Radiation Hardened Technology for Remote Maintenance

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We will discuss technologies primarily related to reactor maintenance in harsh environments

• Cameras
• Non-Traditional Imaging for Standoff
• Cables and interconnect
• Electronics
The most successful and safest maintenance should occur in a system that has been designed properly

- If you can keep it away from radiation, do it
- If you can keep it away from heat, do it
- If it’s near radiation, don’t use electronics nearby
- If it needs electronics nearby, use MI cable
- If it needs flexible cable, use a hardened cable
Cameras

- Electronic cameras have been around since the early part of the 20th century

- There are two primary methods of transduction
  - First and oldest – cathode ray tube (CRT)
  - A variety of types (image orthicons, vidicons, others)
  - Most have a beam of electrons scanning an image plate to sense varying degrees of intensity
Cameras

- Second method of transduction.
  - Solid-state sensors
    - Charge-coupled device (CCD)
    - Active-pixel sensor (APS)
Cameras

• CRT applicability for maintenance
  – Most types presently used are CRT
  – This is due to extreme hardness of vacuum electronics
  – Photo-sensitive element is the weak point
  – Rasterized image (limited resolution)

• Solid State applicability
  – Can be high resolution
  – Not rasterized
  – Historically rad soft by 2-3 orders of magnitude
  – New work for ITER looking at 1 GRad dose
Cameras

• Commercial CRT camera components are available
  – Mirion (R941 can go to 200 MRad)
  – Lights-Camera-Action (RH-300 can go to 200 MRad)
  – Diakont (D40 can go to 200 MRad)
  – Non-browning lenses are available

• Developmental CMOS *color* camera is not available yet*
  – Prototype demonstrated to 600 MRad
  – Very little degradation

Non-Traditional Standoff Imaging

• One approach to hardening is to keep components well away from active work area

• LiDAR (Light Detection and Ranging) – Imaging technique similar to RADAR except using light

• Laser source allows coherent beams to be used so that a true 3D map can be obtained

• Already used for terrain, meteorological mapping and now for automotive

• Ultrasonics – Similar to LiDAR expect using sound with lower resolution

• Potential problem with both is shadowing effect of the work area
Cables and Interconnect

• Cables carry signal and power and some are likely to require exposure to radiation

• Most cables of interest will consist of multiple conductors

• Because cables inherently provide insulation between conductors, cables contain insulation material

• Impedance-controlled cables such as Closed-Circuit TV (CCTV, coaxial 75Ω) and twisted pair like Ethernet (differential 100Ω) need electrically and mechanically stable dielectric

• Individual cables may or may not need flexibility depending on the installation need
Cables and Interconnect

• Flexible cables are commercially available that have hardness from 0.1 MRad to more than 1 GRad

• Least hard materials are polytetrafluoroethylene (PTFE) and Diablax® while most hard are polyimide and thermoplastic polyimide (TPI)

• This does not track temperature however with Diablax® being able to operate at 300C and the others around 250C

• For hardness and high temp, best option is non-flexible mineral-insulated (MI) cables

• These can survive (MgO) to $10^{10}$ Rad and $10^{18}$ n/cm²

• One issue with MgO can be induced electromotive effect (RIEMF)

• Effect is generation of small spurious signals due to neutron and gamma interaction with MgO*

Cables and Interconnect

- Connectors are one of the most well known failure points so therefore must be chosen wisely

- Very important -- Connectors MUST be chosen carefully if they are going to be manipulated robotically

- Manufacturers
  - Flexible cable -- Axon, Mirion, Habia
  - MI cable -- Omega Engineering, Ari Industries, Techno Instruments
  - Connectors -- TE Connectivity, Lemo, NAMCO
Electronics

• Most useful measurements require some sensor and likely some form of signal conditioning

• Preferred sensors are those that allow large standoff distance to the electronics so that no rad hardness is required

• More complex sensors may require close processing such as
  – Solid-state cameras
  – Advanced fission chambers
Electronics

• There are multiple types of amplifying devices available
  – Complementary Metal Oxide Semiconductor (CMOS, Silicon, SiC)
  – Bipolar (Silicon, SiC)
  – Junction Field Effect Transistor (JFET, Silicon, GaN)
  – Vacuum devices (vacuum tubes, vacuum micro/nano)

• Of these, CMOS Silicon, traditional vacuum tubes and vacuum micro have been tested to high doses

• All of these are capable of exceeding 100 MRad Total Integrated Dose (TID) if properly designed and fabricated
Electronics

- Complementary metal-oxide semiconductor (CMOS) is why the electronics industry has ‘exploded’
- Since both electrons and holes are used as carriers, they are truly complementary
- Reproducible circuits that can perform almost any function can be made cheaply in quantity
- Low power and high speed are readily available
- Radiation hardening by design (RHBD) techniques allow hardness approaching 1 GRad in existing processes
- If you aren’t designing to at least 100 MRad, you aren’t state of the art
Electronics

- Vacuum tubes have been available for a century (Edison diode-1904)
- They are made of glass insulator and metal (naturally very rad hard)
- Readily available due to audio/musical instrument market
- Now made in Russia and China

**BUT**

- They are not complementary - single type of charge carrier (electrons)
- All circuits will need resistors or tube loads and capacitor coupling
- Circuitry will therefore need to be simple and limited
- Naturally power hungry
- Limited life due to materials
Electronics

• Anything but traditional thermionic tubes are still experimental

• Much work in micro- and nano-tubes

• Most are Fowler-Nordheim emission devices and are triode structures

• Micro thermionic devices at LANL in the ‘80s showed hardness above 250 MRad*

• Smaller devices being researched but
  – Still no complementary device so circuits will need to be simple
  – Not clear if wafer-level vacuum devices will be as rad hard as transistors since electrodes are closer and built on insulator

In summary....

• Most technologies that would be used are commercially available

• There don’t seem to be any real gaps

• There may wind up being gaps for unforeseen circumstances

• The maintenance needs to be thought through carefully at the beginning of the plant design

• Solid state electronics trend is towards small feature size silicon integrated circuits using rad-hard by design (RHBD) to reach > 100 MRad TID

• Although the technologies exist, many electronics functions are not yet available as rad hard

• Industry continues to introduce more options for rad-hard electronics and rad-hard cameras