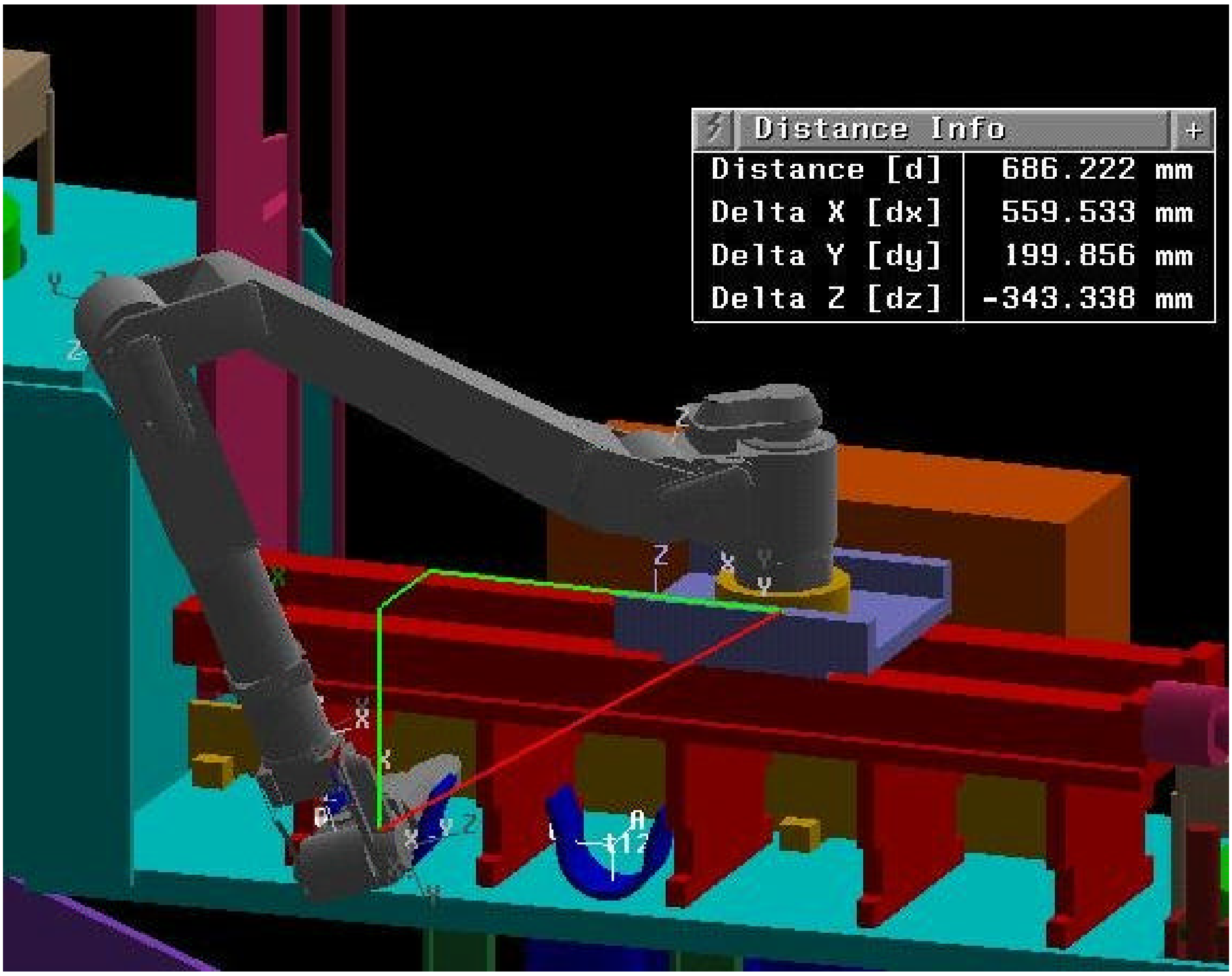

Figure 2 : Validation of the tool racks designed for use inside the DTP

Beside the MAESTRO setback, the Graphical Supervisor that make use of a computer model of the DTP, controls the MAESTRO implementing the Graphical Language concept and exchanges data with the supervisory system of the whole DTP is now ready (figure 3). It has been remotely tested with the ENEA system using commands and feedbacks sent through Internet.

Finally, the assessment of the water hydraulic mockup (figure 4) has been completely performed, displaying results that are quite equivalent to those obtained with a classical oil hydraulic actuator.

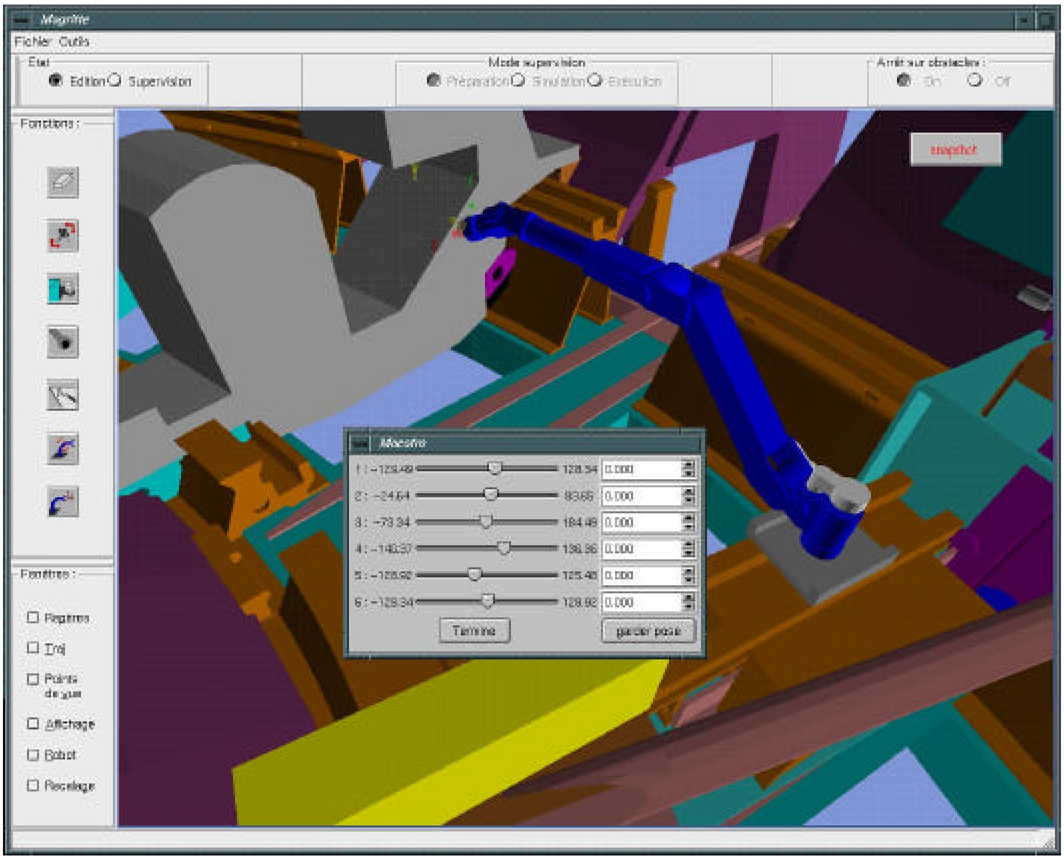

Figure 3 : Interface of the Graphical Supervisor

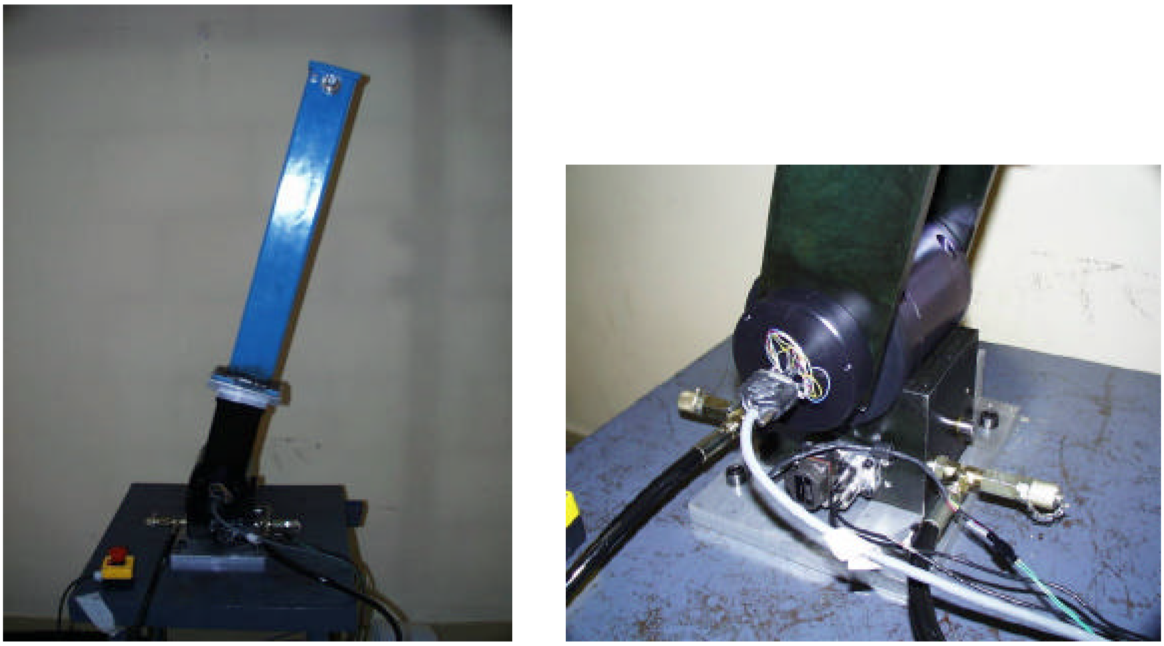

Figure 4 : The water hydraulic mockup that has been evaluated by CEA/STR

CONCLUSIONS

From a general point of view, the progress made during year 2000 is considered with mixed feelings as the final objective of task T329-5 has not been achieved as scheduled. On the other hand very good work has been performed for preparing the Brasimone mission and we are confident that, save for new problems that may always be experienced with a prototype manipulator, the complete action will be completed in the first half of 2001.

