RADIATION TOLERANCE ASSESSMENT OF CIDAS® MkX CRITICALITY INCIDENT DETECTION & ALARM SYSTEM

Stephen J. A. Bellamy
BIL Solutions
Thomson House
Birchwood Science Park, Risley,
Warrington, Cheshire WA3 6AT
United Kingdom
steve.ja.bellamy@bnfl.com

Andrew Cooper
British Nuclear Group
Hinton House, Risley
Warrington WA3 6AS
United Kingdom
Andrew.j.cooper@bnfl.com

ABSTRACT

BIL Solutions (formally BNFL Instruments) manufacture and supply a criticality incident detection and alarm system known as CIDAS® MkX.

It is important that the system functions correctly under the high gamma dose rates and neutron fluences generated during criticality events. It is at this time that the system must operate successfully to evacuate the facility in which it is installed.
ANS 8.3 requires the system to be "robust" when exposed to the maximum radiation expected and ISO 7753 states a minimum dose level which detectors must withstand however, more information about the system is required for plant designers to locate the detectors and control panel adequately.

BIL Solutions and BNFL therefore decided to characterise CIDAS® to ensure the system will provide the evacuation alarm if ever required to do so and provide important data to be considered in the location of the equipment within fissile material handling facilities.

The paper will address the appropriate distances from a criticality event which the system can operate and the corresponding gamma dose and (more importantly) the neutron fluence levels which might be tolerated. Determination of a strategy for the assessment and testing of CIDAS® is also described.

A paper based assessment of the electronic components of the system was undertaken. The results of this necessitated further analysis of the commercial electronics of the system to determine the effects of component failure or degradation.

In order to provide further confidence in the paper based assessment a representative system was manufactured and trials were carried out on the VIPER Pulsed Reactor at AWE Aldermaston. A Short video is available of this test. An explanation of the results of these trials is given. Some design changes were necessary as a result of this exercise and these are also explained.

The results of the investigations are used to improve the company standards used by BNFL for the provision of criticality detection systems on its nuclear licensed sites.

Key Words: Criticality, detection, alarm, radiation, tolerance

1 INTRODUCTION

1.1 Description of CIDAS®

The CIDAS® MkX Criticality Incident Detection and Alarm System is installed in several United Kingdom and North American facilities where its sole purpose is to detect the occurrence of a criticality event and then swiftly sound an evacuation alarm to instruct personnel to leave the facility. This reduces dose uptake by personnel.

The system detects the incident using a number of Geiger Muller tube based detectors located in precise positions around the areas where an event is deemed possible. The detectors are arranged on three separate rings giving a triplicated detection system. Positions are carefully chosen so that if a minimum design basis criticality event were to occur at least one detector on each of the three rings would be triggered. A two out of three logic within CIDAS® will initiate the alarm signal if any two rings are triggered thus allowing one ring to be in an unrevealed failed state without affecting the ability of the system to provide its safety function.
The CIDAS® detectors are arranged in a 'daisy chain' fashion and are wired back to a central equipment control panel.

The audio evacuation alarm system is an integral part of CIDAS®. The alarm being generated by an electronic tone generator and audio power amplifiers with loudspeakers used as the final element.

Power is supplied via three uninterruptible power supply units with back-up storage being lead acid batteries.

The system thus comprises, detectors and loudspeakers around the building, and detector power supplies, solid state logic, electronic audio equipment and battery chargers located in a central control panel suite.

1.2 Reason for assessment

The CIDAS® system is a safety system with the function of evacuating personnel quickly if a criticality occurs. It must be capable of detecting the minimum incident of concern which requires detectors to be positioned close enough to the incident location so that they detect the gamma radiation produced at a dose rate of at least 1mGy/h. Any intervening shielding has, of course, to be taken into account. It also has to be able to function when the event is the largest anticipated incident in terms of fission yield. The detectors must be able to withstand the gamma and neutron fluence levels and function for a range of incidents that span four orders of magnitude. If the gamma and neutron fluence levels were to cause detector failure then the alarm may not be raised. This would be unacceptable.

