Reliability and radiation tolerance of robots for nuclear applications

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Abstract  The reliability of a robot for nuclear applications will be affected by environmental factors such as dust, water, vibrations, heat, and, in particular, ionising radiation. The present report describes the work carried out in a project addressing the reliability and radiation tolerance of such robots.

A widely representative range of components and materials have been radiation tested and the test results has been collated in a database along with data provided by the participants from earlier work and data acquired from other sources. A radiation effects guide has been written for the use by designers of electronic equipment for robots. A generic reliability model has been set up together with generic failure strategies, forming the basis for specific reliability modelling carried out in other projects. Modelling tools have been examined and developed for the prediction of the performance of electronic circuits subjected to radiation. Reports have been produced dealing with the prediction and detection of upcoming failures in electronic systems.

Operational experience from the use of robots in radiation work in various contexts has been compiled in a report, and another report has been written on cost/benefit considerations about the use of robots. Also the possible impact of robots on the safety of the surrounding plant has been considered and reported.

The present report is an edited version of the final report for the CEC/TELEMAN project No. FI2T-CT90-0011, ENTOREL.

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Introduction

From 1990 to 1996 the European Commission ran a research programme, TELEMAN, with the aim to develop robots for use in radiation environments, in particular with a view to the nuclear power industry. A total of 21 projects were run under TELEMAN, related to development of components and subsystems, and designing and building test machines. An important part of the programme was the study of reliability and radiation tolerance. One of the projects, ENTOREL, was devoted to these subjects in general and, in addition, the subjects were integral parts of three of the other projects. The present report describes the results of the ENTOREL project.

The reliability of a "TELEMAN machine" will be affected by environmental factors such as dust, water, vibrations, heat, and ionising radiation. The effects of many of these factors on the components and materials in question were well known prior to TELEMAN, but knowledge was missing about the effects of large doses of ionising radiation (=10^6 Gy) which were relevant here. Furthermore, there was a need to establish knowledge at system level, i.e. about complete TELEMAN machines. Components and materials which are especially susceptible to radiation damage are: electronics, sensors, fibre optics, signal communication systems, insulating materials, lubricants, and adhesives.

In order to assess how much the various factors influence the reliability, the project was to provide data as well as models for the calculation of the reliability of TELEMAN machines as a function of time and exposure. Furthermore, failure strategies were to be developed to plan the difficult task of recovery of a stranded machine. Reliability data already existing with the partners and elsewhere for relevant equipment were to be collated in a data base. Possible gaps in the existing data were to be covered by component or materials testing. Concurrently, reliability models as well as other models for the assessment of the behaviour of the machine were to be set up. A very important part of the work throughout the project was to be the collection of data and other information from external (to TELEMAN) sources and the dissemination of this information as well as information generated by the project to the partners of all the TELEMAN projects. Procedures to detect emerging radiation induced failures at an early stage were to be proposed, based on knowledge about failure mechanisms in materials and electronic systems. By literature studies and contacts to robot operators operational experience with robots was to be collected with a view to assessing the benefits and drawbacks in the use of robots.
The ENTOREL project team

The ENTOREL project had four contractors: Risø National Laboratory (Denmark, coordinator), SCK•CEN, Mol (Belgium), Siemens Energieerzeugung KWU (former Interatom) (Germany), and AEA Technology - Harwell Laboratory (UK) (the AEA group participating in ENTOREL now resides at the Culham laboratory). In addition, three subcontractors have been active during the project, the IMEC laboratory of Leuven, Belgium, Radiation Experiments and Monitors (REM) of Oxford, England, and Roger Horne, RHC, France. Furthermore, Spur Electron Ltd., England, under a special study contract has produced software for the import of data from the European Space Agency.

In addition, most of the ENTOREL partners have taken part in other TELEMAN projects. This gave the project good contacts to the TELEMAN community, enabling it to direct its work towards the needs of the machine-building projects, and at the same time gather data from these projects for inclusion in the ENTOREL database.

Work carried out on individual tasks

In the following, the work performed and results achieved are described task by task, using the task numbers defined in the project's Technical Annex. Some of the tasks were carried out by one partner alone, others had more than one partner working on them. Where possible, the description below gives an indication of which work was carried out by which partner.

Task 1: Definition of work scope.

The first part of the whole programme was the preparation of a document defining its scope and the types of equipment and components most in need of environmental/safety/reliability assessment. This document also provided rather more detail of the environmental conditions being considered for TELEMAN machines in order to enable the ENTOREL participants to tailor their testing programmes to yield relevant and useful data.

The report [1] was issued during the first year of the project. Three classes of machine were outlined: a mobile vehicle for inspection, monitoring and intervention purposes in low to moderate radiation environments; a gantry-based manipulator for operational and maintenance tasks in high radiation environments; and a long reach device for internal pipe work in low radiation environments. The list of tasks and duties for each of these machines has enabled a preliminary assessment to be made of the likely requirements in terms of components with a relatively low radiation tolerance, i.e. sensors, on-board intelligence or some materials. In turn, this assessment helped to shape and define the direction of further work packages within the programme.
The report then considered each of the other tasks in detail, describing the aim of each and the end result, be it a report, a computer programme or some other result. Finally, a copy of the ENTOREL technical annex was included for reference purposes.

In addition to the work mentioned above, SCK•CEN carried out a preliminary review of different typical nuclear situations, especially relevant to PWR (normal operation and dismantling tasks) in order to define the environmental conditions [2,3,105].

With regard to the identification of equipment and components most in need of environmental tolerance-, safety-, and reliability assessment Siemens prepared a report on the Criteria for the Selection of Components for Irradiation Tests within the TELEMAN Project [4]. These criteria are related to sensor systems being relevant to the three types of the conceptual manipulators for TELEMAN.

The work scope was extended when the project was extended into the second phase of TELEMAN. This change was reflected in the revised Technical Annex.

In addition, a certain effort was put into amending the scope of the project in 1993/94 in order to cater for possible inclusion of possible new partners under the EC's PECO programme for cooperation in science and technology with central and eastern European countries and with new independent states of the former Soviet Union. ENTOREL was among the three projects under the Nuclear Safety Programme which were mentioned in PECO's information material as projects where partners from the above countries could apply for participation. This led to requests from some 30 companies and institutes, resulting in an application to PECO for support to the inclusion of five new partners from Lithuania, Hungary, the Slovak Republic, Russia and Poland. In order to comply with the conditions set out by PECO, the contributions of the new partners had to be additional features to the scope of the project. Most of the work in formulating the additions and the application was carried out by the coordinator. As it turned out, no funding was granted to the applicants to ENTOREL, and the effort had been more or less in vain.

Task 2: Database.
The purpose of this task was to modify and amend a database of radiation effects in electronic components which already existed at Siemens (then Interatom). Originally the task had three subtasks, "Modify existing database", "Upgrading gathered information" and "Update database". As the work progressed it turned out to be impractical to make a distinction. Therefore, the work is described under one heading below. It also turned out that the effort needed to adapt the database to the needs of TELEMAN was substantially larger than originally anticipated. This, unfortunately, is a rather frequent phenomenon for software projects. Furthermore, the version changes of the commercial software used has given rise to some inconvenience as well.
As a first step, the requirements for the ENTOREL database were analyzed and assessed, leading to the overall structure of the database, shown in Figure 1. This structure was programmed and adjusted to the formerly existing database at Siemens/Interatom. The three partners carrying out testing (Siemens, SCK•CEN and AEA Technology) had different formats for storing the test results. Therefore, in order to accommodate the test data from these different sources, some data input routines had to be written; this also turned out to be rather time consuming, both for Siemens and the other partners who were not originally assumed to spend manpower on the database task. At an early stage it was decided to put the highest priority to the entry of data for electronic components rather than materials, because the materials data seemed difficult to handle in the database format at hand.

In 1991 an agreement of exchange of data was made with the European Space Agency (ESA) and ESA made its radiation effects database available to ENTOREL. This database contains many data which are not so interesting seen from a TELEMAN point of view, e.g. data for effects from heavy particles which are only met in space. But it also contains many data for the effects of \( \gamma \)-radiation on electronic components which are of interest in nuclear applications. Since the ESA database has a completely different data structure, compared to the ENTOREL database, the feasibility of constructing data transfer software had to be considered thoroughly. This feasibility study was carried out by Spur Electron Limited [5] with an extensive collaboration by Siemens. Spur is the company that runs and maintains the database for ESA. The study showed the general possibility for automatic transfer of total dose data from the ESA/ESTEC database to the ENTOREL database system. Automatic data transfer was chosen, in particular with a view to future, not yet available, ESA-data.

The feasibility study and the following construction of the data transfer software were performed under separate CEC study contracts to Spur Electron. To accept data from the ESA database transfer programme, written by Spur, an interface-system adapted to the ENTOREL database was written by Siemens. A characteristic scheme to sort out TELEMAN irrelevant data from the ESA data was elaborated by Siemens who also specified which total dose data should be transferred. After the different pieces of software had been completed, the relevant ESA data were transferred to the ENTOREL database.