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REPORTS AND PUBLICATIONS

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T329-5: In-Vessel RH Dextrous Operations - Water Hydraulic Joint Results on Qualification for force feedback application (Technical Report STR/LTO/00RT.100), Claude Andriot.

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TW0-DTP/1.1
T329-4

Task Title : CARRIER AND BORE TOOLS FOR 4" BEND PIPES

INTRODUCTION

This project is an R&D program in remote handling activities for Fusion reactor In Vessel maintenance.

The removal/installation of Vacuum Vessel components often requires cutting, welding and inspection of cooling pipes. To allow the replacement of these components while minimising the space requirements, bore tools are preferred to orbital tools for these operations.

Following the latest ITER developments, an effort to standardise the pipes inside the cryostat is underway. One of these standards could be 4" pipes (100 mm ID). These pipes will be bent with a bending radius greater than 400 mm and cutting / welding will be required up to 10 meters away from the tool insertion point. The objective of this task is to demonstrate the feasibility to operate with bore tools in 100 mm bend pipes and to study the associated mechanism required.

This task includes design activities, manufacture and testing of a demonstrator of the basic steps of 100 mm bend pipes maintenance.

A modular carrier design was proposed to fit the requirements:

- Set up tools from pipe entry point to working zone (10 meters).
- Position tools at the correct location.
- Generate stress in pipe:
    * clamping on pipe,
    * compensate internal pipe stress after cutting (100 daN),
    * align two faces of pipe before welding (20 mm axial, 10 mm radial 100 daN).
- Provide necessary rescue functions.

Process tools required for pipe repair are:

- Milling, to cut 80% of the pipe.
- Final cutting with a swaging tool.
- Tack welding.
- Butt welding with filler metal.
- Non destructive testing to check the quality of the operation.

Feasibility of such a concept was studied during 1998. Manufacturing of a prototype carrier was made during 1999 focusing on the most critical functions needed by the carrier. Clamping modules, an alignment module, a tack welding tool and a swaging tool were designed, manufactured and tested separately.

This year's work was dedicated to a general upgrade of the carrier. A paper study was made in order to see what was the size reduction potential of the present design without changing the whole concept. Upgrading the carrier means also changes in the processes and a laser cutting and welding tool was designed in cooperation with ENEA/RTM. Test of the tool will be made in 2001.

Last year's tests showed some imperfections in some mechanisms and a new clamping design integrating the specific requirements of the laser tool were proposed, manufactured and tested. Particular attention was also paid for the umbilical management and a storage wheel was built and designed.

2000 ACTIVITIES

SIZE REDUCTION

An analysis of all the function modules (clamping, alignment) and tools was made in order to see what are the reduction potentials of each modules. Reducing the pipe diameter has a major impact on the process which means that milling is no longer possible. The swaging tool therefore has to cut the whole thickness of the pipe and evolutions in the tool design have to be made.

Considering that swaging becomes the main cutting process, reducing the pipe diameter to 3.5” means is possible but the bent radius will be increased to 425mm because of the swaging tool which is today the most stringent.

For all the other tools and function modules a 350mm bent radius seems to be reachable with little work. A pipe reduction to a diameter of 3” means that the carrier will be able to navigate straight pipes only.

UPGRADE ON THE PROCESSES

Reducing the number of process and the processing time is always an important goal for maintenance work. In our case, pipe cutting could be made with a single operation by using a YAG laser.

Other advantage of this technology, the laser cutting tool it is also the welding tool. A special tool was designed and fitted to the carrier's requirements. Manufacturing of this tool is underway and testing of the tool will be made during 2001. All the basic functions of the carrier couldn't be kept and special modules such as winch module and a dedicated clamping module were needed. Manufacturing of these modules is now finished and tests are underway.

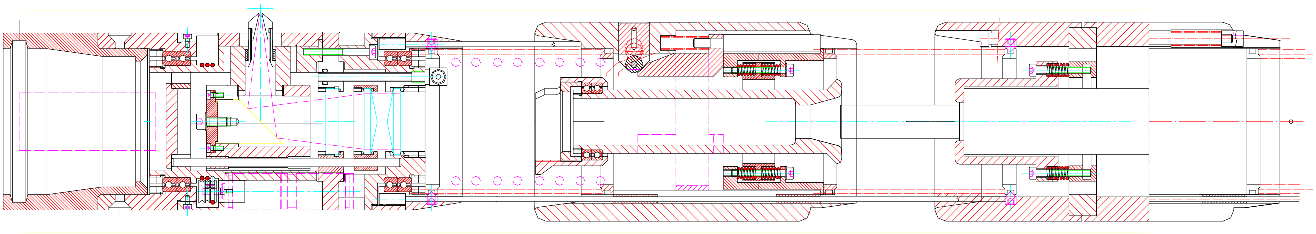

Figure 1 : ENEA/RTM laser tool for bent pipes design

Figure 2 : Winch module

UPGRADE OF THE FUNCTION MODULES

A powerful clamping is perhaps the most important feature needed by the carrier. The existing clamping design had to be modified to fit the requirements of the new laser tool. Improvement were also made to have a more powerful and reliable clamping module. The minimum needs of a carrier are of two clamping modules. The new solution proposes a design in which only one of the modules is motorised. This increases global safety and reliability of the systems. The performances of the new design are more than twice better than the older one. It is now possible for the carrier to withstand a 250daN axial force with a sliding of the carrier limited to 0.2mm.

Significant work were also made on the alignment module. In order to achieve the axial motion, the older module needed the help of a groove machined in the divertor's side of the pipe. Avoiding the use of machining parts is always interesting, that's why this groove is now useless with the new module. Modifications of the cams inside the tool also led to an improvement of the global performances of this module.

Figure 3 : New rear clamping module

UMBILICAL MANAGEMENT

The carrier is pushed towards the working area with help of a fibre glass rod. This rod, the umbilical and the sleeves of the cables are stored on a wheel which is powered by the rod pusher.

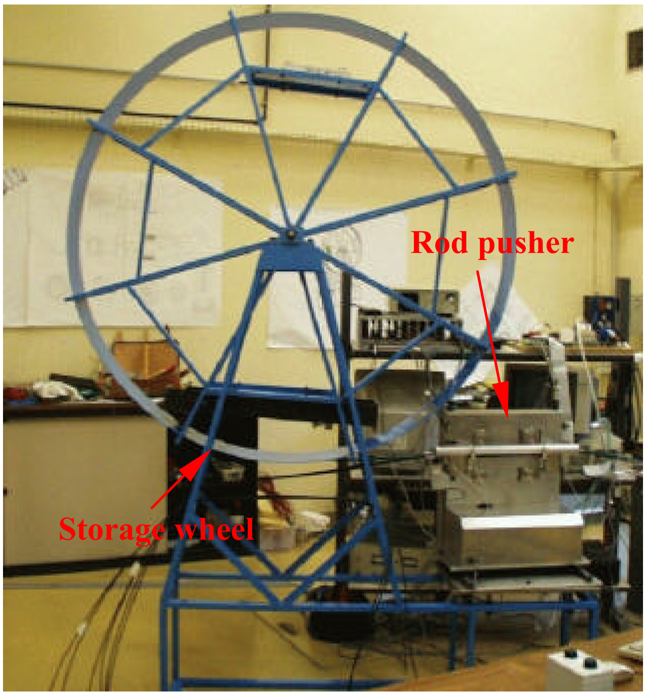

Figure 4 : Umbilical storage wheel

CONCLUSIONS

An innovative modular system of carrier was proposed and designed in 1998. Manufacturing and testing of the functions and tools of the carrier has been made during 1999. An upgrade of the basic functions of the modules and processes were made during 2000. A prototype carrier including all the functions required to perform one maintenance operation is now available. Integrated tests should start soon on a dummy pipe line. Future work on a standardisation of all the elements and techniques used in the carrier should be made in order to simplify the existing design. Reflections and tests on cutting processes reducing the power needed by the tool will also be a challenge for the next year.

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TW0-DTP/1.2
TW0-DTP/1.4

Task Title : PROTOTYPICAL MANIPULATOR FOR ACCESS THROUGH IVVS

INTRODUCTION

This project takes place in the Remote Handling (RH) activities for the next step of the fusion reactor ITER. The aim of the R&D program is to demonstrate the feasibility of close inspection of the Divertor cassettes and the Vacuum Vessel first wall of ITER. We assumed that a long reach and limited payload carrier penetrates the first wall using the 6 penetrations evenly distributed around the machine and foreseen for the In-Vessel Viewing System (IVVS). The IVVS designed for ITER EDA includes laser camera able to perform In-Vessel metrology. This system is mounted on a rigid mast deployed through a 10 meters long access. From a fixed point inside the vacuum vessel volume, it is able to perform accurate measurements. The need to access closer to the Vacuum Vessel first wall and the Divertor cassettes had been identified. This is required when considering inspection with other processes as camera or leak detection.

The objective of this task is to demonstrate the feasibility of such operations along the vacuum vessel wall with access from existing IVVS penetrations. This carrier will be called In Vessel Penetrator (IVP).

This task began in 2000 includes design activities, manufacture and testing of a demonstrator of an articulated manipulator.

First phase achieved concerns conceptual design activities. Main requirement that drive the choice on the IVP kinematics and structural architecture concerns the access to the VV first wall from any of the 6 IVVS penetration holes.

From this first analysis, three candidates solutions were proposed and pre-designed. After selection of the most promising one, starts design, manufacture and test of a first module of the IVP foreseen in 2001.

In parallel, a feasibility study of limited maintenance inspection operation under vacuum has been made (subtask 1.4) and provides recommendations to modify the design for intervention under vacuum and temperature.

2000 ACTIVITIES

ANALYSIS OF THE REQUIREMENTS AND SPECIFICATIONS OF THE IVP

The IVP is developed to carry an inspection tool inside the vacuum vessel. From the IVP design point, this tool is considered as a payload.