It is also essential that the system panel and its enclosed electronic circuits are unaffected by the gamma and neutron fluences produced in the largest anticipated incident.

Traditionally CIDAS® control panels have been located at a conservative distance away from the criticality event. This distance was based on an assumption that the electronic components would survive as the estimate was so conservative.

2 REVIEW OF THE STANDARDS

ANS 8.3 (1997) describes a requirement of the detection system to be located or protected from fire, explosion, corrosive atmosphere, or other extreme conditions. Extreme conditions may be taken to include radiation. It must also be “sufficiently robust as to actuate the alarm signal when exposed to the maximum radiation expected”.
ISO 7753 (1997) does not discuss a requirement for the control panel to withstand any extreme conditions but detectors must trigger when subjected to 1E3 Gy/h.
IEC 860 (1987) discusses the requirement for the detection sub-assembly to be tested at 1E3 Gy/h.

The above omissions can be explained by the overriding requirement that the system must meet its basic function of detecting the criticality incident and then generating the alarm signal.

It is important that plant designers are aware of the capabilities and limitations of the selected system. The sensitivity of detectors and their detection range need to be known to perform the placement process. Knowing the radiation tolerance of the control panel rather than making a conservative estimate of it allows it to be located closer to the criticality event which simplifies plant design and allows more flexibility. It is the determination of the levels of resistance to gamma and neutron fluence which were investigated.

3 LEVELS CONSIDERED

The BNFL Emergency planning total yield is 1E+18 fissions (ref. 4). For this assessment the radiation tolerance levels used assumed that the initial spike was 1E+18 fissions occurring over a duration of 1ms.

In some cases CIDAS® MkX detectors may need to be positioned as close as 1m, unshielded, from a potential criticality event in order to detect the minimum incident of concern. At this distance it must survive the effects of the larger reference criticality and function correctly by detecting the event and signaling to the control panel. 1m was thus chosen as the target distance between a detector and an unshielded criticality.

The control panel location is not important from a detection viewpoint but needs to have a reasonable level of radiation tolerance to simplify the system cabling design. The traditional levels of radiation tolerance used in the UK are based on a neutron fluence of 1E9 n/cm^2. This gives an unshielded distance of 165m which is generally impractical and necessitated shielding between the incident and the control panel. It was decided to try to certify CIDAS® to a higher radiation tolerance based on an unshielded distance. This would allow plant designers a high level of flexibility without the need to perform shielding calculations. The target distance of the control panel from an unshielded criticality was chosen as 10m.

The above distance and criticality specifications allow the total dose, dose rate and neutron fluence levels which should be withstood to be calculated. These are detailed in Table I.

TABLE I. Gamma and neutron desired assessment levels

	Integrated Gamma Dose (Gy(Si))	Gamma Dose Rate (Gy(Si)/s)	Neutron Fluence (n/cm^2) 1MeV (Si) Equiv.
Detector (1m from incident)	552	5.6 E5	2.8 E13
Panel Electronics (10m from incident)	5.5	5.5 E3	3.0 E11

These levels were compared against published data in an effort to determine the likelihood of the equipment surviving the incident. Typical data is shown in the following charts,