In order to record the degree of confidence in the data entered into the ENTOREL database three validation categories (high confidence, some confidence, low confidence) were defined by the partners [6]. The validation "marks" given by the persons entering the data into the database later on was tested by an independent validation of part of the data sets from different contributors [7, 8]. Samples were selected for validation with a slight view to "dubious looks", and some had to be degraded in classification because some formal requirements were not met; but, in general, the data were deemed to be of good quality.
The final version of the ENTOREL-database by the end of the project contains more than 600 data sets, including all tests performed by AEA Technology, SCK-CEN and Siemens as part of the project. Furthermore, the above mentioned ESA data are included, as well as data provided by the partners from other sources, e.g. the Fusion research programme. The ESA data were produced by the test houses CNES, HMI and MBB. The database provides steady state, total dose radiation test data. It gathers results of total dose tests performed on electronic components in the Mega Gray dose ranges of gamma radiation. The database holds more than 40 device subclasses, 250 different device types and about 60 manufacturers. Additional 38 records on literature relevant to the tests are provided. A list of the data sets in the database is supplied in appendix A. Some of the data may not be freely available, but the database will hold information about their existence and a reference to the source.

The database now exists in a fully operational PC-version which has been installed at each partner site. The use of the database is to a large extent self-explanatory, but is supported by a user's manual [9]. The database is suitable for selecting devices during the design stage of robotics and remote systems for nuclear environments.

The user application of the ENTOREL-Database is distributed as a PC runtime version of a read-only database. With more than 600 tests gathered, its size is about 17 MB. The database management system is DataEase 4.2, and the graphics programme used is GRAFTALK 5.0.

All information is accessible on the one hand by overview tables, referring to e.g. device subclasses, device types or manufacturers, and on the other hand by different query paths, as there are requested device subclasses, requested device types and requested manufacturers. All of the requests may be carried out with a request or without a request for an indication of threshold values. The term threshold value here represents a value of accumulated dose where a defined degradation of a component takes place.

The data in this database refer to discrete components such as diodes, transistors (bipolar, FET) as well as to integrated circuits like amplifiers, comparators, multiplexers, microprocessors and others as fibre optic cables, force sensors and inclination sensors.

The tests cover a range of maximum accumulated dose from $2 \times 10^3$ to $1 \times 10^7$ Gy (Si) with respective dose rates of $0.27 \times 10^3$ to $3.3 \times 10^7$ Gy(Si)/h and a maximum accumulated dose from $1 \times 10^3$ to $1 \times 10^8$ Gy(H$_2$O) with respective dose rates from $0.085 \times 10^3$ to $11.4 \times 10^3$ Gy(H$_2$O)/h. Main query paths in the ENTOREL-database are the views of threshold values and parameter dependence of device subclasses, device types and manufacturers.

Queries result in data output of lists with device data (device classes, device types, technology, manufacturers), piecepart identification (lot number, serial number, date of manufacture), test data (test facility, test identification, test conditions, number of samples),
measurement data (parameters, bias conditions, temperature, damage criteria), radiation data (total dose, dose rate, threshold value, annealing) and quality assurance (data validation, data sources, comments on data). In addition, tables of measurement data for mean-, max- and min-values for device parameters may be looked up and the same values are given in a graphical presentation according to the relevant query. The whole structure of the ENTOREL-Database is shown in Figure 1 [62].

Two guides for installation of the ENTOREL-database’s runtime version have been provided [10, 11]. In order to make the ENTOREL-Database known to the public and interested parties, papers have been prepared for national and international conferences [126, 131 and 121]. One of these efforts to make the ENTOREL-database known resulted in the interest of the Florida University (USA) to take data from the ENTOREL-Database on to the WWW (World Wide Web).

After the completion of the ENTOREL project the database will be maintained and distributed by one of the ENTOREL partners.

**Task 3: Testing.**

Task 3 involves the radiation tolerance assessment of components and subsystems considered susceptible to the effects of radiation. Work on this task was carried out by three of the project partners, AEA Technology, SCK•CEN and Siemens.

The choice of items to be tested in the first part of the project was made based mainly on the experience of the partners with respect to components and materials used in already existing robot systems. In addition, advice about which sensors and materials to test was sought from other TELEMAN contractors by means of a questionnaire [52], mentioned later.

The technical annex divides Task 3 into the seven subtasks, listed below.

3.1 Testing of high power electronic components  
3.2 Testing of low power electronic components  
3.3 Testing of sensor systems  
3.4 Testing of multiplexing and communications systems  
3.5 Testing of vision systems  
3.6 Testing of materials  
3.7 Testing of a selected group of subsystems

Within the first six areas, lists of relevant tests already performed were set up before plans for testing were prepared. As a special exercise within this task, comparative tests were performed of a few selected components by all three testing partners. The main reason for carrying out these common tests was to show what differences exist due to the partners'
different methods of testing, thus enabling them to compare their other results. The tests concerned small-signal transistors and their results are described in more detail under task 3.2.

As the work progressed the distribution of activities on the above mentioned subtasks between the testing partners was changed somewhat compared to the original planning set out in the Technical Annex. This fact reflected the change in priorities among component types and - for the part of Siemens - the lack of irradiation facility when the Jülich reactor they were using closed. However, the total effort put into task 3 was close to the planned one.

**Task 3.1 Electronic Components, High Power.** The assessment of radiation effects on four types of power bipolar transistor, five types of power diode and seven types of power MOSFETs has been carried out in both Co-60 and spent fuel radiation environments.

Parameters measured were as follows, with data being obtained before irradiation and at seven increasing stages of total integrated dose (1, 3, 10, 30, 100, 300 and 1,000 kGy):

Power bipolar:  
- forward current gain ($h_{FE}$)  
- saturation voltage ($V_{CE(sat)}$)  
- breakdown voltage ($BV_{CEO}$)  
- leakage current ($I_{CEO}$)  

Power MOSFETs:  
- gate threshold voltage ($V_{GS(th)}$)  
- gate leakage current ($I_{GS}$)  
- drain-source breakdown voltage ($BV_{DSS}$)  

Power diodes:  
- forward voltage ($V_F$)  
- reverse breakdown voltage ($V_{(BR)R}$)  
- reverse leakage current ($I_R$)  

Results were much as expected with a fall in gain, increase in saturation voltage and breakdown voltage and a small rise in leakage current for the bipolar transistors, an increase in threshold voltage, leakage current and breakdown voltage for the MOSFETs; and very little change in any parameters for the power diodes.

In addition, some measurements have been carried out on power bipolar transistors in order to characterise the nature of radiation-induced defects on a microscopic scale. These have included deep level transient spectroscopy (DLTS) and forward and reverse transit time measurements. All measurements have been made before and after each of a series of increasing total integrated gamma radiation doses and a total of four device types has been studied.
The work provided detailed information on the effects of radiation on these components, covering total integrated doses across the whole range of interest to TELEMAN. Differences between the effects caused by the two different radiation environments have been shown to be negligible.

This subtask was carried out by AEA solely.

**Task 3.2 Electronic Components, Low Power.** All three testing partners were active on this subtask. At an early stage of the project the comparative tests, mentioned above, were carried out. These tests were performed on four device types, all small signal bipolar transistors: BC108 (NPN, metal can), 2N3704 (NPN, plastic package), BCY70 (PNP, metal can) and 2N3906 (PNP, plastic package). To assure homogeneity in the devices tested, devices from the same batches have been used for the tests. Siemens used a spent fuel irradiation facility (up to 0.8 MGy at up to 500 Gy/h) for the tests [12]. At SCK•CEN the transistors were tested up to a total dose of 300 kGy at a rate of 300 Gy/h using Co-60 sources. They were tested as part of the RIT-1 irradiation described under Task 3.3 [13,14,15]. At a later stage SCK•CEN performed further irradiation of the transistors up to a total dose of 830 kGy [16]. At Harwell testing took place in a Co-60 irradiation cell (up to 1 MGy at 10.5 kGy/h) [17], and periodic re-testing of the transistors took place in order to assess the annealing of radiation effects.

A comparison of the obtained results showed some slight differences due to the measuring conditions, dose rates and energy spectrum. In general, a good consistency was observed between transistor types and experimental sites. Both for the amplification factor hFE (Figure 2) and for the saturation voltage Vce(sat) (Figure 3), some variation of degradation speed could be observed along the dose build-up, with even slight recovery in some cases. This can be due to the different mechanisms responsible for degradation and changes in their relative importance with time. Figure 4 from the Harwell tests illustrates the spread in results for hFE for 15 transistors of the same type tested simultaneously. A detailed discussion of the common tests was published in the International Journal on Microelectronics and Reliability [110]. Furthermore, comparisons are reported by Siemens and Harwell in separate reports [18,19], and a paper [118] was presented at the RADECS'93 conference in St. Malo, France.

Apart from the common tests, many other tests were carried out.

At Harwell, component types examined under this heading have included small-signal bipolar transistors, signal- and zener diodes, i.e. the fundamental semiconductor components of any electronic circuit. A comparison of the effects of radiation from cobalt-60 and spent fuel has also been carried out for these components. This yielded similar results to those found in WP3.1, i.e. that the differences between the two environments did not lead to significantly different effects in the devices.
A further assessment covered four types of operational amplifier and four types of comparator [20,21]. Some examples of these components were found to be suitable for operation in active environments. Their use would permit significant reductions in the size and number of cables penetrating cell walls and would make mobile operation of equipment possible. Figure 5 shows the results of measurements of one parameter for two device types.

Richard Sharp from Harwell carried out a thorough study of the published literature relating to radiation effects on bipolar devices and silicon samples, in conjunction with the Risø National Laboratory programme for visiting scientists. This covered work published over the last 45 years, dealing with gamma, beta and neutron radiation effects on bulk silicon samples, bipolar test structures, discrete bipolar devices and bipolar integrated circuits. The aim of the study was to attempt to identify any underlying properties which are easily measurable and also direct indicators of the radiation tolerance of a device before any exposure to radiation has taken place.