Two cases are considered:

- 1 kg payload - Inspection with video camera at 200 mm from the FW,
- 10 kg payload - inspection (TBD) with a 10 Kg tool (could be Helium leak testing) in contact with the FW.

The IVP will penetrate the vessel routed from the storage cask to the vessel through the bio-shield and inside the cryopump port and exits the first wall.

It enters the VV through a square hole cut out between the Divertor cassette and the first blanket module.

PROOF OF PRINCIPLE MOCK UP OF HIGH TORQUE ARTICULATION

Prior to the IVP design activities, a proof of principle mock-up activities has been launched.

When considering design issues of an IVP, first concerns relate to the high load applied on the mechanical structure and joints (cantilever configuration, long reach).

Therefore, high priority is put on the stiffness and weight of the IVP mechanics. First each joint should be compact and light weight and should also provide high torque. Mechanics of links between joints should be stiff and light.

A first tentative of high performance joint is proposed to support conceptual design activities. This joint is foreseen to sustain all the IVP weight when in cantilever configuration.

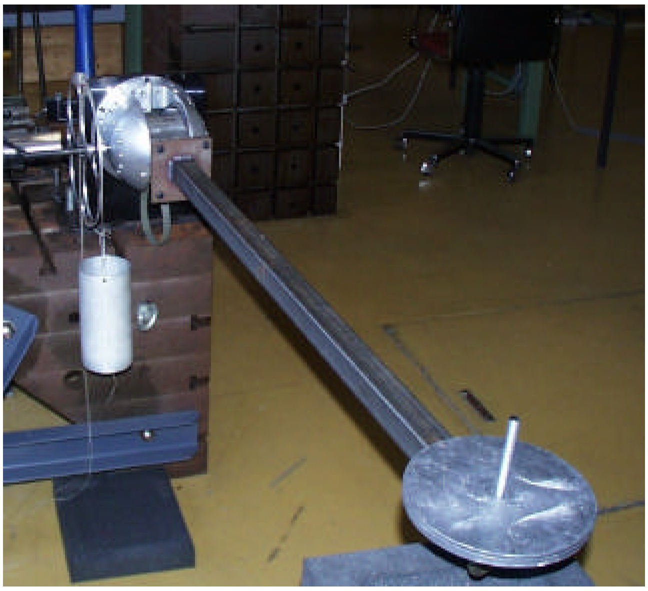

Figure 1 : High torque pivot joint test bench

Performances:

- Torque of 1200N.m (pitch joint at the base of the robot when IVP weight 50 kg).

CONCEPTUAL DESIGN ACTIVITIES

Three concepts of IVP architecture have been studied based on kinematics and structural considerations. First kinematics proposal includes only series of open loop pivot joints, the second one includes series of pivot and prismatic joints. The last proposal includes a series of pivot joints and closed loop parallelogram structures.

All kinematics allows to access correctly the VV first wall. Kinematics criteria does not allow to select one concept for its benefits. Computation of load applied on the structure is required.

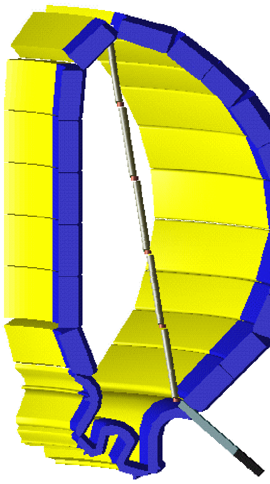

Figure 2 : IVP with 5 parallelogram structure modules in the VV

Results from analysis shows:

- Series of open loop pivot joints architecture:
    * Limitations to sustain loads.
    * Kinematics requires wide amplitude for pitch and jaw joints (hard to design).
- Series of pivot and prismatic joints architecture:
    * Sustains the load.
    * Risk on prismatic joint design due to the load and lack of space.
    * Kinematics requires wide amplitude for jaw joints (hard to design).
- Series of pivot joints and closed loop parallelogram architecture:
    * Sustain the load.
    * Joint designable.

IVP DESIGN

As a result from the pre-design phase, main characteristics of the IVP are:

- The IVP is made of 5 identical modules, with jaw an pitch joints on each module.
- A parallelogram structure (four bars mechanism) keeps the jaw joint axis always vertical.
- The IVP is powered by electrical motors.
- The range of these axis are +/- 90 ° for the jaw joint, +70° / -20° for the pitch.
- The length of each module is 1640 mm, total length of the IVP is 8200 mm (not considering the trolley required for the transfer through the Divertor duct).
- The maximal payload is 10 Kg,
- The external max section is a square of 150 * 160 mm. As a design margin, we consider an external diameter of 150 mm for the IVP modules.
- The IVP is transferred through the Divertor duct to the VV by means of a trolley module along the permanently installed IVVS rails.

The assembly drawing of one module of the IVP is presented in the next figure:

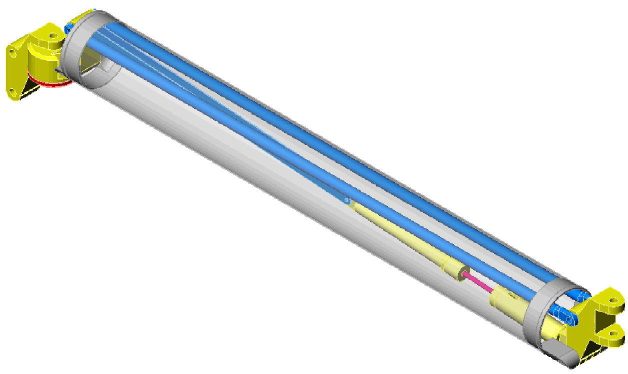

Figure 3 : IVP basic module design

FEASIBILITY STUDY OF LIMITED MAINTENANCE INSPECTION OPERATION UNDER VACUUM AND TEMPERATURE

In parallel with the design of the IVP, a feasibility study with objectives to analyze the consequences of temperature and vacuum on a robot was started.

As a support of the study, a CEA long reach manipulator has been analyzed in order to classify components of the robot from their resistance to temperature and vacuum. From this classification, the feasibility study has been performed. Possible solutions to sustain the constraints have been underlined.

CONCLUSIONS

Analysis and pre-design of the three concepts have shown that most promising principle is the series of pivot joints and closed loop parallelogram architecture. This concept is selected to design the IVP. Design shows a 5 modules configuration with 10 joints to fit the requirements.

Feasibility of the mechanics will be then validated in 2001 with support of scale one mock up of a single IVP module.

In parallel a feasibility study under vacuum has been made and provides recommendations to modify the design for intervention under vacuum and temperature. Proof of principle of this option should be performed, impact on the IVP design should also be carefully assessed.

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UT-RH1

Task Title : REMOTE HANDLING TECHNIQUES
Technology and control for remote handling systems

INTRODUCTION

Hydraulic manipulators are candidate for fusion reactor maintenance. Their main advantages are their large payload with respect to volume and mass, their reliability and their robustness. However, due to their force control limitations, they are disqualified for precise manipulation. For the same reason, they are dangerous for the environment and themselves in case of desired contact or unexpected collision with the environment. CEA, in collaboration with CYBERNETIX and IFREMER has developed the advanced hydraulic robot MAESTRO. Force and hybrid control has been developed in order to avoid these problems. The mock-up of a rotary hydraulic actuator equipped with pressure servo-valves has been used to validate the new control laws. The performances of these servo-valves fit the requirements but requires improvement to satisfy MAESTRO specifications. A study of the pressure servo-valves integration in the MAESTRO shows the feasibility of a new pressure servo-valves under MAESTRO constraints.

The design of the servo-valve is achieved. This development was made following the requirements and specifications for a fusion reactor. This new servo-valve is known under the reference number 1572100.To summarize the previous report, the pressure servo-valve allows to simplify the MAESTRO architecture and to suppress all electronic components inside the manipulator.

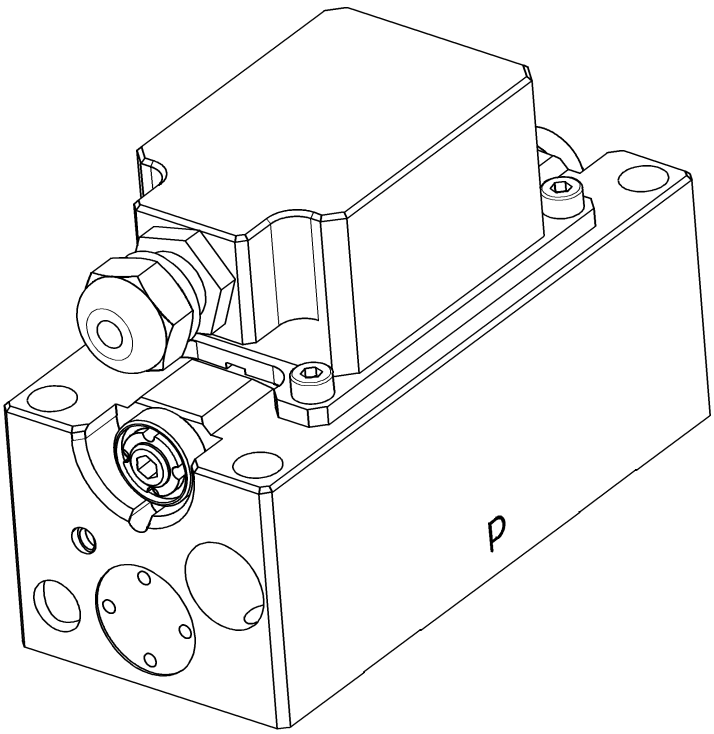
Thanks to this development the MAESTRO can work with a 10 Mrad integrated dose. The limiting components to increase this resistance are the seals of the rotary joints. The task will continue on R&D development of hydraulic technology.