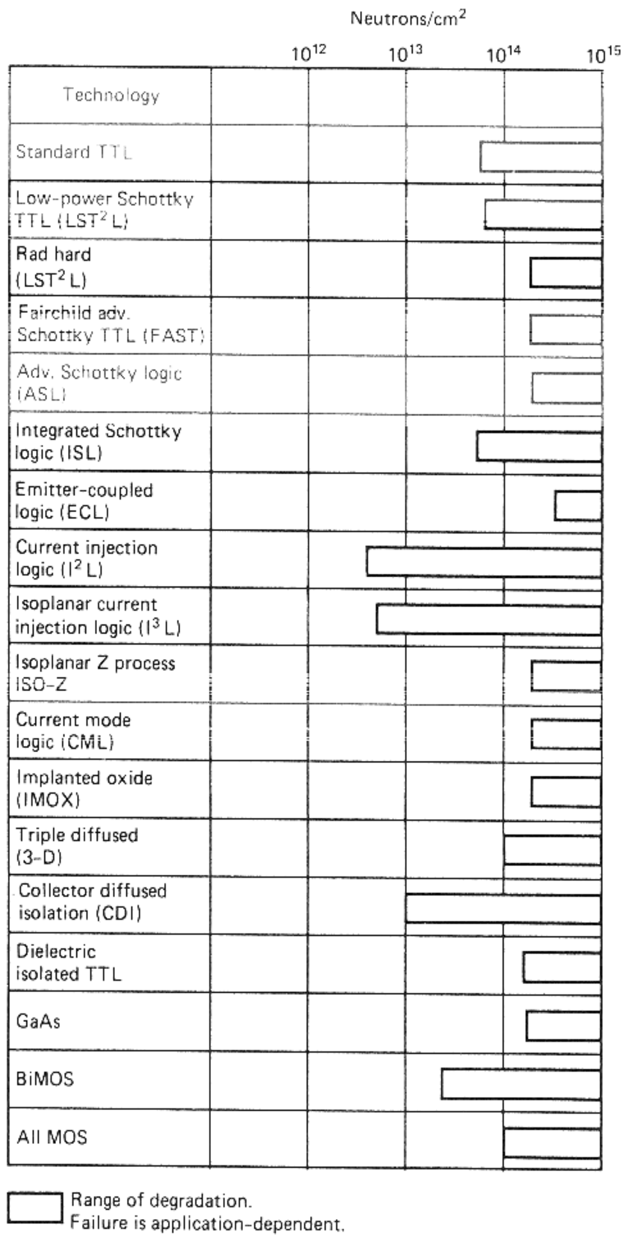

Figure 1. Neutron fluence hardness levels for integrated circuit families circa 1990 (Ref. 7)

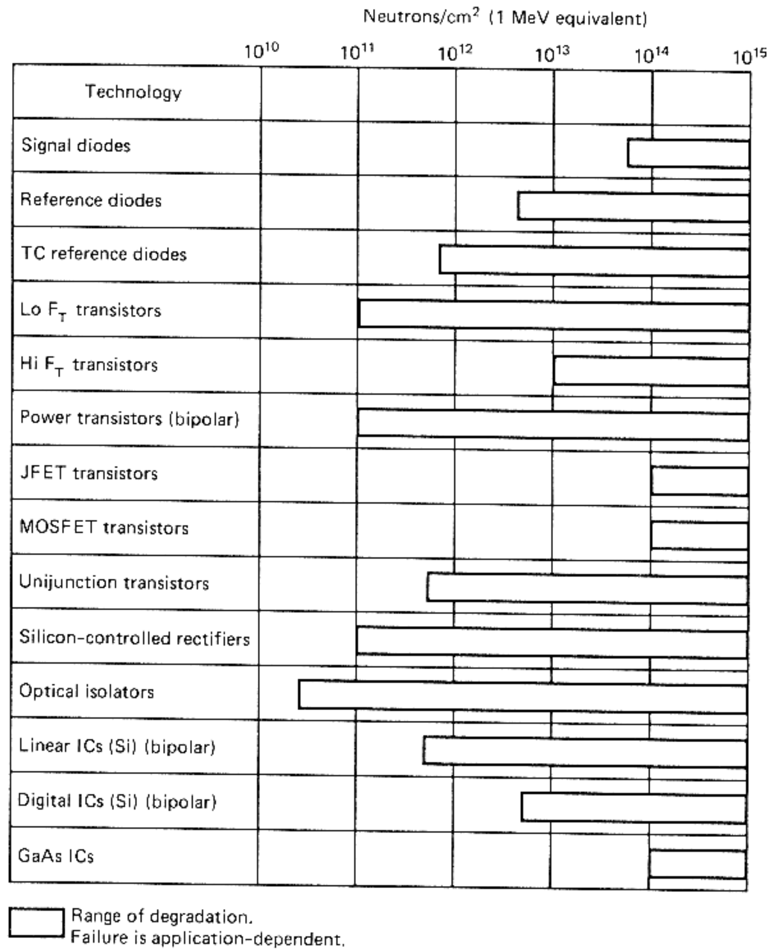

Figure 2. Neutron fluence hardness levels for mainly discrete device families circa 1990 (from Ref. 7)