At Harwell, furthermore, the usability of pMOS dosimeters at total integrated doses between 1 kGy and 1 MGy was examined. This work was part funded by other sources. Two types of dosimeter were included in the trials, one from REM and the other from NMRC. Furthermore, the REM type was tested in two different package styles. Irradiation was carried out at two widely separated dose rates, 13.6 kGy/h and 85 Gy/h, to a series of total integrated dose stages. Irradiation data sheets presenting the results obtained to date have been issued [22].

Also at Harwell, a comparison of the effects of radiation on devices packaged in both standard and surface mount versions has been made for three pairs of bipolar transistors [23]. This showed that within the limits of accuracy of the measurements (generally 15% or better), no significant differences between the two styles of packaging were discernable. A paper summarising this work was published at the RADECS’95 conference [149].

For Siemens’ tests, spent fuel was used as the gamma source where the mean energy as well as the decay characteristic was measured and calculated exactly. The tests were carried out in accordance with the ESA/SCC Basic Specification No. 22900 and MIL STD-883C, Method 1019.2. To cater for constant measuring values current sources were used for power supply to keep the current conditions very stable, and a four-wire technique was used to minimize errors resulting from voltage drops over contact points and cabling. For each device type measured (bipolar transistors and linear ICs) a special technique was developed making allowance for a manual measurement of the single parameters. An automatic test equipment may in some cases, where temperature or electrical effects impact the measured device, give erroneous results. In addition to the common tests, described above, operational amplifiers (Type TAA 765A, LM 741 CH, TBA 222 BS1, MAX 400 CPA) were tested up to 580 kGy. Static and dynamic parameters were measured in accordance to the experience and results
gained from the common tests. Some devices turned out to be suitable for the application in a high radiation environment. The test results are evaluated and reported in [24].

**Task 3.3 Sensor systems.** The main part of the work at this task was done by SCK·CEN. At the outset, particular attention was given to a review of typical sensors with respect to their radiation hardening availability. The sensors considered were:

- ultrasonic proximeters (capacitive and piezoelectric types)
- inductive proximeters
- capacitive proximeters
- LVDT contact sensors
- tactile sensors
- infrared proximity switches
- encoders and resolvers

Industrially available position sensors were evaluated and in some instances procured. Laboratory tests were conducted prior to real environment testing. Particular attention was given to their constitutive materials, their tolerance to degradation and their reliability [106].

In addition, it was decided to assess the needs of all the TELEMAN participants in terms of their sensor requirements. The vast range of different types of sensor means that any arbitrary choice made by the ENTOREL team alone is less likely to be relevant than a choice based upon the individual project needs. To this end, a questionnaire requesting information on the types of sensor intended for use was prepared and circulated to all TELEMAN participants [25]. This yielded several replies, although there was little consistency between them. The replies, summarised in [26], led to the selection of two types of inductive proximity detector for radiation testing in order to give indicative results for the programme.

Testing at SCK·CEN took place in two different facilities, the CMF spent BR2-fuel facility, where a series of experiments called GASTAFIORE took place, and the RITA Co-60 facility, where experiments in the RIT- series were carried out. Some of the tests were funded in part or fully by other research programmes, such as the European Fusion Technology programme or the Dismantling programme. The following tests were performed and the results entered into the ENTOREL database.

**Irradiation test GASTAFIORE II**

This gamma irradiation test contained the following items:

- Seven optical fibres, six of them being monitored on-line
- One inductive proximity sensor
- One capacitive sensor
- Three ultrasonic sensors
- Two multiplexer designs (monitored on line)
- Four types of relays (monitored on line)

The radiation dose rate was 20 kGy/h, and the test was performed up to a maximum total dose of 10 MGy. The results, detailed in [27], showed that carefully chosen fibre optics, inductive and ultrasonic sensors can be used at the highest levels of radiation specified for the TELEMAN machines. The tolerant design of multiplexing circuit was also found to be feasible at these levels [28,103].

Irradiation test GASTAFIORE VII

This experiment was performed in 5 irradiation campaigns, at a dose rate of 20 kGy/h, leading to a total dose of 10 MGy. Targets were ultrasonic sensors, potentiometers and inclinometers. The following specimens were tested:

- Penny & Giles (UK) Inclinometer: radiation hardened potentiometer based tilt sensor, specified to at least 1 MGy by manufacturer.
- Penny & Giles (UK) Potentiometer: radiation hardened rotary potentiometer, specified up to a total dose of 1 MGy by manufacturer.
- Pewatron (Switzerland) Inclinometer: accelerometer type tilt sensor.
- Pewatron (Switzerland) Potentiometer: rotary potentiometer.
- MicroMeasurement (USA) strain gauge: K-alloy and constantan fully encapsulated strain gauges.
- Sensy Loadcell (Belgium): 500 N radiation hardened load cell.
- MuRata (Japan) ultrasonic transducers: piezoelectric ultrasonic transducers.

The tests, performed also partially for the fusion programme, show that the Penny & Giles inclinometer did not reach the total dose specified by the manufacturer: after the second irradiation campaign, at a total dose of 0.5 MGy, the sensor was jammed, due to solidification of the damping liquid.

The Penny & Giles potentiometer showed no significant degradation up to a total dose of 2.7 MGy, which was reached after the 4th irradiation campaign. After the 5th irradiation campaign, at a total dose of 7 MGy, the potentiometer did not operate any more. Post irradiation examination revealed that corrosion, probably from gas releases of the plastic parts of the sensor, damaged the thin leads from the potentiometer resistor to the contact pins, outside the potentiometer.

The Pewatron inclinometers showed a relatively good behaviour up to a total dose of 7 MGy. The output range of the sensor slightly decreases, and a decalibration was observed. The linearity of the sensor remained good.

The Pewatron potentiometers only showed a small decrease in output range up to a total dose of 7 MGy. At this dose an increased friction of the bearings was observed. After the last
irradiation campaign, at a total dose of 10 MGy, the friction of the bearings was so high that it was impossible to turn the potentiometer without breaking it.

The strain gauges showed no significant degradation in sensitivity and performance. Special attention has to be put however on the soldering pads to connect the instrumentation wire to the gauges. When small pads are used, they tend to come loose easily with possible damage to the strain gauge.

The load cell shows a large offset (150 %) at 10 MGy, but remains linear. The electronic control unit allows for compensation of this offset, and hence the loadcell can provide force measurements up to 10 MGy total dose, when regular compensation of the offset is done.

The ultrasonic transducers showed a decrease in sensitivity and sound pressure level of up to 50 dB. This, however, did not influence the distance measuring capabilities of the sensor system built around these transducers. The maximum detectable distance decreased from 4 m down to 2.5 m, but the system still allows to measure a distance ranging from 30 cm to 2.5 m with a 2 % accuracy. A dedicated electronic circuit was built to allow remote operation with long cables between the transducer and the electronic control circuit: tests with cable length of up to 30 m showed no degradation in performance.

**Irradiation test RIT-1**

This experiment was performed in six irradiation campaigns, up to a total dose of 300 kGy, at a rate of 350 Gy/h [29,30]. The targets were the following:

- Two types of piezoelectric ultrasonic sensors
- One capacitive sensor
- Light Emitting Diodes, phototransistors and photodiodes
- Transistors, as part of the common ENTOREL test described under Task 3.2
- Tactile force sensors, one of which coming from a complementary TELEMAN project (TM-18, Univ. Brussels)
- Two optical fibres including their connectors.

The experiment showed that piezoelectric ultrasonic transducers are well suited for nuclear operations at least up to a dose of 300 kGy. The tests on optoelectronics showed a performance decrease, in particular the optical output power of light emitting diodes and the optical sensitivity of photodiodes and phototransistors, but no failure. The components are still operational at 200 kGy and their degraded performance can be eventually compensated by a proper circuit design. A decrease of 15 dB is for instance observed at this dose. All components show a particular dependency on irradiation and biasing history (Figure 6) [29,30].
Tactile sensors, based on variable resistance of polymers have been shown to be operational up to at least 250 kGy, and offer a good solution for contact detection. Tactile sensors based on optical measurement of polymer dimensional changes (in collaboration with TELEMAN project TM18) showed a good behaviour of the polymer (stable elasticity), but improvement of the optoelectronic parts is required to achieve sufficient radiation tolerance.

The experiment confirmed the good results obtained for optical fibres focusing on mechanical resistance of cabling material, buffer and coating, up to 300 kGy, and radiation tolerance of connectors.

Irradiation test RIT-2
The RIT-2 experiment was performed in six irradiation subcampaigns, up to a total dose of 300 kGy at a dose rate of 300 Gy/h [16]. The following targets were tested:
- capacitive proximity sensor
- optical fibre couplers and optical fibre switches
- one resolver type absolute encoder.
- some targets already irradiated in RIT-1 [30]: bipolar transistors (see Task 3.2), ultrasonic sensors, two types of optical fibres, a tactile sensor.

Irradiation test RIT-3
The RIT-3 experiment was performed in six irradiation subcampaigns, up to a total dose of 300 kGy at a dose rate of 270 Gy/h [31,32]. The following targets were tested:
- two types of capacitive transducer ((one already irradiated in RIT-2 [16])
- one visible laser diode
- radiation hardened optoelectronic components, to compare their behaviour with the not resistant counterparts, as irradiated in RIT-1 [30]
- several RADFETs (dosimeters), provided by REM
- some targets already irradiated during the previous campaigns (bipolar transistors as part of the common ENTOREL test described under Task 3.2, one type of piezoelectric transducer, a prototype of optical fibre proximity switch, two types of optical fibres, optical fibre couplers and switches, a resolver).
- radiation resistant multiplexing circuits (cf. Task 3.4)

The results obtained in RIT-2 and RIT-3 can be summarised as follows.

