Radiation Hardened Technology for Remote Maintenance

Chuck Britton, PhD.

David Holcomb, PhD.

Nance Ericson, PhD.

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

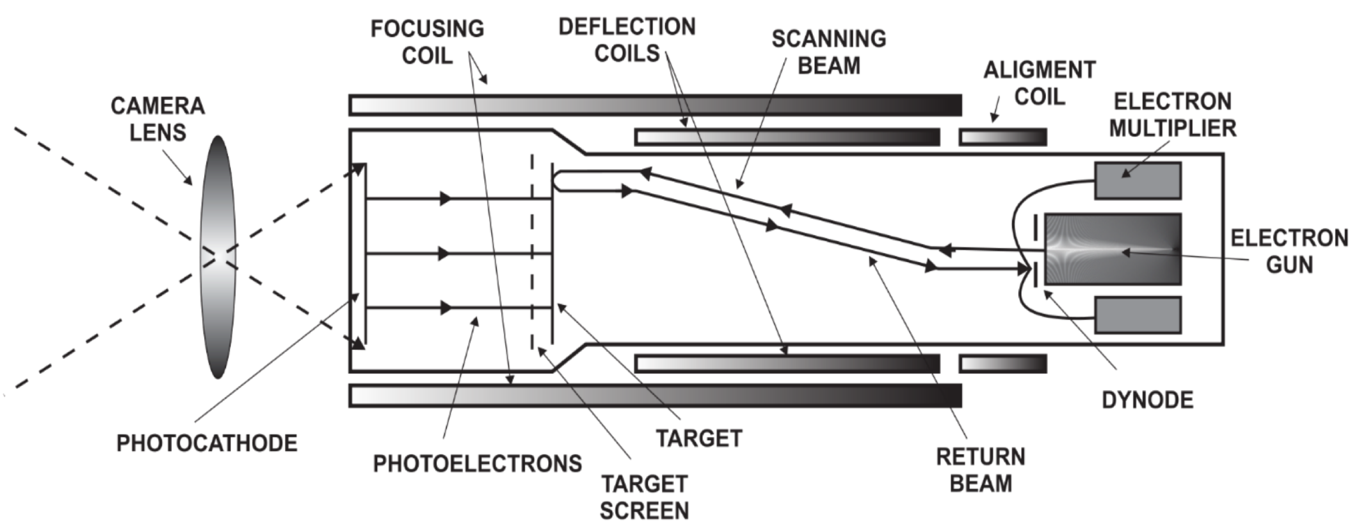
- Cameras
- Non-Traditional Imaging for Standoff
- Cables and interconnect
- Electronics