For neutron fluence, Integrated Circuit performance begins to degrade in the region of 5E12n/cm². Discrete components begin to degrade in the region of 1E11n/cm². Integrated gamma dose degradation tends to commence at about 5Gy to 10Gy for discrete, linear and digital devices, 10Gy for MOSFET integrated circuits and around 100Gy for bipolar integrated circuit families.

Gamma dose rate degradation occurs from about 5000Gy/s for discrete device families and for bipolar and MOSFET ICs. (ref. 7).

Based on this information it was expected that the panel circuits would probably be immune to effects at the levels in Table I for neutron fluence, gamma dose and gamma dose rate. However, it was expected that there would be some degradation of the transistors and diodes in the detector circuit. This expectation necessitated further investigation.

4 STRATEGY FOR DETERMINING RADIATION TOLERANCE

In view of the levels to be proven and the expected results based on very general information on the effects of radiation on the electronics a strategy was developed to give confidence that CIDAS® MkX would function correctly to these required levels.

This strategy involved performing an analysis, of all the critical electronic components of the system by means of a general literature search. Any items which were identified as being susceptible to degradation were then to be given a more detailed assessment. Finally if any components were discovered for which sufficient confidence could not be attributed then testing would be performed.

BIL Solutions engaged the services of Matra BAe Dynamics Ltd. (MBDA), Radiation Effects Group to perform the study.

Components lists for all equipment used in the CIDAS® detection and alarm system were compiled. List compilation required the involvement of sub-component suppliers as well as in-house produced equipment. Three main suppliers were involved supplying the uninterruptible power supplies, the solid state two out of three logic, and the tone generation/audio equipment. Lists of the components were assessed for radiation tolerance to the previously determined levels shown in Table I. For each component a Nuclear Hardness Assessment Form was complied detailing the effects of gamma dose, dose rate and neutron fluence. A typical form is shown in Figure 3.

The component assessment was based on existing data in the MBDA UK Ltd Radiation Effects Group database, comprising data from; parts tested by the Radiation Effects Group, data contained in reports produced by the Radiation Effects Group and various external data sources and data books. The references section lists the data sources used.

Design margins were applied to the exposure radiation levels specified in order to account for the statistical variations in component degradation response. The following design margin factors were applied:

i) Dose rate: multiplication factor of 3 applied to the specification dose rate.
ii) Total dose: multiplication factor of 2 applied to the specification total dose.
iii) Neutron fluence: multiplication factor of 2 applied to the specification neutron fluence.

CIDAS Nuclear Hardness Assessment Form			
Line Reference:	001 to 006, 138 to 144		
Part No.:	See Table 2.	Part Type:	Fast Recovery Diode
Manufacturer:	Unknown	Technology:	Bipolar
Comments:			
Dose Rate Assessment: (1.0E5 cGy(Si)/s, 1.25E7 cGy(Si)/s)			

Data source:	Various	Sample Quantity:	-
Part No./Type:	Typical	Date Codes:	-
Manufacturer:	Any	Test Facility:	-

Typical Effects and Test Summary:

Many data exist for rectifier and recovery diodes. These diodes are relatively hard to dose rate effects up to 9E9 cGy(Si)/s and will usually survive up to the maximum reverse voltage.

Reverse biased diodes may conduct for dose rate duration at >1E7 cGy(Si)/s

Comments: Generic data suggests survival at over 9E9 cGy(Si)/s at the maximum reverse voltage.

Total Dose Assessment: (180 cGy(Si), 1.25E4 cGy(Si))

Data source:	Various	Sample Quantity:	-
Part No./Type:	Typical	Date Codes:	-
Manufacturer:	Any	Test Facility:	-

Typical Effects and Test Summary:

Generic data suggests that these diodes are considered hard to the effects of total dose >1.25E4 cGy(Si).