Piezoelectric ultrasonic transducers are well suited for nuclear operations, at least up to dose of 730 kGy. Particular attention should be put on the materials used for any acoustic impedance matching and acoustic focusing, since standard polymers become too brittle.
A commercial **capacitive transducer** has been identified, without observable degradation with respect to sensing distance and linearity. Another capacitive transducer shows small degradation with increasing dose and a decrease of hysteresis up to 220 kGy.

The experiment confirmed the results obtained for **optical fibres** with respect to attenuation. Mechanical strength of the fibre depends on the radiation resistance of buffer and coating, and interaction with corrosive gases can damage the surface of the fibre at the connector side.

**Fibre optics switches and couplers** show relative good results: radiation induced attenuation and functionality remain within tolerable limits up to 300 kGy. For higher total doses, the corrosion of the fibre surface at the connector side gives rise to an attenuation which exceeds 50%.

The **tactile force sensors** show a decrease in sensitivity for higher total dose, but still remain usable for contact detection.

The **resolver type absolute encoder** did not undergo any noticeable degradation with respect to repeatability and resolution, and this up to at least 480 kGy.

The **visible laser diode** showed no optical output at a total dose of 0.8 kGy.

**Radiation resistant optoelectronic components** prove to show better performances than their standard counterparts [30]. The degradation is smaller and stabilizes at a total dose of 100 kGy. Bias conditions and presence of radiation also have less influence (Figure 7).

The results on **RADFETs** have been analyzed by REM [33]. They show the applicability of RADFETs for on-line monitoring of doses on a nuclear manipulator.

**Irradiation test RIT-4**

This experiment was carried out in nine irradiation campaigns. Campaign number 1 to 8 were conducted at a low dose rate (22 Gy/h), leading to a total dose of 15 kGy. Campaign number 9 was conducted at a dose rate of 267 Gy/h, up to a total dose of 34 kGy. The following targets were tested:

- three types of strain gauges,
- one special design force-torque sensor,
- one rad-hard design 500 N loadcell.

The tests showed that the strain gauges keep a very good behaviour up to the specified total dose. The zero reference shift varies from 1 μe up to 12 μe, and the response to applied forces changes less than 1% before and after the irradiation. A custom designed force-torque robot wrist sensor was provided by JR3 (USA). The sensor showed no noticeable degradation up
to a total dose of 34 kGy. A radiation hardened load cell, provided by Sensy (Belgium), proved to show no degradation at all up to 30 kGy.

Finally, at SCK•CEN an experiment was performed on optical fibre with partial support from the ENTOREL project. It was focused on the use of fibres in the visible spectrum for fibroscopy. A special Russian fibre with aluminium coating and very low OH and Cl content in the silica core has shown to be very resistant in the visible spectrum, up to 1.5 MGy. The optical degradation shows a quick levelling-off and this hardening phenomenon is anticipated to continue up to the higher doses.

At Harwell, two types of inductive proximity detector have been tested. Irradiation test reports have been issued for both types [34, 35]. Very different behaviour was observed to occur in the two types of detector. One type showed complete failure after a total integrated dose of only 3 kGy, while the other type all continued to function, albeit with a slight rise in switching distance, to a total dose of 1 MGy.

**Task 3.4 Multiplexing and communication systems.** Work on this task was performed by SCK•CEN alone.

Communication between sensors and control unit needs specific links that must be chosen carefully in order to ensure their environmental resistance and their operational practicality. The following aspects have been studied:

- cable connection
  - radiation hardened cables
  - radiation hardened optical fibres and connectors
  
  Results of experiments reported under WP 3.3 showed the feasibility of optical links up to high doses.

- multiplexing capabilities
  - an analysis of available rad-hard integrated circuits, and their integration in a prototype multiplexing circuit including Analogue to Digital Conversion was carried out and tests performed as part of the RIT-3 experiment [36]. The tests show that all components failed at total doses lower than indicated in the manufacturer’s data sheets. The analog devices (the analog multiplexer and the analogue-to-digital converter) proved to be more sensitive to radiation (failure between 1 and 2 kGy) than the digital components (the latch and the parallel in/serial out register), which failed at about 3 kGy.
  - rad hard optical time domain multiplexing
In part supported by the TELEMAN/INGRID project an irradiation experiment was performed on commercial radiation hardened components for multiplexing. The components include analog multiplexers (HSI-508ARH), analog to digital converters (HSI-9008RH), tri state latches (HCS373DMS), and parallel to serial shift registers (HCS 165DMS), all manufactured by Harris. Figure 8 shows the circuit lay out of the prototype. They were tested in the MUSCADET experiment, performed in the spent fuel irradiation facility in BR3. All components were irradiated to total doses well above the dose specified by the manufacturer.

During irradiation, some of the characteristics and the performance of each component was monitored on-line. The experiment was performed in 5 irradiation campaigns. Campaigns 1 to 4 involved the testing of each component separately. Finally, a prototype 24 to 1 multiplexing circuit was built and irradiated during campaign 5.

The analog multiplexer, irradiated up to a total dose of 18 kGy, showed no degradation in performance. The switch-on resistance of each channel increased from 1000 Ω to 1200 Ω, but remained within the specifications of the manufacturer (1400 Ω).

The analog to digital converter, irradiated up to 18 kGy, showed no degradation in performance. The supply current increased slightly by 5%.

The latch circuits, irradiated up to 36 kGy, showed no significant degradation in performance and an increase in supply current of almost one order of magnitude.

The parallel to serial shift registers, irradiated up to a total dose of 50 kGy, showed no significant degradation in performance. It has to be noted, however, that this component was very sensitive to environmental noise and produced sporadic false measurements. The supply current decreased with increasing dose.

The prototype 24 to 1 multiplexer circuit (basic lay out shown in figure 8), using 3 analog multiplexers, one analog to digital converter and one parallel to serial shift register was irradiated up to a total dose of 54 kGy. Up to 42 kGy the circuit showed no faults in performance. For higher total dose, the analog multiplexer part was not able any more to switch between the different channels.

A paper [155] was presented at the Robotics conference, ISRAM '96, in Montpellier, France, May 1996, on the results of the latter irradiation experiment.

**Task 3.5 Vision systems.** The main part of this task has been carried out by AEA Technology; SCK•CEN has prepared external data (on glass types for lenses in high radiation fields) from the fusion programme for transfer into the ENTOREL data base.
At the outset of the project, a review of equipment standards and test procedures for the dose rate and total dose radiation tolerance assessment of CCTV cameras was carried out. As a result, dose rate radiation testing over six levels can now be completed in one hour, rather than two days, as previously (see Figure 9). The procedure permits data capture by video recording, still photography (35 mm), digital frame stored images, vectorscope images (for colour cameras) and oscilloscope waveforms. All measurements are carried out under computer control, allowing efficient 24-hour operation. The procedure also restricts the total dose uptake of the camera during dose rate testing to about 5 Gy, allowing total dose testing to commence from a realistic "zero". A poster paper describing this work was presented at the First European Conference on Radiations and their effects on Devices and Systems, RADECS-91 at Montpellier [101]. Furthermore, another paper [112] relating to the radiation tolerance assessment of CCTV cameras was presented at the BNES conference on Remote Techniques for Nuclear Plant conference in Stratford, UK in May 1993. A third paper [116], relating to the modelling of radiation effects on CCTV cameras was presented at the Institution of Nuclear Engineers conference on Modelling and Simulation for the Nuclear Industry in Glasgow in September 1993.

One example of a monochrome, CCD-based camera has been radiation tested [37]. This camera (a Panasonic WV-BL200) was tested according to the standard Radiation Testing Service procedure [112], incorporating both dose rate and total dose assessments, in a cobalt cell at Harwell. The highest dose rate at which this camera gave an acceptable picture was about 270 Gy/h. At higher dose rates, there was sufficient "snow" on the image to render it unusable for most tasks. For tasks requiring fine detail and high resolution, a lower dose rate limit would be appropriate. The sensor used in this camera was of the line transfer type and so the picture deteriorated in the usual fashion, with a reduction in charge transfer efficiency becoming apparent by "smearing" of the image. The degree of smearing had progressed to such an extent that the picture was judged unusable after a total integrated dose of 600 Gy. This figure is marginally lower than for some other, typical CCD-based cameras but, as only one example was tested, a suitable margin of error should be applied to the results.

Task 3.6 Materials. This task was approached in the same manner as Task 3.3, by a questionnaire [38]. Rather fewer replies were received regarding materials but, again, these have been summarised [26]. At Harwell it was judged that no irradiations were feasible because of the difficulty in choosing materials that would be used on TELEMAN machines. Published data has indicated the extreme variations that can arise in organic materials, depending on the precise composition of the material, the temperature, dose rate and atmospheric conditions. Thus, results from one manufacturer's particular material could bear no relation whatsoever to those for a second manufacturer of nominally the same material. This variation has been shown to be up to three orders of magnitude of total dose. Therefore, work at Harwell was restricted to an awareness exercise, indicating the problems that can
arise. In addition, a standard procedure for radiation testing of organic materials incorporating the provisions of the IEC-544 [201] was set up with a view to testing for other customers.

Some tests on organic material samples have, nevertheless, been carried out by AEA Technology in conjunction with other irradiations. These have included circuit board materials, cable and wire insulation and adhesives.

Circuit board materials examined include glass fibre, synthetic resin bonded paper (SRBP) and synthetic resin bonded fibre (SRBF). All three of these survived intact up to a total integrated gamma radiation dose of 1 MGy, although the SRBP had started to lose some of its mechanical strength at this point. SRBP is not recommended for applications requiring 1 MGy over periods longer than a few weeks.