2000 ACTIVITIES

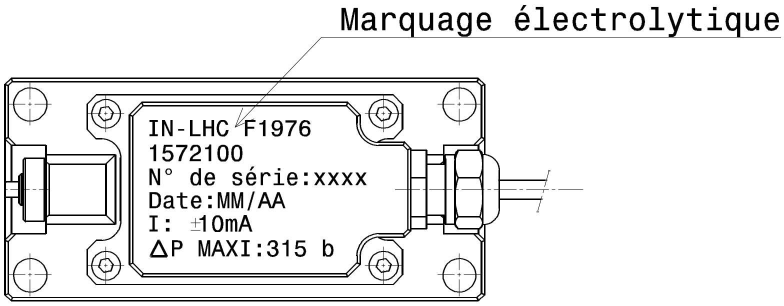
The external design has been specially study in order to avoid contamination area. The surface has been kept as smooth as possible to simplify cleaning procedure.

Servo-valve usually used in aeronautic application follows specific constraints. Vibrations specifications for an airplane environment are useless in a robotic arm. Therefore safety specifications were developed regarding nuclear applications.

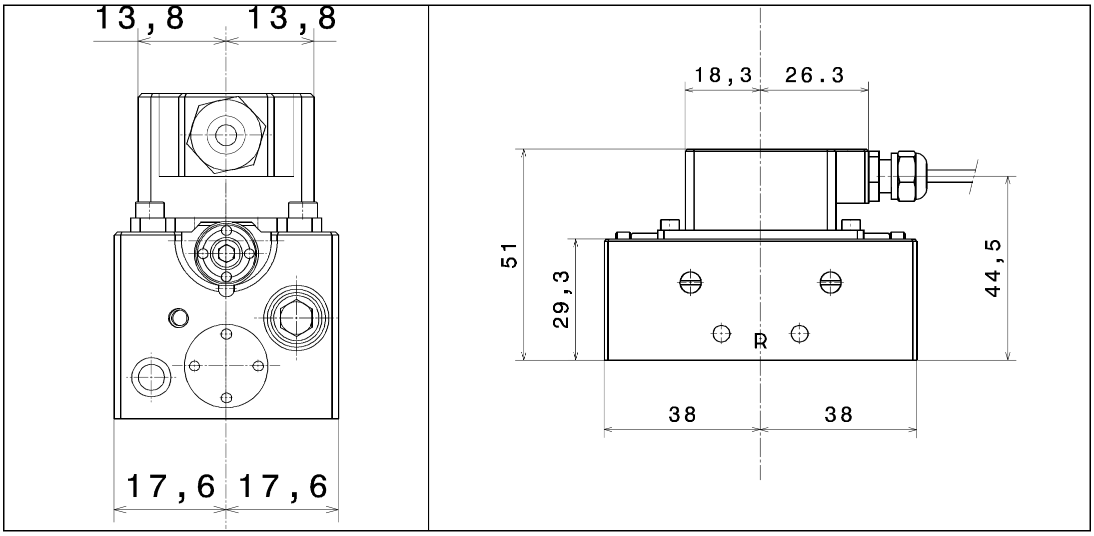
The edges have been broken to protect the overalls of the maintenance operator.
The marks on the servo-valve are made using electro-chemical method to avoid contamination concentration points.
The material used in this servovalve has been checked with CEA/DCC/UDIN. The electrical cable will be purchased by CEA (cable AXON). The coils are tested under 10 Mrad radiations.

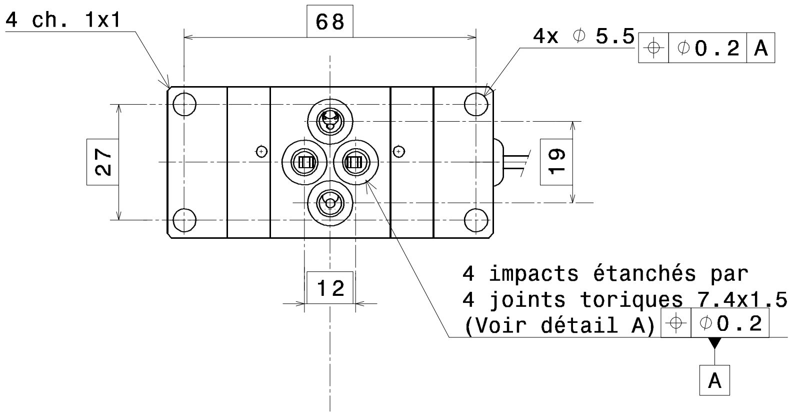


Servovalve 1572100



Dimensions of the servovalve feet with an integration in the MAESTRO





CONCLUSIONS

The design of the servolvave is now achieved. The task will continue with manufacturing of the prototype and by controlling the performances of these prototypes on mock-ups.

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Task Title : REMOTE HANDLING TECHNIQUES
Graphical programming for remote handling

INTRODUCTION

In the frame of the current UT-RH2 action, the STR has developed and validated the concept of Graphical Language for the supervision of remote controlled tasks. The objective of this research was to allow operators to easily perform ITER maintenance work using telerobotics systems.

The Graphical Language [2] is based on a representation of the remote environment generated from a 3D geometrical data base modelling the real workspace. The operator observes this environment on a graphical computer interface and he selects the most appropriate points of view with a mouse (figure 1). His part mainly consists in specifying the tasks to be carried out by manipulating inside the 3D model various virtual tools that interact with the environment objects :

- some of these tools stand for the processes required by the mission (welding torch, pipe-cutter, ...) ;
- others are associated with the robotics functions that are used for carrying out these processes (the automatic orientation of the tool perpendicularly to a surface, for instance) ;
- the purpose of the last ones is to define the parameters of the previous processes and robotics functions (such as measurement tools that help the operators to finely position a mark on the surface of an environment object or a frame in space).

These virtual tools have their own graphical shape and behaviours (like moving along the surface of an environment object) that ease their manipulation by the operator.

The goal for 2000 was the development of a graphical programming module dedicated to the preparation of remote handling missions.

It is intended to be utilised by operators who are not specialist in computer science, nor in robotics.

For that purpose, the provided software tool combines virtual reality techniques with high level programming functions where the tasks are expressed in terms of the maintenance operator's work.

During the year, the graphical programming module has been specified and developed. It was then tested in simulation by operators that have the same training as the foreseen final users.

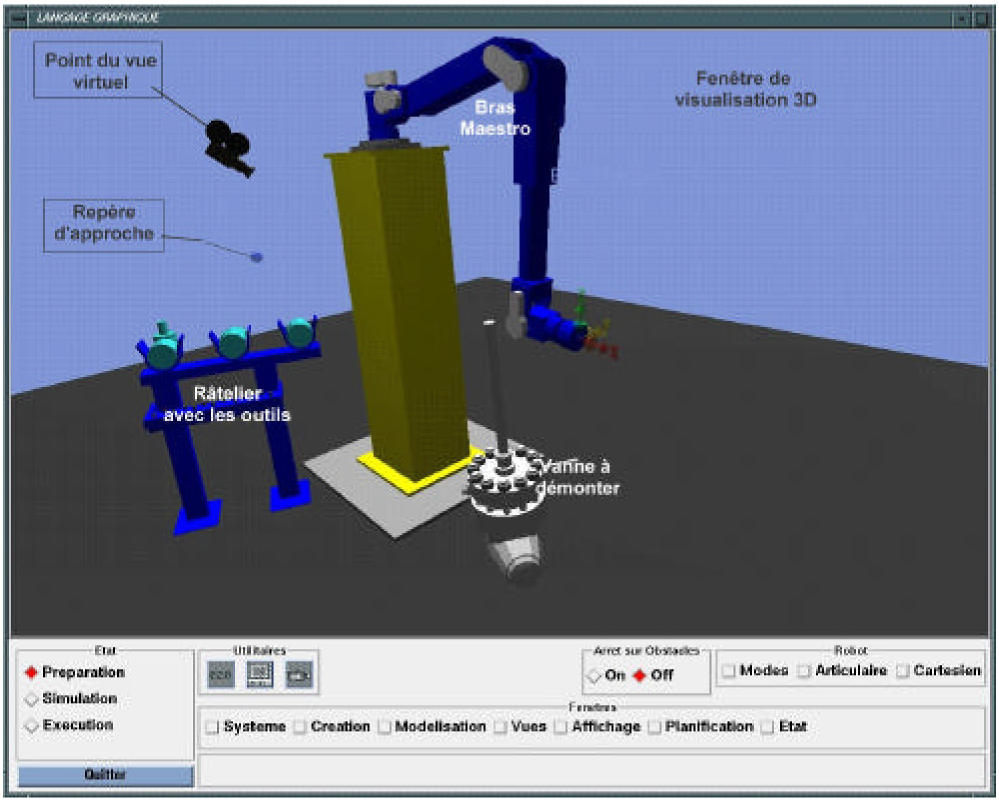

Figure 1 : Man-computer interface of the Graphical Language control station

2000 ACTIVITIES

The experience obtained up to now has shown that while the graphical language concept significantly facilitates the control of the telerobot during the execution of a mission, the preparation of the programmed sequences always require robotics engineers.

Moreover, these programmed sequences are often considered with doubts by the operators who do not understand their contents and hesitate to intervene when an incident occurred.

On the other hand, missions that were efficiently rehearsed in simulation using the Graphical Language could not be stored in a flexible way for future use.

These were the main reasons for developing the graphical programming module.

This graphical programming module complements the graphical language control interface.

It is used both for preparing a task, for recording a mission that may be off-line simulated and validated or modified and for controlling its execution on-line.

Graphical programming thus offer a way to remember temporal sequences of actions that have been created using the standard Graphical Language interactions which are more adapted to spatial reasoning.

The main features of the graphical programming module are :

- A programming hierarchy : the language integrates three levels of programming instructions : processes, operations, and robot instructions. The operator may thus select the level of details he wants to deal with ; for example, intending to operate in full manual mode he will find the highest level quite sufficient, while automatic execution requires programming with a maximum amount of details.

- Graphical programming : the design of a programme is made interactively on a 3D model of the environment, thus allowing the operator to immediately observe the result of his programme, with a possibility to go back to the previous state of the world.