Comments:

Neutron Fluence Assessment: (1.0E9 n/cm², 1.25E13 n/cm²)

Data source:	Various	Sample Quantity:	-
Part No./Type:	Typical	Date Codes:	-
Manufacturer:	Any	Test Facility:	-

Typical Effects and Test Summary:

Many data exist for rectifier and recovery diodes. Forward voltage typically changes by a few percent and typically less than 10% at levels up to 1E13 n/cm². Reverse leakage currents may increase by an order of magnitude at 1E12 n/cm² and another at 1E13 n/cm².

Effects to neutron fluence of 1E9 n/cm² would be considered as negligible.

Comments:

Data Provided by Radiation Effects Group, Matra BAe Dynamics (UK) Limited

Figure 3. CIDAS® Nuclear hardness assessment form

4.1 Results of the Literature Search Assessment

The literature search assessment produced a list of several components for which there was no data or the results indicated that they would not withstand the neutron fluence levels desired. The panel electronics did not show any components expected to be susceptible to total dose or dose rate but some detector components required further analysis. As there were several components for which there was no data, testing was recommended.

The list of components for which there was a concern was analysed in further detail by determining the actual function of the component in the circuit. This resulted in one of the following conditions,

- The component did not prove to be in the critical circuit for detection or annunciation of the criticality, for example they might have had diagnostic or display functions.
- It was found to be sufficiently over rated so that parameter changes would still allow the component to operate as intended.
- Failure would be in the ‘safe’ state, i.e. the alarm would still be raised.

One item of equipment which was considered was a set of VICOR DC/DC power converters. Radiation tolerance data for various products in the VICOR range was available in the form of test data from experiments performed at Sandia National Laboratories. This data lead to the conclusion that these items would remain operational. Later analysis found that the test reports were not applicable to the actual units then used on CIDAS®. This is described later.

In view of these results it was decided that a complete CIDAS® system, including the UPS battery charger, should be manufactured and tested on the VIPER pulsed reactor at AWE Aldermaston, UK.

5 VIPER REACTOR TESTING

5.1 Description of VIPER

The VIPER reactor has been operating since 1967 and was the first fast pulsed reactor in Western Europe, and the first with a variable core composition. It is intended to provide isolated pulses of intense neutron and gamma radiation for a wide range of radiation effects studies. The acronym – Versatile Intermediate Pulsed Experimental Reactor – briefly sums up its characteristic features.

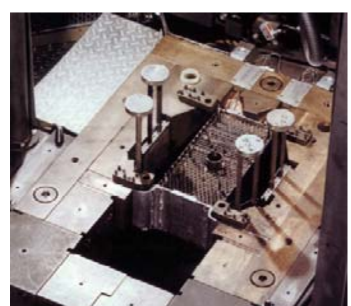

Figure 4. - VIPER core & test cavity

5.2 First VIPER Test

The representative CIDAS® panel and a stack of six detectors were positioned carefully within the reactor cell. The detectors were placed within the test cavity inside the reflector. The panel was mounted on a platform above floor level so that the panel centre was on the reactor core centre line. The UPS, mounted inside a second panel was positioned as close as possible to the core centre line. Sulphur tablets were installed inside the equipment so that the actual fluence received would be known.

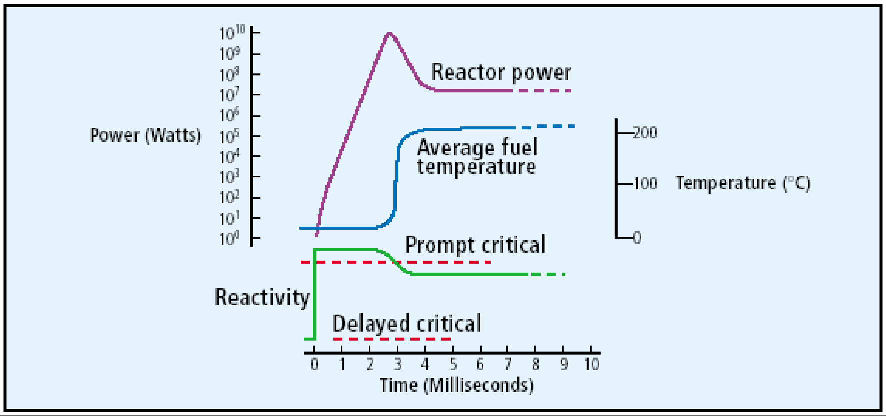

Figure 5. Reactor power, fuel temperature & reactivity variation in a typical pulse