Cable and wire insulation has been tested where used as power or signal leads for other experiments. Materials covered include PEEK, PVC and polyurethane. All of these survive to 1 MGy under non-oxidative conditions, i.e. at dose rates greater than 1 kGy/h. However, the PVC emits hydrogen chloride which hydrolyses to yield hydrochloric acid, causing corrosion of surfaces in contact with the material and of the material itself. Under oxidative conditions, mechanical failure would be expected after about 10 kGy and the hydrogen chloride problem still occurs. PVC is not recommended for applications requiring a radiation tolerance of greater than 10 kGy or for time periods of more than six months in a radioactive environment. Polyether-based polyurethane survives well up to 1 MGy. Polyester-based polyurethane also survives to 1 MGy under dry conditions but will not exceed 10 kGy in the presence of water as it readily undergoes radiation-induced hydrolysis. PEEK survives up to and beyond 1 MGy under all conditions but is rather stiffer than the other materials mentioned.

At SCK•CEN some irradiation tests were conducted on polymers as parts of tactile sensors, as reported under Task 3.3. Furthermore, selected electrical cables were tested. The selection was based mainly on the insulation material: halogen free insulation materials were chosen as well as materials that are known for their inherent radiation resistance, such as polyimide (Kapton) and PEEK. The irradiation was performed in several irradiation campaigns. Irradiation was performed in inert atmosphere (N₂) at a dose rate of 20 kGy/h and an ambient temperature of 50°C up to a total dose of 40 MGy. Further irradiation continued at a dose rate of 5 kGy/h and a temperature of 30°C, up to the total dose of 60 MGy. The cables were regularly bent during irradiation to simulate dynamic operating conditions in manipulator use. The results confirm the data obtained in static conditions for the selected polymers: no major degradation of Kapton and PEEK insulation material has been observed.

In addition, external data (on radiation and chemical resistance of O-rings, sealing materials, insulation, etc) were transferred to the ENTOREL data base by SCK•CEN. These tests
identify materials undergoing only small radiation induced loss of elasticity, with no
correlation between radiation and acid interaction. Silicone O-rings, on the other hand, tend
to harden quickly, and even in an accelerated way in the presence of acids.

**Task 3.7 Radiation testing of a selected group of subsystems.** This task was added as part
of the extension of ENTOREL into phase 2 of TELEMAN with a view to testing subsystems
specific to the test machines designed during this phase. Accordingly, contacts were taken to
other TELEMAN partners in order to identify testing needs of specific subsystems. This
involved the gamma camera in TELEMAN project TM45 (Ciemat), the LACWAP project
(ATNutech) and the ROBUG III project (Portech). However, the preliminary contacts did not
lead to a real test with samples provided by external partners. The reason was considered to
be mainly the lack of any TELEMAN continuation beyond phase 2. But the contacts showed
that some subsystems are critical to achieve large scale installations. Such a subsystem is the
multiplexing circuit allowing to reduce the burden of cable management. This subsystem,
therefore, was studied extensively as reported under task 3.4.

**Task 4: Radiation effects guidelines.**
This task was carried out by Siemens with proof-reading assistance from the other partners
as well as subcontractor Andrew Holmes-Siedle, REM. The resulting report "A Guide to Total
Dose Effects on Electronic Components" [39] was distributed to more than 120 participants
of other TELEMAN projects. The 123-pages guide is intended for use as an aid to the
electronics design engineer in understanding the processes involved in radiation absorption
and their effects on, mainly, semiconductor components. It was not intended to be an
assurance of radiation tolerant design. Particular emphasis is given to the radiation
environments specified for the TELEMAN machines.

The contents of the guide comprise chapters on basic effects of ionising radiation and more
detailed information on the effects in specific types of electronic device, e.g. diodes,
transistors and integrated circuits. A large number of tables and diagrams give the results of
tests carried out by ENTOREL partners or available from literature. The guide, furthermore,
contains a useful glossary of terms used within the field and a comprehensive literature list.

**Task 5: Simulation of faulty electronic circuits.**
The PSPICE modelling software for electronic circuits was chosen to be the basic tool used
for this task. It is a well proven package with all the necessary facilities for this purpose and,
furthermore, it is fairly easy to install and operate.

Data for the degradation of semiconductor components under irradiation was collected from
inside the ENTOREL group, and the modelling of irradiation effects on a few circuit designs
was carried out. Special attention was paid to a Schmitt trigger circuit developed at SCK•CEN
as a basic building block for an irradiation resistant digital multiplexer. Irradiation until
breakdown of this circuit had previously been carried out in Mol, thus facilitating a good check of the result of the simulation.

PSPICE has a facility to scan its simulations over sets of parameter values both in the case of discrete sets of values and for algebraically expressed dependencies. An algebraic expression for irradiation dependent current amplification of the transistor type used was derived and inserted in the PSPICE model. The diagram and the outcome of the simulation are shown in Figures 10 and 11. The Mol experience was that the circuit stopped working a little above 1 MGy. This is in good agreement with the simulation results. From the curves it can be seen that the output voltage swing, which must be around 5 volts to secure operation, becomes insufficient between 1.0 and 1.2 MGy.

The next object of study was CMOS-circuitry, which in the last few years has gained a wider application in radiation hardened equipment. This is mainly because new radiation tolerant integrated circuits have appeared on the market. The simulation work concentrated on life prediction of a fairly simple flip-flop circuit constructed from elements of the CD4007 integrated circuit, which contains separate complementary MOS transistors. The total dose effects on the so-called threshold voltage is used in the simulation, based on published curve material.

The simulations with PSpice raised a number of questions. One problem is to predict reliability for scenarios where normal stochastic faults and the deterministic wear out of components due to radiation are mixed. No direct methods were found in the literature, but some guidance was given which, however, was in the direction of very complex methods. For the purpose of this task it was chosen to study only scenarios where the deterministic contribution to faults are overwhelming, so that the stochastic ones can be neglected.

The formulation of circuit failure criteria, which are needed when simulation results are used to predict failure situations, can be based on traditional specifications according to manufacturers' handbooks, but often such judgements will be too conservative, especially for scenarios, where continued operation even by degraded equipment will be of value. In the present task, these failure criteria assessments were based on designer experience.

The work on this task led to the general conclusion that the use of simulation is a fruitful way for the prediction of circuit behaviour when the dependence of component parameters on radiation dose is known. The results were reported in [40] and, furthermore, presented at the EURISCON '94 conference [124].

The work was carried out by Risø National Laboratory, and as the project progressed, it was closely intertwined with the work of task 15, Fault detection and prediction, and thus the work of subcontractor Andrew Holmes-Siedle, REM.
Task 6: Reliability models.

This task was carried out by Risø National Laboratory.

Based on the assumptions and specifications concerning design and operation of the "TELEMAN machine" laid out in the work scope report (Task 1) and the call for proposals to TELEMAN phase 2, a qualitative reliability analysis was carried out for a gantry-type of machine, outlined in figure 12. The analysis comprised a Failure Mode and Effects Analysis (FMEA) and a fault tree analysis (FTA). The FTA served as the starting ground for identifying components and systems with an especially great impact on the reliability of the overall system. Furthermore, it can serve as the basis for a quantitative analysis, even though "hard" reliability data will be missing for a long time. In the analysis, failures of three different types were considered: equipment failure, human error and organizational error. The influence of each of these types differs, depending on the operational mode of the machine (manual, semi-autonomous or autonomous).

Since the design of the machine was not yet settled the top events were defined in general terms and on a functional basis rather than on a component and system basis. They were classified in 3 levels of severity and effect on the continued functioning of the machine (this number is not "magic", there may be more or fewer levels).

- **Level 1**: The machine is lost.
- **Level 2**: A task is not accomplished and repair is necessary. The machine can be recovered for repair, but this may be dangerous or difficult due to radiation and contamination.
- **Level 3**: A task is not completed or is performed incorrectly, but the failure can be corrected remotely.

Examples of events leading to these top events are:

**For level 1:**
* irrecoverable loss of communication between the machine and the control/operator
* irrecoverable loss of gantry mobility due to failures at inaccessible locations in the power transmission system or the motion system
* component failure causing the robot to end in a locked position from which it cannot be recovered

**For level 2:**
* loss of tool
* loss of power to tool
* loss of critical (with respect to the task considered) sensor capability

**For level 3:**
* loss of orientation
* wrong tool
* wrong sequence of operations
Based on the anticipated design of the robot, a failure mode and effects analysis (FMEA) was carried out. The format used for the FMEA was based on a standard format used in the European System Reliability Benchmark Exercise, modified for the special conditions in this analysis (e.g. radiation damage). Figure 13 shows one page from the FMEA as an example.

Based on the result of the FMEA a fault tree was constructed for the level 1, 2 and 3 events described above. The following scenarios were included:

* Failure of a drilling operation
* Failure of a decontamination operation
* Failure of an ultrasonic inspection

The generic reliability analysis was described in a report [41] which was distributed to the ENTOREL partners, to the members of the TELEMAN Users Group, to all the coordinators of TELEMAN phase 2 projects and to all the partners in the TM48 (INGRID) project.

The generic analysis formed the basis for the work on failure strategies in Task 7. Furthermore, the reliability analysis which the Risø team carried out as part of the TELEMAN/INGRID project was based on the ENTOREL work. The INGRID analysis, on the other hand, generated some problems of a general nature for TELEMAN machines which were subsequently taken up in the framework of ENTOREL. The problems related to the way to treat the radiation dependent degradation - which to a large extent is of a deterministic nature - together with the traditional probabilistic reliability parameters. The problem was approached in two alternative ways: 1) attempts were made to convert radiation degradation to failure data, 2) reliability- and radiation degradation analyses were made separately.