- Extensibility : the programming language can be easily augmented with new processes and new operations.

- Execution control : the same module allows the operator to visualise the instructions being executed both when simulating and executing a mission.

The activities performed during the year were the functional specification of the module and its software implementation. It was then evaluated for programming the same mission as for the real demonstration realised to validate the graphical language concept at the end of 1999 i.e. the dismantling, inspecting and re-assembling of a floodgate with the MAESTRO manipulator [1] (see figure 2).

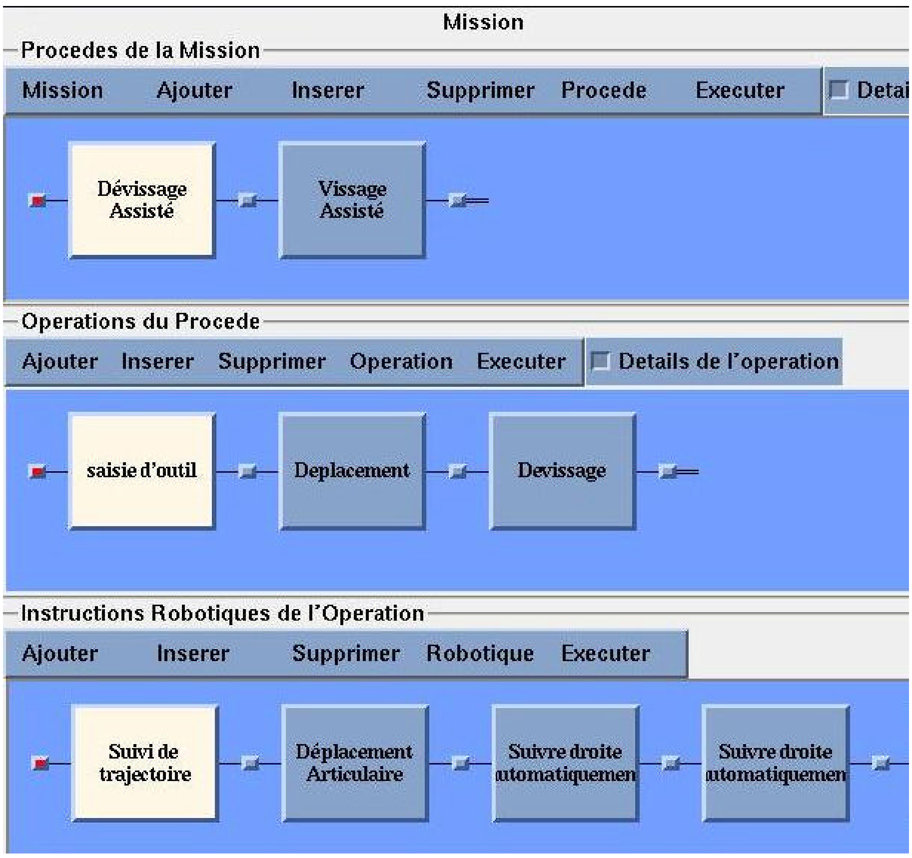

Figure 2 : Display of a part of the program designed for inspecting the floodgate

The figure shows the programming hierarchy with maintenance processes at the top level (i.e. computer assisted drilling), tool operations at the intermediate level and robot instructions at the lower level. At each level, the instructions are represented by boxes labelled with name of the corresponding action. Between each boxes are small buttons that are associated with the state of the world before and after the execution of the action. By clicking on one of these buttons, the corresponding state of the world is displayed on the 3D interface. During the preparation of the mission, the programme may be validated at different level by checking that the states of the world are completely defined. At the execution phase, the operator may display the description level he requires and the instruction being executed is graphically highlighted.

RESULTS

The study target was to perform a simple and intuitive system in order to make possible the programming of a teleoperated mission by operators who are not robotic specialists but who know the application field of the mission (maintenance, dismantling, intervention). We made a human factors evaluation with operators who are representative of the final users and who were not involved in the development of the system. All these tests were performed in simulation only but the global assessment was very encouraging. Besides a number of small remarks mainly directed at the operation of the man-machine interface, the whole concept was praised by the evaluators.

During this development, the emphasis was put on validating the concept of graphical and hierarchical programming. It would be interesting then to complement the current set of instructions by adding conditional expressions and control structures, as well as a capability to define variables and subroutines. This augmented set of instructions would be very useful to program repetitive actions and incident recovery procedures.

At its lowest level (robot instructions), the programming language is not specific of any particular robot, nor of any peculiar language. The graphical programming module may thus deal with various robotics language. In particular, it would be interesting to consider a post-processor for generating programs into well known robot languages like V+.

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UT-RH3

Task Title : REMOTE HANDLING TECHNIQUES Advanced technologies for high performances actuators

INTRODUCTION

Maintenance of fusion reactors induces high requirement on robotic device. In addition of the hazardous environment condition; maintenance requires high performances for robotic devices. In fact, high load are required to be handled, and narrow space is available for the motion.

Conventional design of robotic device reach its limit in such condition. In order to build adequate handling or inspection RH device, R&D activity is required on this field.

State of the art actuator used to drive robotics devices need improvement in term of lead capacity versus size of actuator.

An overview of possible solution is required to identify what technology would lead highest improvement. This is closely related with the type of actuator; linear, rotary, continuous motion,...

2000 ACTIVITIES

OVERVIEW OF THE POSSIBLE APPLICABLE TECHNOLOGIES

During the first reporting period we made a survey of several actuation technologies that could provide high force per mass or volume unit to cope with weight or space limitations in remote handling applications. Most of them are alternative to the electromagnetic actuators whose limits are well known. They are classified by type of energy conversion. When available, commercial products are well distinguished from laboratory prototypes.

The report also provides an example of specifications of an application for which we planned to use actuators with a high force-to-mass ratio. The criteria the actuator must fulfill are detailed. The different technologies are considered in order to find the best existing solutions or at least the best potential solution.

The main conclusion shows that actuators based on the expansion of a material during the transition between the solid phase to the liquid phase can deliver a very high forces to volume and weight ratio. As opposite to Shape Memory Alloy (AMF) the forces and displacements are obtained without the need of complex education cycle which make them unique. As for any device driven by temperature change, they have a long response time which will prevent them to used in general applications.

We chose this technology to develop special actuators that are intended to work in a very reduced volume within application where the response time is not a critical issue.

"PRE DESIGN OF POSSIBLE ACTUATOR, EVALUATION OF CANDIDATE TECHNOLOGY"

The principle of phase change actuators

It is based on the expansion of a material during a phase transition, and mainly the transition from the solid phase to the liquid phase. It is then easy to build a linear one way cylinder that works when the active material is heated. Paraffin and wax are the usual choice. They display a good expansion factor and a transition temperature between 60 and 120 °C. No leaking problem occurs when they are at rest in the solid phase.

The main characteristics are :

- A working pressure as high as 150 MPa can be achieved leading to a high force to dimension ratio. As a consequence, the seals must be carefully designed.

- They are one way actuator so they need a return spring or an antagonist actuator although the controllability of such a device is not yet established.

- As for any thermally activated device, the response time is dominated by the temperature change which can be slow especially in the cooling period.

Eltek actuators

Italian company Eltek sells thermoactuators based on the Fornasari patent [9]. When heated by an external electric resistance the material A expands and the piston 3 slides in seal 4.

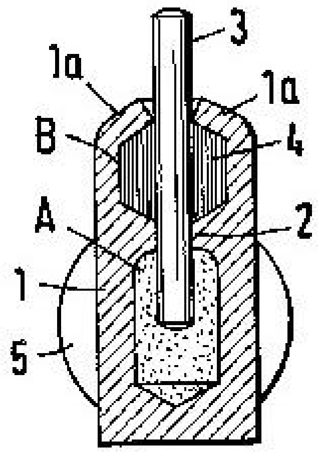

Figure 1 : Eltek thermoactuator

Tests made at our laboratory show a very good energy-to-weight ratio (160N for a 4g actuator) with a long time response when cooling with natural convection.

Lifetime under high forces and strokes have not been investigated yet.

The measured characteristics are [8]:

Table 1 : Eltek thermoactuators: models 331 and 319

	Model 331	Model 319
Stroke	6 mm	12 mm
Force at max stroke	160 N	
Mass	4 g	5 g
Dimensions (L×l×h)	6×6×15 mm^3	6×6×17 mm^3
Type of command	Current through the actuator	
Velocity	~ 1 mm/s	
Efficiency	~ 1 %	

Table 2 : Summary of Eltek thermoactuators characteristics

Force or torque	++
Displacement	+
Mass	+++
Energy-to-mass (J/kg)	240 and 380
Energy-to-volume (J/cm^3)	3.3 and 3.1
Resolution	- -
Velocity	-
Lifetime	++ when used in a 10 N application
Command in open loop	Easy
Efficiency	- -
Sensibility to external conditions	Temperature

New prototype

So we made a new design using high tensile aluminum (FORTAL) for the body.

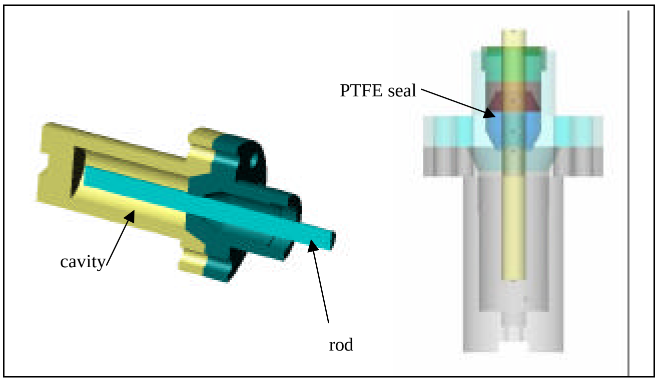

Figure 1 : New prototype

Dimensions

Following the results of the first prototype an expansion rate of 9% is expected for a working pressure of 90 Mpa.

At null stroke a force as high as 4200N is expected for a pressure of 240 MPa.