The CIDAS® system was powered up and operational for the test. During the reactor balancing operation the detectors were subjected to dose rates above their 1mGy/h trip level and the criticality alarm was raised. This was reset after balancing and before the actual pulse.

The final pulse was a 3.5E17 fission event and had a duration of 1ms (400µs FWHM). Due to the proximity of the equipment to the core the detectors and the panel were exposed to a gradient of neutron fluence and dose. The mean values being 2.6E13 n/cm² and 25Gy for the detectors and 3.1E11 n/cm² and 1.8Gy for the panels. Neutron Fluence is 1MeV (Si) equivalent. Gamma Dose applied to the detectors was less than required as a 25mm thick lead shield was required inside the test cavity to stop premature tripping of the detectors and subsequent inability to reset the system into its pre-alarm state. The areas of the detectors above the lead shield were exposed to in excess of 200Gy but were less than 500Gy. These areas contained the components under test.

5.3 Test Results

During and after the test it was possible to view the CIDAS® system status on CCTV and to hear any alarm signal sounded.

The incident did in fact cause partial failure of the system and the alarm was not raised. It could be seen that the detectors had operated correctly from various LED indicators on the panel, however these signals were not processed by the system logic and the audio system was seen to fail. The cause was traced to complete failure of three VICOR DC/DC power converters. This caused a complete power loss to the logic and audio tone generators. These results indicate that the CIDAS® system in its current form using 48V UPS and DC/DC converters to provide 24V supplies for the system electronics is not able to operate at a distance of 10m from a 1E18 fission criticality.

As the first test was successful only in proving the detection system a further test was required. It still needed to be shown that the logic and audio electronics, which raise the evacuation alarm, would operate correctly. It was decided to reduce the neutron fluence levels to 25% of their previous level which would equate to an equivalent distance of 20m unshielded, from the criticality. This was still an acceptable distance allowing adequate flexibility to plant designers in the location of the equipment.

Replacement DC/DC converters were procured even though two had failed temporarily and had recovered after power had been cycled. One DC/DC converter had failed catastrophically. No other equipment was changed.

5.4 Second VIPER Test

The second test took place in March 2004, 17 months after the first test. The delay being due primarily, to a major overhaul of VIPER.

The specified gamma dose, dose rate and neutron fluence for the panel was 1.375 Gy prompt gamma, 1.375E3 Gy/s and 7.5E10 n/cm² (1MeV equivalent). This is equivalent to 20m from a 1E+18 fission incident. The DC/DC converters were arranged differently for the second test with one unit in its usual location, one on the panel floor and the third outside the panel in a remote location. Filament lamps were used to monitor the presence of output voltage from each converter so that any failure would be immediately apparent. CIDAS® design allows for failure of up to two converters without affecting the ability of the system to raise the alarm.