A Polish guest scientist to Risø performed an analysis of some of the test results from the common radiation tests described under Task 3.2, in order to examine the possibilities for deducting reliability data, so-called Δ-factors, from that kind of test data [42]. Due to time limitation this work was not carried completely through to an operational method.

At a later stage, a Russian guest scientist visiting Risø in the period August 1994 to June 1996, who is a specialist on reliability data analysis, took another approach to the subject. Investigations were performed on the possible use of the theory of fuzzy sets and the Bayesian approach [43, 140]. Further investigations, still going on by the end of the project, include use of the Dempster-Schafer theory of evidence for eliciting useful reliability data for a given component or system from generic data. This is often necessary in systems like the ones studied in TELEMAN where many components are prototypic. The work on this subject has been presented at one conference [140], and proposals have been made for other conferences as well as for articles in journals.
Since the attempts to unite the reliability- and radiation tolerance data were not quite successful, the practical approach taken in the various TELEMAN projects (TM18, TM44, TM48) was to treat the two phenomena separately, but using the same reliability model. The approach was developed mainly under the headings of TM48 (INGRID) and ENTOREL. The idea is to use radiation degradation factors as input to the reliability model instead of the usual failure frequencies. The radiation degradation factors, $\Delta$, are defined as:

$$\Delta = \min\left\{ \left| \frac{P_0 - P_t}{P_0 - P_f} \right|, 1 \right\}$$

where

$P_0$ = Value of a characteristic parameter before exposure.

$P_t$ = Value of the characteristic parameter after a total radiation dose $D_t$.

$P_f$ = Value of the characteristic parameter at failure.

Similar to the usual failure probabilities, $\Delta$ will lie in the interval $[0;1]$.

The parameter values were estimated for the relevant components and subsystems from radiation degradation functions. These functions were derived from radiation testing data from ENTOREL and literature. The degradation functions used have been, mainly, piece-wise linear functions with logarithmic dose values and linear parameter values, as illustrated in figure 14. In some cases only the doses at failure were available, and in these cases a logarithmic/linear curve was assumed in the entire range of exposure, cf. figure 15. A particularly simple version of the degradation function is the one shown in figure 16. This function has the value 1 up to $D_t$, above which it has the value 0, i.e. the component is assumed to fail abruptly at the threshold dose.

When the radiation degradation factors are input to the cut set evaluation instead of the usual failure probabilities, the result will be a list of cut sets, ordered after radiation sensitivity. This list will serve to show the designer where more tolerant components may be needed. It has not been attempted to go any further than this list of cut sets; i.e. no calculation of a "system radiation degradation" has been performed.

The experience gained by the Risø team by performing the ENTOREL reliability work and the reliability analyses for TM18, TM44 and TM48 has been summarized in a report issued by the end of the project [44]. Furthermore, this work has been published in various contexts [111, 139, 143, 153, 156, 164].

**Task 7: Development of failure strategies.**

This task was carried out by Risø National Laboratory.

Based on the generic reliability model developed in Task 6 failure strategies were formulated for the gantry-type of machine considered, taking into account the functional characteristics of the robot as well as the relevant robot tasks and environmental conditions.
In general, a failure strategy comprises all the systematic precautions, that are taken for the purpose of ensuring an appropriate performance of a system at an acceptable level of risk due to failures of its equipment or human errors. The failure strategy, therefore, includes both precautions for the prevention of events which contribute to the risks and the consequence mitigating measures to be taken if the events do occur. The risks can concern either the robot itself or its surroundings and can involve damage to humans or equipment.

In order that a failure strategy be as efficient as possible, precautions must be taken in all of the following phases of a project:

1. Design, manufacturing and installation
2. Operation
3. Repair, testing and maintenance

The failure strategy analysis was carried out in two steps. The first step was based on the fault tree developed in the reliability analysis and comprised a systematic review of the fault tree corresponding to the top event: Loss of the robot. During the first step of the analysis a series of potential single failures were identified in the motion systems, which could lead to the top event analyzed.

On the basis of the result of the first step, the design of the motion system was suggested to be modified by introducing redundancies, which remove the possibilities for the above consequences of single failures. A fault tree for the modified machine was constructed. The modified system was analyzed for common cause failures (CCFs), and in total 13 possibilities of such failures were identified and included in the fault tree and basic event data files.

In the second step the cut sets for the top event analyzed were calculated. The probability of two components being hit by a CCF was very difficult to estimate in this analysis. In a number of other applications the probability is estimated to lie in the range of 0.05-0.15 times the corresponding single event probabilities, but in this system ionising radiation acts as an additional contributor to the CCF causes, while on the other hand the condition monitoring serves to counteract both single events and common cause failures.

The cut sets were reviewed systematically. During this review proposals were made for additional measures against failures relative to the ones implied in the design basis and the assumptions underlying the reliability analysis. All such measures in the three project phases, which were necessary in order to reduce the risks to an acceptable level, were included.

The proposed failure strategy was divided into two parts: Preventive measures and Consequence mitigating measures. The preventive measures concern all the three phases of a robot project, mentioned above. An example of a preventive measure concerning the design phase is:
• Condition monitoring should be applied, for instance to the following parameters:
  - The integrated gamma dose to the end effector, the electronics closest to the end effector, the pneumatic cylinders and the travel bridge and transverse carriage drive motors and wheel bearings.
  - The current and temperature in the windings of the drive motors for the travel bridge, the transverse carriage and the robot.

In case that any of the parameters monitored approach a critical level, clear unambiguous advice should be presented to the operator by appropriate indications, warnings and alarms, in order that the operator will respond in time, so that failures can be avoided as far as possible.

The consequence mitigating measures concern only the operating phase of the project. An example of consequence mitigating measures is:

• In case of situations, where high radiation prevents access to the transverse carriage in its entire travelling distance, special attention must be paid to the travel bridge motion system in order to avoid failures in this system, which will cause a loss of the robot. Routine checks of all parameters subject to condition monitoring in this system should be performed more frequently, and special care should be taken to avoid overloading of its equipment.

The work was reported and comments were received from ENTOREL partners. The final version of the report [45] was distributed to the ENTOREL partners, to the members of the TELEMAN Users Group, to all the coordinators of TELEMAN phase 2 projects and to all the partners in the TM48 (INGRID) project. The findings in the study formed the basis for the considerations concerning failure strategies for the INGRID reliability study.

Task 8: Coordination.
The coordinator of the project was Risø National Laboratory. The work comprised the administration of the funding and writing of progress reports, as foreseen. But in addition a number of other activities have been counted under this heading, for instance the preparation of papers to and participation in conferences where ENTOREL was presented [102, 125, 145]. Also the extension of the project, the incorporation of subcontractors REM and RHC and the PECO-related activities, mentioned under Task 1, gave some unforeseen work to the coordinator.

Task 9: Gathering of external data.
As already mentioned under WP2, contact was established to the European Space Agency in order to exchange data between ESA’s and ENTOREL’s databases. A study contract was set up between the CEC and the company Spur Electron Ltd. which operates the ESA database. Under the contract, Spur together with Siemens conducted a feasibility study [5] and set up
the specifications for the transfer software. The software was written by Spur under a second study contract and was implemented during the third year of the project.

In addition to the ESA database, a few other relevant radiation effects databases have been identified. Harwell has accessed the JPL/NASA radiation effects, RADATA, database by PC and distributed some examples of data amongst the ENTOREL partners. This database covers total dose and Single Event Upset (SEU) radiation effects in a space context, i.e. useful for relatively low dose TELEMAN missions and for ruling out certain component types. The database is available to everyone by dialling up the database server in the USA.

Another database which has been identified by Harwell in the UK Ministry of Defence (MoD) database SIRE (Semiconductor Index of Radiation Effects), covering gamma total dose and neutron- and gamma dose rate radiation effects in a military context, i.e. very low dose missions. Access to this database is restricted to MoD contractors.

SCK•CEN established contact with the IMEC laboratory at Leuven, Belgium. This microelectronics research laboratory works on radiation hardened electronics for space application. A state-of-the-art report was produced in October 1991 on suitable radiation hardened silicon processes [46]. Common tests performed outside the ENTOREL frame, have been performed on prototype SOI GAA transistors [47,48,122].

Contacts were established, both by Harwell, SCK•CEN and Siemens, to SPAR Aerospace in Canada, mainly with a view to collaboration under the European Fusion Technology Programme. No direct data exchange with ENTOREL resulted from the contacts, however. Other contacts have been made to the PSE&G utility in the USA and Ontario Hydro in Canada. Also the Microelectronics User Group at CERN has been contacted by Harwell with regard to the use of electronics in high energy detectors [49, 50]. Their requirement is for a total dose gamma radiation tolerance of 100 kGy over ten years.

In particular SCK•CEN has gathered data from the Fusion Technology- and Dismantling programmes and transferred these data to the ENTOREL database.

ENTOREL partners have been involved in work under several other TELEMAN projects, and some data have been brought to ENTOREL from these activities.

Risø has collected reliability data in the context of analyses carried out for the INGRID, ROBUG III and Gripper projects. These data have been put together in a report [51]. The data comprise failure rate data from reliability literature for robot components which could be found there, as well as data derived by means of "engineering judgement" for prototypic components which could not be found in the literature.
Task 10: Dissemination of data to other TELEMAN projects.