Table 3 : Dimension datas of new prototype

Rod diameter	5 mm
Working pressure	90 Mpa
Expected force	1600 N.
Expansion rate	9%
Stroke	18 mm.
Max expected pressure	240 MPa
Max expected force	4200 N
Cavity volume	4.5 cm^3
Weight	90g

Results

Serious leakage problems have occurred preventing the prototype to work properly.

Table 4 : Experimental results of the new prototype

Force	Pressure	Stroke	Expansion rate
880 N	45 MPa	12 mm	5.2 %
1100 N	56 MPa	10 mm	4.4 %

The results are below expectation and were not reproducible.

All the attempts to solve the leakage problems were unsuccessful.

Finite element analysis

A finite element analysis has been done in order to check if the body of the actuator could withstand the very high pressure.

The computations have been made for a 250 MPa which the highest achievable pressure for a null stroke.

Locally the stresses are very high, up to 1000 MPa leading to plastic deformations.

The strain is not very important but probably enough to cause leakage.

Such a design will be submitted to fatigue.

It must be reinforced and its shape should be optimized.

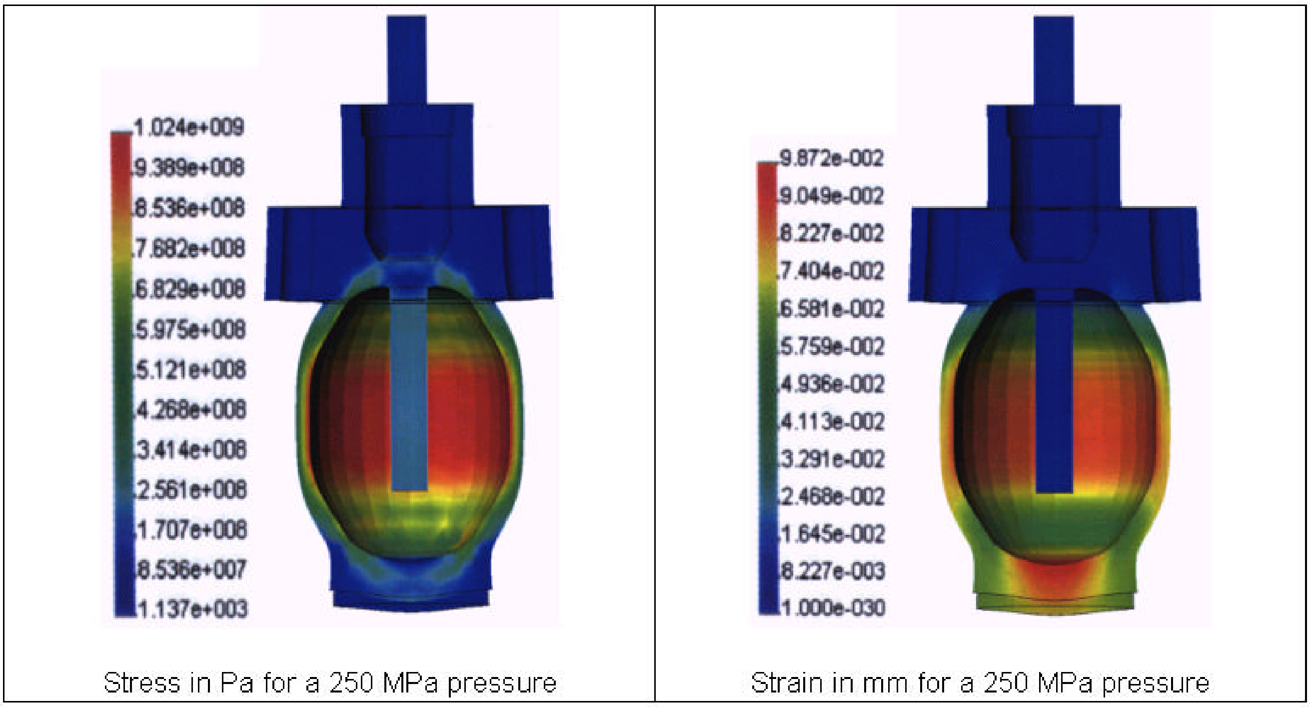

Figure 2 : Finite element analysis of the new prototype

CONCLUSION

The thermally expandable actuators can achieve very forces for a very low weight. A 40 10^3 N/kg ratio is reached by actuator from the Eltek Company. They are well suited for high forces slow motion in very constraints environment.

The building of a modular actuator which can be easily disassembled for laboratory purpose, proved to be not easy.

Future Work for Year 2001

- Improvement of the actuator with new design.
  - Monobloc concept
  - Barrel shape of the body

- Use of Eltek actuator in new applications.
  - Multi imbedded parallel actuators

PUBLICATIONS

CEA/DPSA/STR/LAM/00RT.050/ Issue.0 "Overview of the possible applicable technologies"

CEA/DPSA/STR/LAM/00RT.084/ Issue.0 " Pre design of possible actuator, evaluation of candidate technology."

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Task Title : REMOTE HANDLING TECHNIQUES
Radiation tolerance assessment of electronic components from specific industrial technologies for remote handling and process instrumentation

INTRODUCTION

The main objective of works made for RH-UT4 task is to assess the radiation tolerance of emerging technologies and components in order to be used on the remotely controlled handling unit, the vessel inspection and/or the standard process instrumentation. Representative tests should be also performing up to fusion relevant total dose. In order to take into account constraints of cost and availability of final users, attention will be mainly made on industrial components usually named COTS for Components Off The Shelf.

Scheduled program for this year have considered evaluation of SiC and SiGe technologies. Unfortunately, availability of SiGe basic components like transistors or simple logic functions has not been guaranteed by manufacturers. Instead of such work, recent end components (transceivers and receivers) for RF links have been characterised. Evaluation of SiC components has been done.

Some results have been reported on this document.

WORK PERFORMED ON RF END COMPONENTS

For this experiment, LVDS components from different manufacturers were selected and irradiated. At least, four samples of each have been tested.

Up today, the most common digital data transfer protocol is RS485 norm, mainly by the differential signalling used to drive data on twisted wired links. Great tolerance to most of noise sources allows distances of few kilometres between emitters and receivers with a bit rate of few ten Mb/s. Specific components are designed to implement this protocol.

The ability to support radiation is depending of the technologies used to manufacture them. But, some electronic systems using them are already working on civilian nuclear plants [1]. LVDS (Low Voltage Differential Signalling) norm is an evolution of RS485. This signalling technique lowers the output voltage level to reduce the power, increase the switching speed, and allow with a 3,3V rail. Components designed to realise such new protocol are mainly built under CMOS technology. Emitters and receivers proposed on the market allow a significant transfer rate of 400Mb/s with the same order of distance than older one.

It seems to be interesting to follow them under radiation. Elsewhere, results obtained on various CMOS technologies, and shown on Task T252 reports, have concluded that such technology was a good opportunity to realise electronic modules under very hard environments.

Description of the working states of the components: the intended application of these devices and signalling techniques is for point to point and multidrop (one emitter and several receivers) data transmission over controlled impedance media of approximately 100Ω.

Timing of different signals is represented on Figure 1. Digital data (Ve) is entered on LVDS emitter at low level voltage (0-3.3V), and then transformed in two differential signals (Diff+ and Diff-) with levels between 1Vand 1.4V. As shown, the value of digital 0 or 1 is depending of the differential outputs. These two last signals are driven on twisted wires to the receivers. The first stage of the receiver builds the internal signal Vid by operating (Diff+ - Diff-). The useful output (Vs) is then produced at low level voltage (0-3.3V). If components are not enabled (communication not allowed), the outputs of emitters or receivers or either are on high impedance state and no signal is appearing.

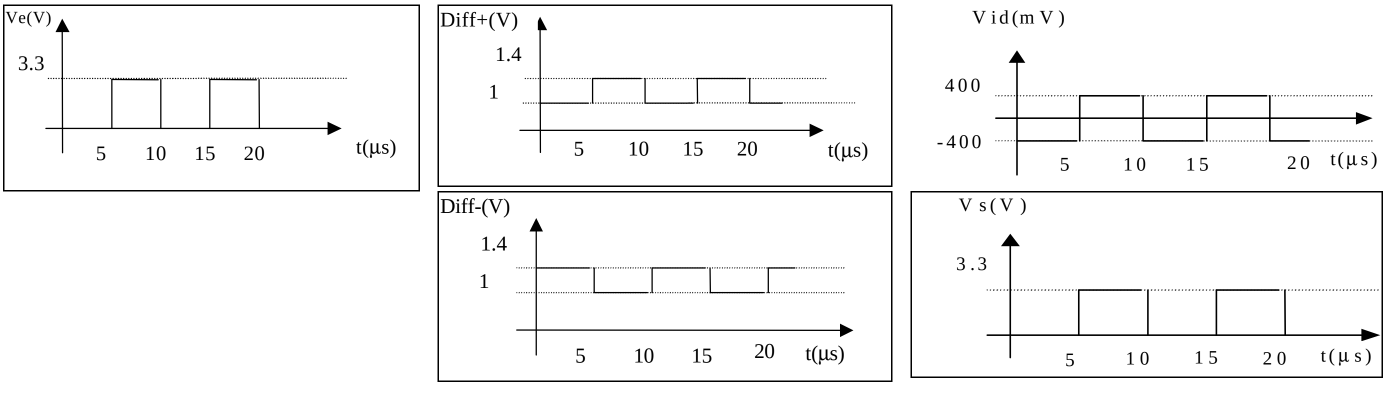

Figure 1 : Timing signals from input of emitters to output of receivers

Description of the test benches: the methodology used to understand the behaviour under radiation of such components is similar to that used for characterisation of logic components (*see T252 reports).* Figure 2 represents part of test cards and the connection schema.

Bias conditions are applied to the components. High-impedance state (emitter or receiver disconnected) is also studied. All the pairs of emitters and receivers are linked on the test card in order to simplify wiring and look at mainly influence of radiation.