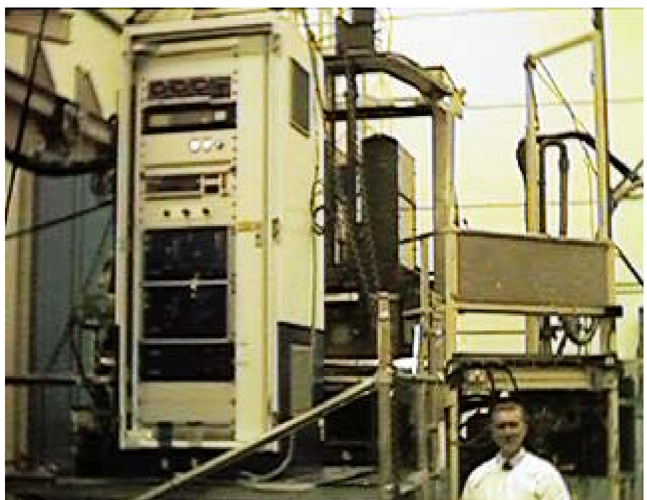

Figure 6. CIDAS Panel in position prior to second test

The detectors were on this occasion placed beside the panel, and not inside the reactor test cavity. This was acceptable as they had already been proven in the first test. The UPS was also located away from the reactor. These changes simplified system set up. The pulse provided levels of dose, dose rate and fluence at the centre of the panel of 0.88 Gy, 8.8E2 Gy/s and 7.5E10 n/cm² (1MeV (Si) equivalent).

The system did operate correctly on this test with the event being detected and the audible alarm being raised apparently instantaneously with the criticality. On closer examination two of the DC/DC converters were once more seen to fail with only the unit distant from the reactor operating correctly. The system logic and audio circuits however stayed powered up and were proven.

The failure of the DC/DC converter units during both tests required immediate consideration. A design change was necessary and it was decided to remove the component completely from the system. This resulted in the output voltage of the UPS being changed to 24V DC rather than 48V DC. This change has minimal effects on the UPS rectifier and the audio amplifiers and it was deemed that additional testing would not be required. These were the only items affected by the voltage change.

All CIDAS® systems manufactured since this test have been to the 24V specification. A BNFL 'Learning from Experience' investigation has been undertaken to determine if any actions were required on existing 48V systems already installed and operational.

6 CONCLUSIONS

The result of the exercise is that the company now has minimum distances from a reference criticality incident at which the detectors and electronics panel are known to stay operational. These distances are 1m for the detectors and 20m for the panel. It is probable that they will tolerate being closer than these distances but this is not proven.

Company standards will include this data ensuring that future systems will be designed and installed taking cognisance of the effects of the radiation from the criticality event. This will give confidence that the system will perform if required.

The importance of monitoring suppliers of components and sub-systems is recognised of being of great importance if the above findings are to be maintained.

7 ACKNOWLEDGEMENTS

We would like to thank Phil Greatorex, Environment, Health, Safety & Quality Dept. British Nuclear Group, for the funding of this project. The staff at Matra BAe Dynamics Radiation Effects Group, particularly Michael Moutrie and Rod Jones for their work on the analysis of the individual components. Dr. Neville Bainbridge, Neutron Effects Group, AWE and his team for their advice and assistance in performing the tests on VIPER. Justin Haworth of Safety & Risk Management, British Nuclear Group, for his calculations of tolerance requirements and continued expert assistance.

8 REFERENCES

1 ANS 8.3 (1997) Criticality accident alarm system
2 ISO 7753 (1997) Nuclear energy – Performance and testing requirements for criticality detection and alarm systems
3 IEC 860 (1987) Warning Equipment for Criticality Accidents
4 SCN-91 The characteristics of Criticality Excursions – A Review for Criticality Safety considerations - T B Austin January 1994
5 DR24378 – Revised Radiation Tolerance Analysis of BNFL Instruments
6 Criticality Incident Detection & Alarm System (CIDAS® MkX), incl. Detectors - Report prepared by MBDA UK Ltd Radiation Effects Group

7 Messenger and Ash, The Effects of Radiation on Electronic Systems (2nd Ed), 1991, ISBN 0-442-23952-1.

The following references were used as sources of Radiation Tolerance Data,

8 Test data from parts tested by MBDA UK Ltd Radiation Effects Group
9 ERRIC Electronic Radiation Response Information Centre operated by DASIAC
10 RMCS Nuclear Hardening Course Handbook from the Royal Military College of Science
11 SIRE Semiconductor Index of Radiation Effects, available from UK MoD
12 L.W.Ricketts, Fundamentals of Nuclear Hardening of Electronic Equipment, 1972, ISBN 0-471-72100-X