In order to examine the needs of other projects for data and other information generated by ENTOREL a questionnaire was set up and distributed to all TELEMAN contractors [52]. The questionnaire asked for wishes concerning the way of disseminating information and concerning the components and materials to be tested, as already mentioned above. A total of 11 answers from nine projects were received. Concerning the way of distributing information, the following options were given: newsletter, electronic mail, electronic conference, only on request, database on floppy disk. The most popular options turned out to be a newsletter and database on floppy disks. Consequently, a newsletter was prepared and issued three times during the project [63, 64, 65] and once after the formal end of the project [66], reporting on ENTOREL progress and running special articles on selected subjects. In addition, an address list of the ENTOREL partners was given. The newsletter was distributed to a total of 130 persons involved in TELEMAN projects and a few outside of TELEMAN. Although the feedback from readers has been very limited the newsletter was considered the best way of communicating the results of ENTOREL to other TELEMAN projects - apart from conference participation and replying to direct questions on specific matters.

In a number of cases other TELEMAN projects (TM-2, TM-18, TM-44) have been given assistance on request in the search for radiation tolerance data (for materials, electronics in general, sensors, optical fibres, multiplexers and microprocessors).

Task 11: Assessment of the performance of TELEMAN prototype machines in a radiation environment.

This task was initiated by approaching the other TELEMAN projects with a questionnaire [53] in order to establish the needs and wishes of these projects for interaction with the ENTOREL partners concerning reliability and radiation tolerance. After a couple of reminders replies were received from most of the TELEMAN phase 2 projects. However, the task proved somewhat difficult to get going along the originally planned lines, because feedback from other TELEMAN projects, specifying their needs, was very scarce. Therefore, the partners performing radiation testing have sought to define themselves the needs for testing of components and subsystems which could be relevant to the prototype machines - taking into consideration the components and subsystems mentioned in the replies to the questionnaire. The subsequent testing was carried out as part of the tasks 3.x.

With respect to reliability assessment, Risø used this task to enhance an analysis which was performed as a subcontract to TELEMAN project 44, ROBUG III [54]. Calculations were performed on a design containing more radiation hardened components than the original design. In addition, Andrew Holmes-Siedle, REM, as part of his subcontract to Risø carried out a special analysis of the radiation tolerance of the microcontroller [55] and of a dosimetry system [56] for ROBUG III.
Meetings were held by Risø with representatives of the Fraunhofer-Gesellschaft/IPA concerning possible assistance to their part of the IMPACT project, and by SCK•CEN with representatives of AT Nutech concerning the LACWAP project; but in neither case did we receive further feedback.

**Task 12: Robots and plant safety.**
A literature survey was carried out in order to identify useful experience - also from other than nuclear applications of robots. The findings, together with experience from the TELEMAN reliability analyses, were written into a report [154]. The report highlights areas where particular attention is necessary when taking more or less autonomous robots into use in plants which are expensive and/or where damage to the plant may lead to safety problems. The report was issued in the Risø-R series, giving it a distribution to a large number of libraries in relevant research institutions, in addition to entry into relevant databases.

**Task 13: Cost-benefit investigation of the use of robots.**
For this task a subcontract was entered with Roger Horne, former CERN now a private consultant on remote handling. Based on his long experience with remote handling, RH produced a report [57], drawing the attention to a large number of factors apart from money which should be taken into consideration when assessing the costs and benefits of applying robots in a given situation. Draft versions of the report were studied and commented by Risø as well as by the TELEMAN office. The final versions of the report was sent to ENTOREL partners, coordinators of other TELEMAN projects, members of the TELEMAN Users Group, and one external recipient.

**Task 14: Formulation of testing strategies.**
This task, which was to be performed by Risø, was abandoned in order to allow time for other tasks such as Risø's work on validation of the database in task 2. The formulation of testing strategies, to a large extent, pointed to the anticipated phase 3 of TELEMAN; so, since this phase will not be effectuated, it was considered an acceptable solution to give up task 14.

**Task 15: Fault detection and prediction.**
To perform the bulk of the effort in this task, Dr. Andrew Holmes-Siedle, Radiation Experiments and Monitors (REM), was commissioned as a subcontractor to Risø. The work resulted in three reports [58, 59, 60], dealing with the effects of radiation to MOS devices. The physical effects in the MOS devices subjected to radiation were described and a model was set up of the variation of the threshold voltage shift $\Delta V_T$ as a function of radiation dose. This model can be used in the type of simulation performed under Task 5 in order to predict the failure of circuits and subsystems. The reports also give a survey of the status of hardened MOS technology on the commercial market. Draft versions of the reports were discussed and commented thoroughly by the ENTOREL partners. The final reports were distributed to the
ENTOREL partners, coordinators of other TELEMAN projects and a selection of TUG members. In addition, some people external to TELEMAN have received copies of the reports.

**Task 16: Gathering of operational experience with robots.**
Similar to task 13, this task was carried out by Roger Horne under subcontract to Risø. Based on his long experience with remote handling and knowledge of what has gone on in that world, RH wrote a report [61], describing a large number of solutions to problems encountered in remote handling in radiation environments, mainly at CERN, but also experience from the USA was included. Draft versions of the report were studied and commented by Risø as well as by the TELEMAN office. The final report was sent to ENTOREL partners, coordinators of other TELEMAN projects, members of the TELEMAN Users Group, and one external recipient.

**Project meetings**

During the 5½ years of the project the partners have met in regular project meetings a total of 14 times, i.e. a little more than 2 meetings per year. In addition, smaller meetings have been held between some of the partners, e.g. in the context of the database work. This reflects the closely knit collaboration which has taken place between the partners.

**Conference participation relevant to the project, and related publications**

ENTOREL work or ENTOREL related work has been published at a large number of conferences and in journals during the project’s lifetime, and some publications are still to come during the year following the end of the project. Under a separate heading in the literature list all the publications have been put together in a list; of course, many of them have already been mentioned and referred to in the text.

**Exploitation of the results of the project**

The results of the project were already being exploited during the project through radiation testing of components and materials relevant for the prototype machines being designed in other TELEMAN projects, through other advice given to TELEMAN project participants and by distributing the results of ENTOREL to other projects via newsletters and reports.
Concerning the reliability analysis, ENTOREL work formed the basis for specific analyses carried out under the projects INGRID (TM48), ROBUG III (TM44) and Gripper (TM18).

After the project has finished some of the partners will continue to use the results created by ENTOREL. The radiation effects database will be kept operational and radiation testing will be continued in other contexts, and on a commercial basis. The reliability analysis methods devised during ENTOREL will be carried over to other areas, e.g. unmanned submarines for inspection of pipelines and cables.

SCK•CEN is involved in dismantling work of some of its installations, including a PWR reactor. It also performs waste characterisation research and waste storage assessment. For all these activities, the radiation resistance of instrumentation installed on remote handling equipment is important. Results from the ENTOREL project are here of primary use. Recently, involvement has been started on restoration of contaminated sites. Monitoring systems to be used over long periods are also relying on results obtained during the ENTOREL project. Fusion contracts are connected to the same issue and will continue in the future the testing activities performed under ENTOREL. Finally, SCK•CEN will be further connected into the management of the data base, by providing future data.

The data generated by the project is being and will continue to be used for the design and development of remote handling products by AEA Technology. These products include robots, CCTV cameras and associated equipment. The data will also be used by the Radiation Testing Service as part of its radiation effects consultancy service, providing advice and a design/development capability for suppliers of equipment into applications requiring radiation tolerance.

At the time of writing the final report it had not yet been settled which partner should maintain the ENTOREL database in the future. The work may not find a place in the Siemens organisation. But AEA Technology is prepared to take on the responsibility for making the database available to industry. In this case the database will be converted to run under Microsoft Access. It is planned to extend the coverage to include data on materials as well as on electronic components. Greater search capabilities and improved graphical presentation will also be provided. Further details can be obtained from Richard Sharp or Claudia-Christina Seifert (addresses in the section "Contact points to the ENTOREL partners").

General experience

The ENTOREL project was set up as a "general" project among the TELEMAN programme's component- and machine building projects in order to study subjects which are common to robots that are going to work in a radiation environment. It was an important aim of the
project that it should provide information and guidance to the other projects concerning radiation tolerance, reliability and safety of such robots. The project partners have done their best to provide information about the project results to other TELEMAN participants by sending out newsletters and reports. But the feedback from many other projects has been rather sparse; the best interaction has been with projects where one or more of the ENTOREL partners have also been partners and one or more of the subjects of ENTOREL have been integrated in the project. A useful construction with respect to the information exchange between projects was also the so-called CIRCUIT group of projects in TELEMAN’s first phase, where four projects, including ENTOREL, held regular common meetings. The projects had a substantial overlap of partners, thus facilitating this common activity. Most partners from CIRCUIT went on to form the INGRID consortium in phase 2, where ENTOREL activities were also integral parts of the project.

Should TELEMAN start all over again now it would be prudent to consider a construction where the ENTOREL activities to a larger extent in a formal way were integrated in each project, in order to get an even better utilisation of the results. When this is said, however, it should be stressed that the project has been a very fruitful one to the partners and the synergy between the partners has been very good.

Acknowledgements

The project owes its existence to the European Commission’s research programme TELEMAN which has given the financial support necessary. Furthermore, the continued interest and support from the TELEMAN office’s Brian Tolley and Barry Robertson has been a great inspiration for the project partners and is much appreciated.