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

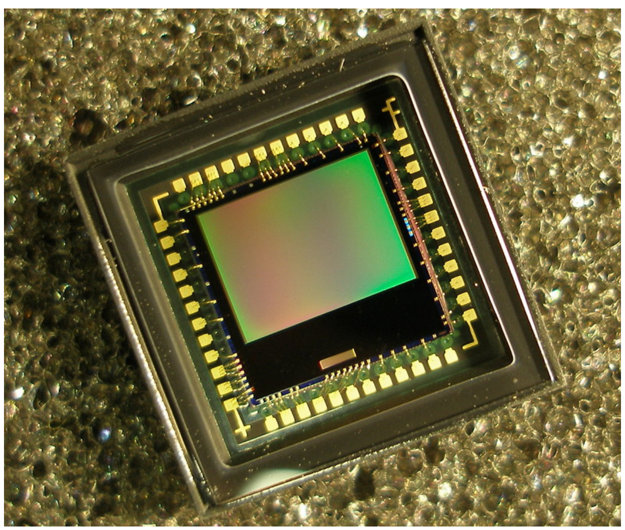
Cameras

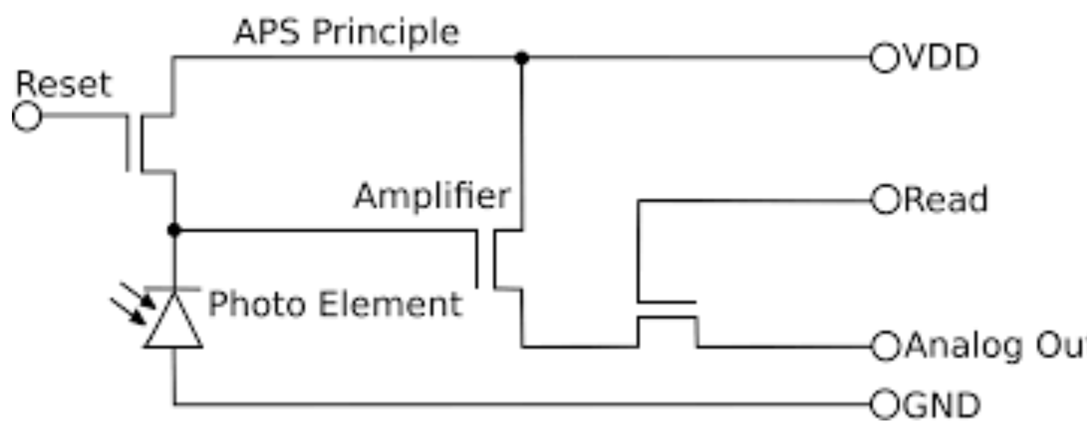
- Electronic cameras have been around since the early part of the 20th century
- There are two primary methods of transduction
  - First and oldest – cathode ray tube (CRT)
  - A variety of types (image orthicons, vidicons, others)
  - Most have a beam of electrons scanning an image plate to sense varying 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

*V. Goiffon *et al.*, "Radiation Hardening of Digital Color CMOS Camera-on-a-Chip Building Blocks for Multi-MGy Total Ionizing Dose Environments," in *IEEE Transactions on Nuclear Science*, vol. 64, no. 1, pp. 45-53, Jan. 2017.

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/cm^2
- 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*

*Review of Scientific Instruments **74**, 4667 (2003); doi: 10.1063/1.1622976

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 <u>if they are going to be manipulated robotically</u>
- Manufacturers
  - <u>Flexible cable</u> – Axon, Mirion, Habia
  - <u>MI cable</u> – Omega Engineering, Ari Industries, Techno Instruments
  - <u>Connectors</u> – TE Connectivity, Lemo, NAMCO

Electronics

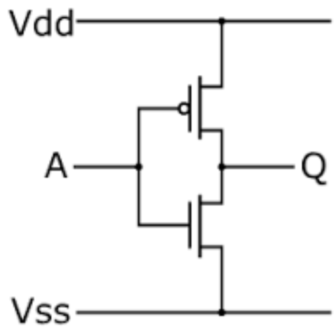
- Most useful measurements require some sensor and likely some form of signal conditioning
- Preferred sensors are those that allow large standoff distance to the electronics so that no rad hardness is required
- More complex sensors may require close processing such as
  - Solid-state cameras
  - Advanced fission chambers

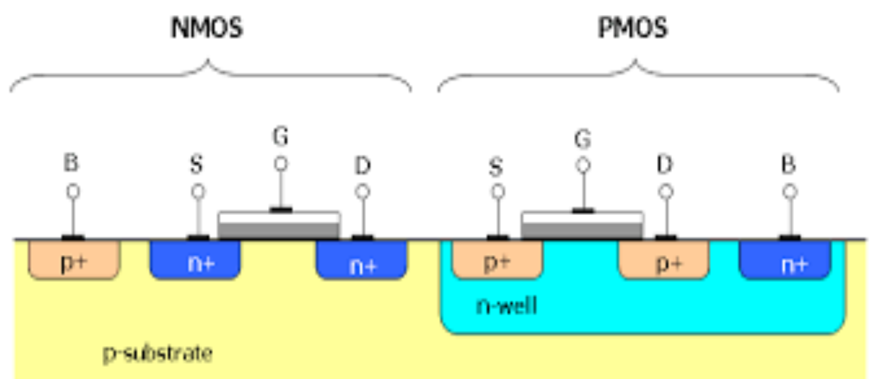
Electronics

- 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) <u>if properly designed and fabricated</u>

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



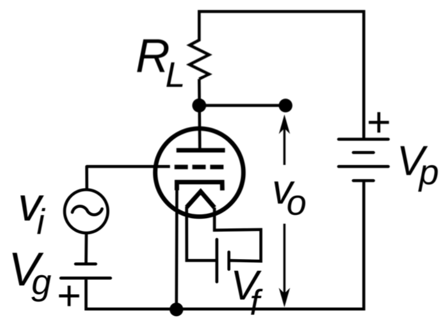


Electronics

- 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

*Lynn, D. K., McCormick, J. B., "Progress in Radiation Immune Thermionic Integrated Circuits" LA-10466-MS, Los Alamos National Laboratory, August 1985.

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