The different bias conditions are summarised:

- Supplied at nominal voltage (3.3V) with communication allowed (enable condition) or no (disable condition) for emitter and receiver. Input Ve is a square signal at 3.3V and 100kHz (usual frequency for remote embedded applications in nuclear plants).

- Under supplied at 2.8V in order to appreciate influence of supply under radiation (under voltage is often observed as a best case for tolerance of CMOS families). Communication and input voltage are the same.

- Supplied at nominal voltage (3.3V) with input voltage Ve at 0V. Communications are allowed or not.

  During previous tests of data transfer components, these conditions are held to be the worst cases, mostly by no recovery of communication functions after irradiation time in high impedance state (not enabled).

During irradiation, parameters Vs, Diff+ and Diff- of most of the pairs emitters/receivers have been observed, through a 15m set of wires, in the control room, but no on-line recordings are done.

The smallest value of supply voltage, Vmin, necessary to obtain functionality of the components has been measured during steps when irradiation was stopped. Already used to control working margins of non elementary components, this parameter have also shown a good appreciation of the influence of the total dose effect on CMOS components. It was used few years ago to control irradiated components [2] and introduce as a patent [3] to measure the ability to work during an other irradiation period.

The drift of this parameter could be seen as an equivalent of the drift of the threshold voltage for a elementary CMOS transistor or logic inverters.

The measurement of the bandwidth has been added in order to verify the tolerance given by manufacturers.

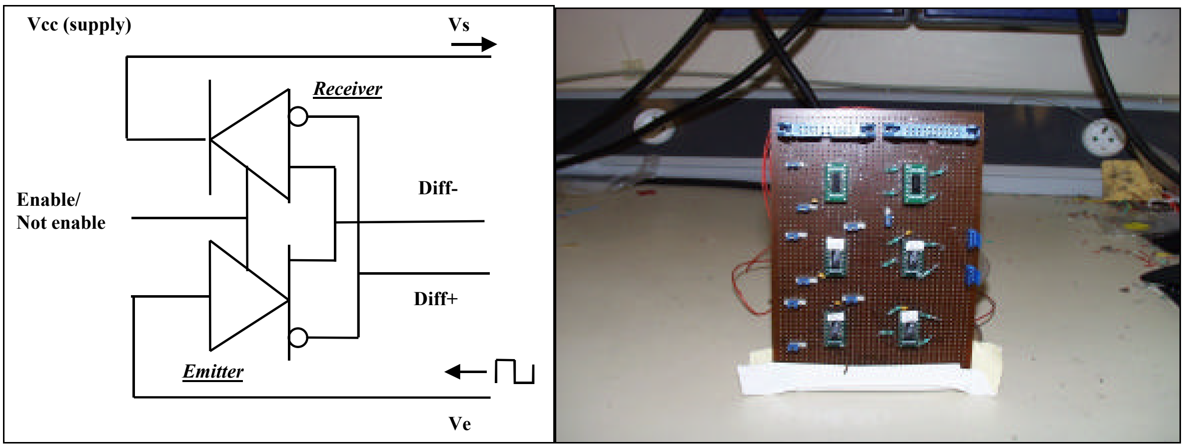

Figure 2 : Test connection principles and one of the test cards of irradiated components

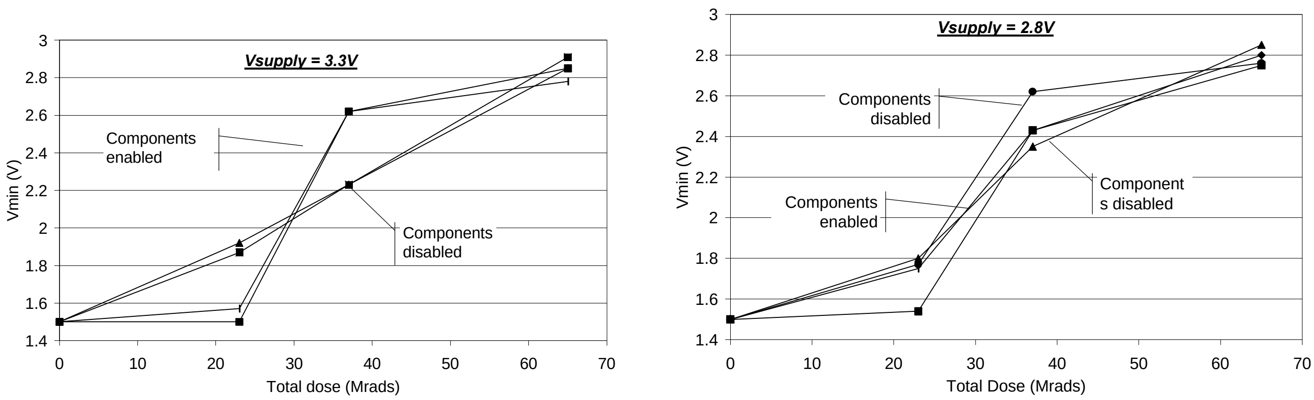

Figure 3 : Minimum voltage necessary to maintain functionality of irradiated emitters and receivers

Results of the experiments

After 65Mrad of total dose, none of the components have failed. Nevertheless, the different controls done during irradiation have shown some damages on the signals driven to the control room. The reason of such disagreement has not clearly appeared but according to the always-available differential signal, it should be due to the length of the cable, inherent noise inside cell, the modulated input signal and some reflections induced by bad adaptation along the cable.

Minimum voltage Vmin has dropped to near 2.8V and confirmed the availability of this parameter to appreciate sensitivity to radiation. The undersupply state does not seem to increase total dose tolerance as it did for oldest CMOS technologies. The worst case found previously is not so clear with these emerging components. Results are shown on Figure 3.

One may estimate that undersupply components were near a failure state and nominal supplied components able to support few ten more Mrad. But the possibility of an asymptotic comportment of Vmin may also exist. Complementary experiments are necessary.

Depending of the bias conditions, combined effects of irradiation and temperature increase drift of threshold, shortly for best bias conditions (negative, 0V and dynamic, 2 samples by bias), more deeply for worse conditions (positive). In any case, components were always operational.

Maximum frequency measured after 65Mrad has not exceeded 10MHz with a good Vid and Vs. Such results appear very far from nominal value of 400Mb/s. The reason of this disagreement has been founded later and due mainly to the defection of part of the test bench. In any case, these first results are already interesting for many embedded applications.

WORK PERFORMED ON SiC TECHNOLOGY

Previous studies have shown that Silicon Carbide (SiC) exhibits significantly better radiation tolerance than other classic semiconductor materials such as GaAs or Si [4], which are more susceptible to conductivity or carrier transport-related defects. Over the last few years, as mastery of the substrate fabrication process has improved [5], SiC component development, stimulated by promising results, has been given increasingly greater impetus. With its very broad energy band gap, SiC offers a combination of good temperature resistance and attractive electronic properties [5]. However, it does not seem possible to find easily industrial components like transistors, diodes or logic components. In spit of this lack, some research laboratories have developed specific components for their own needs, particularly hyperfrequency applications. This study examines the static electrical response of MESFETs (“MEtal-Semiconductor Field Effect Transistors”) fabricated by Thomson-CSF's central research laboratory ("Laboratoire Central de Recherches") when irradiated to total dose.

Description of the test bench: the MESFET structure studied incorporates four elementary components on a chip. Each chip is mounted in hyperfrequency packaging. Figure 1 shows a schematic cross section diagram of the elementary cell. Two different structures have been tested, one with a buffer layer included, the other, more recent, with the channel directly on the semi-insulating substrate. More details about the different lengths will be found on [6].

Maximum voltages applied were 100V for V_{ds} (i.e. between drain and source) and -20 V for V_{gs} (i.e. between gate and source).

Four sample transistors were taken from two separate fabrication lots. They were irradiated under different bias scenarios:

- One transistor from each lot in unpowered mode using conducting foam.
- One transistor powered, with $V_{gs} = 0$ (in on-state with I_{ds} limited by a resistor to 4 mA).
- The remaining two transistors powered, with $V_{gs} = -12$ V (in pinch-off state with $V_{ds} = 5$ V).

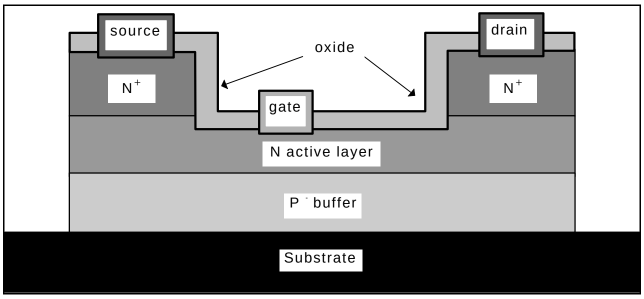

Figure 4 : Schematic cross section diagram of the SiC MESFET with a p-type buffer layer between n-type conductive substrate and n-type active layer

Irradiation of the test samples was performed using a Cobalt 60 source (see Figure 5). Transistor temperature during irradiation was about 35 °C. The static electrical characteristics of the samples were recorded using an HP4145B analyzer. These measurements took place during steps with the components at room temperature.

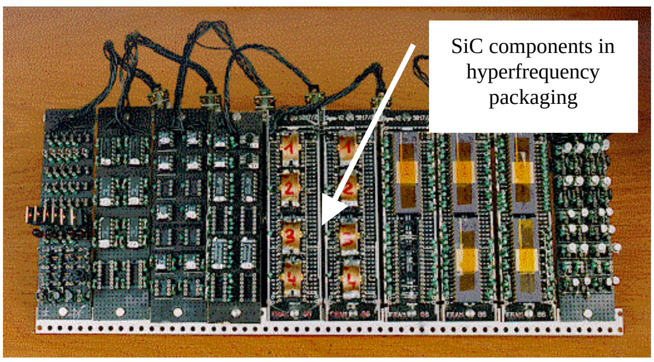

Figure 5 : Test card with SiC encapsulated components

Results of the experiments on first structure: Transistors have significant sensitivity to the biasing conditions applied during irradiation. Figure 6 shows changes in threshold voltage shift (ΔV_{th}) as a function of total dose for transistors irradiated in on-state (same as unpowered state not shown here) and pinch-off state. Maximum V_{th} shift (i.e. value recorded at 1 Grad[Si] minus the pre-irradiation value) is on the order of -1 V for a transistor irradiated in pinch-off state and -2.2 V in the on-state scenario. While several phenomena contribute to threshold voltage shift, in the case of this type of MESFET (as demonstrated later on in the article), ΔV_{th} is mainly attributable to the effect of irradiation on the buffer layer.