Literature

The literature list has been divided into four parts: internal project reports, published papers or reports, non-ENTOREL references, and student theses relevant to ENTOREL. The internal reports are all referenced in the text and the list below is not a complete list of all internal reports produced throughout the project; but it contains the important ones. The conference papers and other publications given in the second part of the list of references is intended to be a complete list in chronological order; not all of these have been mentioned in the text of the present report.
Internal project reports


18) A. Benemann, J. Podgorski, Comparison and Evaluation of Common Irradiation Test Results (ENTOREL) Siemens-04-16-92-05, April 1992
19) Sharp, R E, "Common transistor test results paper", TELEMAN/ENTOREL/Harwell-3.2-9
20) Pater, S L and Sharp, R E, "Radiation effects on electronics: trials on operational amplifiers", AEA Technology report AEA-D&R-0336, TELEMAN/ENTOREL/Harwell-3.2-6;
21) Pater, S L and Sharp, R E, "Radiation effects on electronics: trials on voltage comparators", AEA Technology report AEA-D&R-0337, TELEMAN/ENTOREL/Harwell-3.2-7;
25) Questionnaire on sensors and transducers, TELEMAN/ENTOREL-Harwell-3.3-1;
26) Sharp, R E, "2nd summary of replies to ENTOREL questionnaire", TELEMAN/ENTOREL-Harwell-3.6-2.2;
35) Irradiation Test Report on Klaschka OAS-m-18rg-1K inductive proximity detectors. Harwell irradiation test report TR288
38) Questionnaire on materials, TELEMAN/ENTOREL-Harwell-3.6-1;
48) Simoen, E., Magnusson, U., Born, I., Vlummens, J., Claeys, C., Coenen, S., Decréton, M., Mrad(Si) irradiation effects in Gate-all-Around Silicon-on-Insulator nMOST's, IMEC/SCK-CEN internal report, May 1993.

Conference papers and other publications


112) Sharp, R.E. and Dumbreck, A.A., Radiation testing solid-state sensor-based CCTV cameras the easy way. BNES Conference on Remote Techniques for Nuclear Plant, 10th - 13th May 1993, Stratford, UK.


116) Sharp, R.E. and Scheiwiller, P.M., Simulation of radiation effects on closed circuit TV cameras. Institution of Nuclear Engineers conference on Modelling and Simulation for the Nuclear Industry, Glasgow, 8th - 10th September 1993.


127) M. Decréton, V. Massaut, P. Borgermans, Potential Benefit of Fibre Optics in Nuclear Applications - The Case of the Decommissioning and the Waste Storage Activities, Symposium on Optical Fibre Sensing and Systems in Nuclear Environ-


131) C.-Ch. Seifert, Resistenz elektronischer Komponenten und Systeme gegen ionisierende Strahlung. Paper given on VGB - meeting: 36. Sitzung der AG "Geräteequalifizierung Elektro- und Leittechnik" 22.12.94 Offenbach/Main Germany


148) Andrew Holmes-Siedle, Palle Christensen, Leonard Adams, Claudia-Christina Seifert, Modelling CMOS Radiation Tolerance in the High-Dose Range. Publication on RADECS 95, 18-22. September 1995, Arcachon, France


152) Sharp, R.E., "Radiation effects on advanced bipolar and MOS devices", IEE Digest 1995/033.


157) M. Decrétion, S. Coenen, J. Vermunt, A. Rahn, Gamma irradiation facilities for assessment of advanced instrumentation - New reactors design and plant life extension increase their need, ENS Class I Topical Meeting on "Research Facilities for the Future of Nuclear Energy", June 4-6, 1996, Brussels.


162) F. Berghmans, M. Decrétion, H. Thienpont, I. Veretennicoff, Radiation effects on nematic liquid crystal devices, SPIE Annual Meeting - Conference on Photonics for Space Environments IV, August, 4-9, 1996, Denver (USA).


Non-ENTOREL references


Student theses relevant to ENTORcL

301) S. Demol, Ontwerp van signaalverwerkende elektronica voor een afstand sensor in een hoog radioactieve omgeving (Design of a signal processing electronics for a distance sensor in a highly radioactive environment), Engineering MSc thesis, VUB University of Brussels, July 1993 (in Dutch).


304) V. Moricau, Les capteurs à fibres optiques et leurs applications aux mesures de température en environnement nucléaire (The fibre optics sensors and their applications for temperature measurement in nuclear environment), Engineering MSc thesis, FPMs University of Mons, June 1995 (in French).

305) I. Baetens, Gevoeligheid van microfonen en hydrofonen aan gamma straling (Sensitivity of microphones and hydrophones to gamma radiation), BSc thesis, HIK Engineering School, Geel, June 1996 (in Dutch).
Contact points to the ENTOREL partners

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Figures
Figure 1 Database structure
Figure 2  Common transistor tests. Comparative results for the amplification factor $h_{FE}$
Figure 3  Common transistor tests. Comparative results for the saturation $V_{ce}$ voltage
Figure 4 Change in gain of 15 BC108 transistors with total integrated dose
Figure 5 Change in gain of two types of operational amplifier with total integrated dose
Figure 6  Honeywell phototransistor SD-5443-3 : Photocurrent vs. dose
Figure 7 Photocurrent in PIN diodes as a function of integrated γ-radiation dose
Figure 8  Circuit lay out of the prototype radiation hardened multiplexer
Figure 9 Total dose uptake of a CCTV camera during radiation testing
Figure 10 Diagram of the Schmitt trigger circuit studied
Figure 11  Results of a PSPICE simulation. The changes in output voltage ($V(8)$) and shifting time is shown for different dose levels. $V(1)$ is the input voltage.
Figure 12 Outline of gantry-type TELEMAN machine
<table>
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<th>Identification</th>
<th>Functions</th>
<th>Failure Modes</th>
<th>Failure Causes</th>
<th>Service Interval (h)</th>
<th>Failure Effects on System</th>
<th>Failure Effects on Robot</th>
<th>Failure Detection Possibility</th>
<th>Operator Actions</th>
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<td>No arm motion</td>
<td>Repair</td>
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<tr>
<td></td>
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<td>Failure to operate</td>
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<td></td>
<td></td>
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<td>No arm motion</td>
<td>Repair</td>
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<td>Bearing failure</td>
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<td>Lubricant</td>
<td>Robot Arm Motion System Failure</td>
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<td>No arm motion</td>
<td>Repair</td>
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<td></td>
<td></td>
<td>Electrical failure</td>
<td>Various</td>
<td>Insulation</td>
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<td>Repair</td>
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<td>Various</td>
<td>Component</td>
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<td>Repair</td>
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<td>Sensors</td>
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<td>Robot Motion System Failure</td>
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<td>Repair</td>
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<td>Electrical, mechanical</td>
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<td>No signals from manipulator</td>
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**Figure 13** Example of a FMEA form
Figure 14 Piece-wise linear radiation degradation function

Figure 15 Degradation function based on one point

Figure 16 Simple radiation degradation function
Appendix A: Participating staff from each partner

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## Appendix B: List of data sets in the database

### AMPLIFIER

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Reliability and radiation tolerance of robots for nuclear applications

Kurt Lauridsen, Marc Decréton, Claudia-Christina Seifert, Richard E. Sharp

The reliability of a robot for nuclear applications will be affected by environmental factors such as dust, water, vibrations, heat, and, in particular, ionising radiation. The present report describes the work carried out in a project addressing the reliability and radiation tolerance of such robots.

A widely representative range of components and materials has been radiation tested and the test results have been collated in a database along with data provided by the participants from earlier work and data acquired from other sources. A radiation effects guide has been written for the use by designers of electronic equipment for robots. A generic reliability model has been set up together with generic failure strategies, forming the basis for specific reliability modelling carried out in other projects. Modelling tools have been examined and developed for the prediction of the performance of electronic circuits subjected to radiation. Reports have been produced dealing with the prediction and detection of upcoming failures in electronic systems.

Operational experience from the use of robots in radiation work in various contexts has been compiled in a report, and another report has been written on cost/benefit considerations about the use of robots. Also the possible impact of robots on the safety of the surrounding plant has been considered and reported.

Descriptors INIS/EDB

COORDINATED RESEARCH PROGRAMMES; DATA BASE MANAGEMENT; ELECTRONIC CIRCUITS; FAILURE MODE ANALYSIS; MATHEMATICAL MODELS; NUCLEAR INDUSTRY; PHYSICAL RADIATION EFFETS; RELIABILITY; REMOTE HANDLING EQUIPMENT; ROBOTS

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Telephone (+45) 46 77 46 77, ext. 4004/4005
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Objective
Risø's objective is to provide society and industry with new opportunities for development in three main areas:

- Energy technology and energy planning
- Environmental aspects of energy, industrial and agricultural production
- Materials and measuring techniques for industry

In addition, Risø advises the authorities on nuclear issues.

Research profile
Risø's research is strategic, which means that it is long-term and directed toward areas which technological solutions are called for, whether in Denmark or globally. The research takes place within 11 programme areas:

- Wind energy
- Energy materials and energy technologies for the future
- Energy planning
- Environmental impact of atmospheric processes
- Processes and cycling of matter in ecosystems
- Industrial safety
- Environmental aspects of agricultural production
- Nuclear safety and radiation protection
- Structural materials
- Materials with special physical and chemical properties
- Optical measurement techniques and information processing

Transfer of Knowledge
Risø's research results are transferred to industry and authorities through:

- Co-operation on research
- Co-operation in R&D consortia
- R&D clubs and exchange of researchers
- Centre for Advanced Technology
- Patenting and licencing activities

And to the world of science through:

- Publication activities
- Network co-operation
- PhD education and post docs

Key Figures
Risø has a staff of more than 900, including more than 300 researchers and 100 PhD students and post docs. Risø's 1996 budget totals DKK 471 m, of which 45% come from research programmes and commercial contracts, while the remainder is covered by government appropriations.