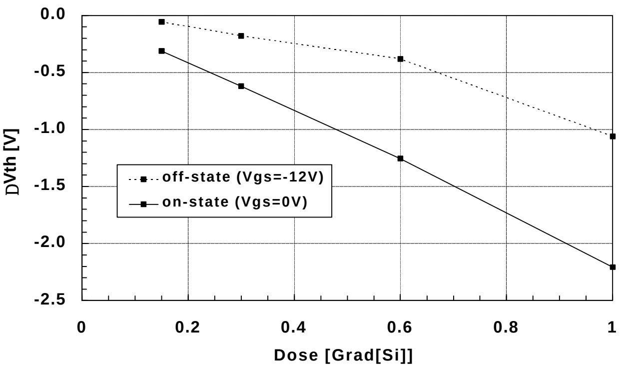

Figure 6 : Threshold voltage shift for transistor with P buffer layer

Figure 7 shows change in I_{ds} at different dose levels, as a function of V_{gs} for a transistor irradiated in pinch-off mode (V_{gs} = -12 V. Subthreshold slope (leakage current when operating under the conducting level of the transistor - Vgs = 0V in the experiment -) remains relatively constant as a function of total dose; and distortions observed in the vicinity of 1 mA result are due to instability in the response of the component associated with the test setup. Irradiation likewise induces an increase in leakage current when the transistor operates in the pinch-off region (around Vgs = -8V). Leakage originates primarily from the transistor gate. For V_{gs} < -8 V, gate current I_g is virtually equal to the sum of drain current I_d and source current I_s : $I_g \approx I_s+I_d$. After a few hundred Mrad of total dose, leakage current increases and becomes less dependent on $V_{gs.}$ Main reasons of such damages appears to be the alteration of the characteristics of the transistor Schottky gate contact [6].

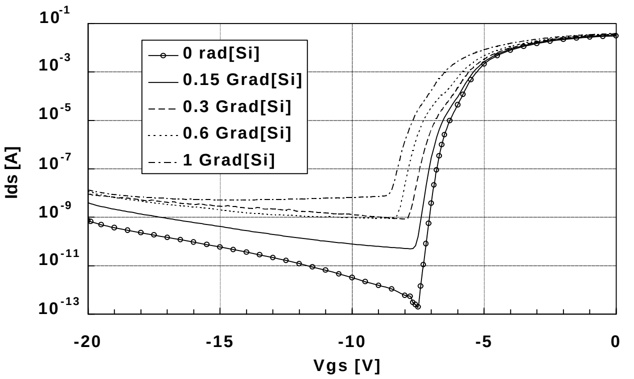

Figure 7 : Ids = f(Vgs) for Vds = 2.5V (transistor biased at –12V during irradiation)

The evolution of components after a first irradiation has to be taken into account in order to appreciate their availability for a new irradiation time.

Following the first phase of irradiation, the components were stored at room temperature on conducting foam for few months. In the case of both lots, all of the transistors irradiated in pinch-off state underwent a major operating transient during the rest phase. At the end of this period, they were again irradiated up to 1 Grad[Si] at a dose rate of 3 Mrad[Si]/h, under biasing conditions identical to those applied during the initial irradiation phase. This treatment (rest, followed by a second irradiation) had no particular impact on the transistors irradiated under V_{gs} = 0 V (in on-state).

Figure 8 shows change, for a V_{ds} of 2.5 V and a transistor irradiated in pinch-off state, in I_{ds} current as a function of V_{gs} at various points in time following exposure to the first Grad. The reference used in this Figure is the pre-storage characteristic of a transistor irradiated in pinch-off state (shown as circles on an unbroken line). Characterization tests performed a few months after start of the rest period shows a radical change, since I_{ds} current can no longer be controlled by gate bias.

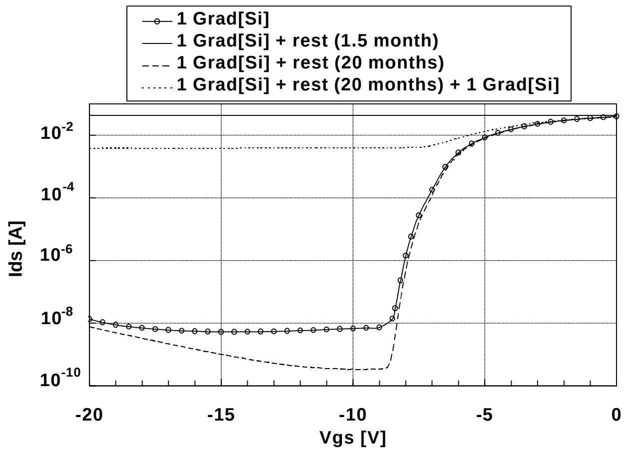

Figure 8 : Recovery phenomenon observed on transistors biaised at –12V during irradiation

Transistor functionality is therefore lost. I_{ds} is then constant at 44 mA for V_{ds} = 2.5 V, whereas, before irradiation, it could only provide 30 mA for V_{gs} = 0 V and V_{ds} = 2.5 V. After the rest period, the transistor had recovered a functionally correct characteristic which, however, still falls short of the initial curve (compare with Figure 5).

After a new dose of 1 Grad[Si], its response immediately after irradiation is again disrupted by a minimum I_{ds} current of about 4 mA between V_{gs} = -20 V and -8 V. Beyond -8 V, the gate regains control of current. Gate current, which remains below the 4 mA I_{ds} value, is a negligible component of measured I_{ds} current.

The substrate current, which was measured by separating substrate and source electrodes, with both potentials maintained at 0V, is also a negligible component of the measured I_{ds} current.

What is clear from the above is that the observed characteristic corresponds to the gate-controlled current superimposed on a parasitic current circulating between drain and source via the buffer layer (see Figure 1). When this parasitic current is less than the maximum gate-controlled current, transistor response is partially preserved, as was the case after the second irradiation. With a parasitic current of 44 mA, as was the case during the rest phase, action on the gate has no effect on I_{ds} Threshold will drift again toward important negative values. At the same time, there is still formation of new interface state with partial recombination. Both effects will reach a definitive stabilisation of threshold however absorbed dose.

Results of the experiments on the second structure: The following section examines results obtained for a MESFET structure fabricated on a semi-insulating substrate. In this design, as already mentioned above, the transistor n-type channel is in direct contact with its substrate. In all, 12 transistors were tested using different bias scenarios. The V_{gs} voltages applied to the samples during irradiation were 0 V, -10 V et -20 V, a little different from previously.

As each transistor, source was grounded, the drain electrode was connected to a 1 kΩ resistor whose lead was biased to 0 V, 5 V or 20 V. Since threshold voltages (V_{th}) ranged from -12 V to -15 V, the V_{gs} values applied during irradiation induced a true on-state (V_{gs} = 0 V), pinch-off state (V_{gs} = -20 V), or intermediate state (V_{gs} = -10 V) in certain transistors. The latter were subjected to a total dose of 1 Grad[Si] at a rate of 3 Mrad[Si]/h.

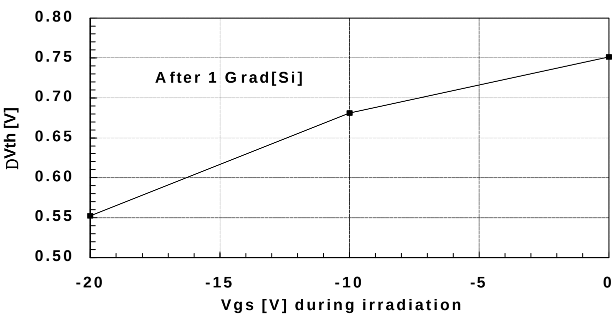

Figure 9 : Threshold shift for a transistor with semi-insulating substrat

Unlike results obtained for the first type of MESFET, in the semi-insulating layer version, we observed no significant failures leading to loss of component functionality, either before or during irradiation.

Only slight (though not necessarily negligible) variations of $I_{ds}(V_{gs})$ were recorded. Gate geometry (i.e. number of interconnected cells) did not seem to have impact. Measured results showed that fairly important differences in behavior were related to biasing conditions.

Whereas drain bias had no significant impact, V_{gs} voltage affected changes in transistor characteristics. Figure 9 depicts changes in average threshold voltage as a function of the bias applied to transistors during irradiation.

The lesser the difference in potential between gate and source, the greater the threshold voltage shift, which never exceeds a few percent of the initial voltage value. V_{th} shift (i.e. value after irradiation minus the pre-irradiation value) is positive, i.e. for V_{gs} and V_{ds} voltages that are identical before and after irradiation, current I_{ds} diminishes with dose. For structures integrating a buffer layer, threshold voltage shift is negative. This means that the dominant phenomena are not identical. In the MESFET with insulating substrate, the observed shift seems primarily due to radiation-induced channel degradation. We consider that the main impact of gamma irradiation on an n-type channel is a reduction in effective doping. This leads to a decrease in the threshold voltage, i.e. a positive shift in this value. A detailed analysis of all the effects is given on [6].

CONCLUSION

The study proposed on this report has shown that industrial components or emerging technologies give a possible answer to the use of electronic on very difficult environment. Drifts of parameters like threshold voltage or minimum supply voltage must not be ignored but, on the contrary, taken into account by the designers of systems to build tolerant architectures. Future studies will examine others technologies, for instance, SiGe (if basic components are finally available). Some complementary experiments should be also added about components tested here (bandwidth, …).

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