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Connecting Visionaries in Radiation Safety, Science and Industry

MIRION Connect 24

Annual Users' Conference

July 29 - August 2 | Omni Dallas Hotel, Dallas, TX

MIRION TECHNOLOGIES

Radiation Impacts on Imaging
Tradeoffs and Decisions

Khalil Divan and David Stewart

PLM: Imaging/Director, PLM: Defense, Security, and…

Mirion Connect | Annual Users’ Conference 2024

Dallas, Texas

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Radiation Impacts on Imaging

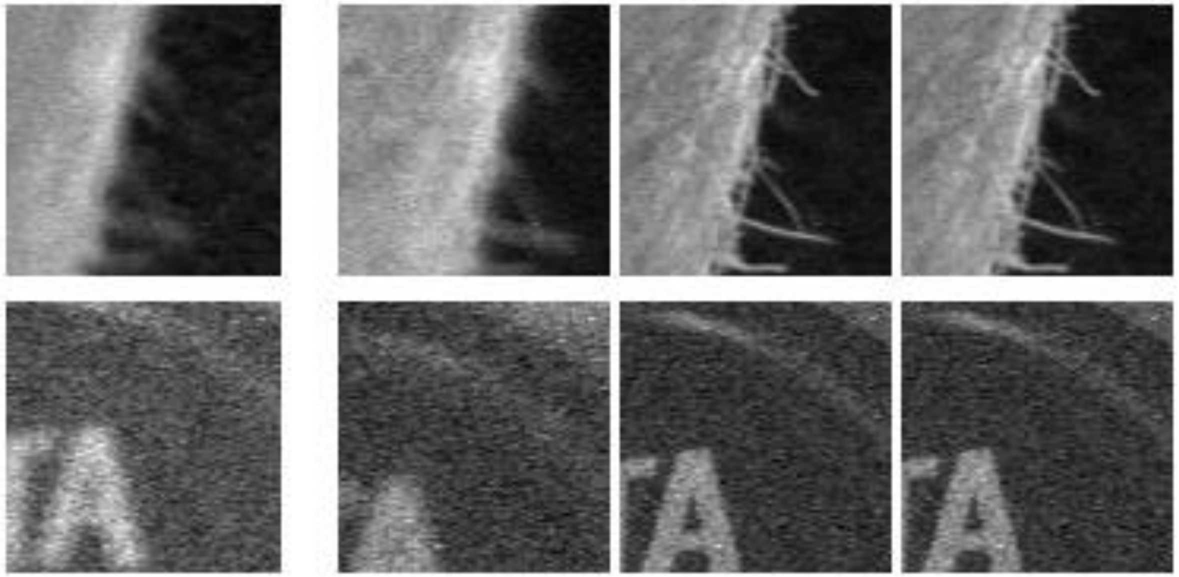
Discuss dynamic dose and cumulative dose impacts on imaging. What can be done to avoid/mitigate both from a device selection to altering the environment. How lighting, size, temperature, and other factors impact your decisions and results.

Introduction

Radiation Tolerant Cameras

- Often compared to cell phones
- In general, the higher the radiation, the fewer onboard/automated features
- May not be obvious, but:
  - Significantly changed the way imaging is interpreted
  - Massive amounts of research and technology gains
- Everyone is now a camera expert

Radiation Tolerant Cameras



- Key features not typically found in radiation tolerant environments
  - Auto focus
  - Auto white balance (above mid-rad levels)
  - High zoom ratios (typically 3x, 6x, or 10x in radiation tolerant lenses)
  - Image stabilization
  - Heuristic based iris
  - High dynamic range

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Determining if Radiation Tolerant

Royal Military College of Science
School of Engineering and Applied Science

Cranfield UNIVERSITY

Cranfield University
RMCS Shrivenham
Swindon SN6 8LA England
Fax +44 (0) 1793 783192
Tel +44 (0) 1793 782551
tel (direct) 01793 785237
fax (direct) 01793 785774
e-mail: lovell @ rmcs.cran.ac.uk

29 August 1997

IST-REES
Rees Instruments Limited
Thornbrook
Weyside Park
Catteshall Lane
Godalming
Surrey GU7 1XE

JJ THOMSON IRRADIATION LABORATORY
COBALT 60 GAMMA FACILITY
CERTIFICATE OF IRRADIATION

This is to certify that the undermentioned equipment has been irradiated in this facility to total doses and at dose rates as described below.

Sample Identification	Dose Rate (rads per hour) (water)	Total Irradiation Time (hours)	Total Dose (rads) (water)
R 985 System Camera Ser No. 97/2191/01	1.54×10^6	24.04	3.70×10^7

Dosimetry

Dosimetry was by N E Technology Ionex 2500/3 Ion Chamber dose rate meter calibrated and traceable to NPL Standard. Calibration Certificate Number IC0143.

Test Procedure

The camera was positioned in the centre of the source at a dose rate of 1.54×10^6 rads.hr^{-1} viewing a test board illuminated by small tungsten lamps. The video output was recorded on a time-lapse VCR throughout the test, and the video signal was routed via an oscilloscope to observe the video waveform.

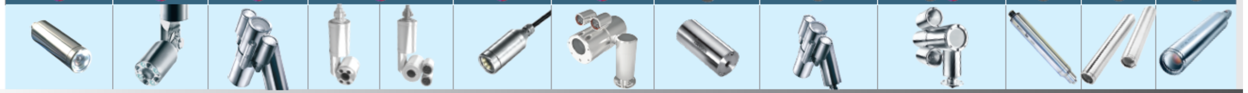
Signed:

K V LOVELL
Radiation Facility Manager

- Done through testing
- Testing should represent both the expected energy levels and dose
- Dose rate impacts on TID is difficult as it is usually in an accelerated environment
- For assurance, always best to obtain 3rd party testing certification
- Dose rate should be done at actual/expected levels
- Usually the cost to deploy/retrieve represents a significant cost

Radiation Tolerance

- Total Integrated Dose
- Dynamic Dose
- Radiation selection is embodied in our matrix based on its importance
- Other considerations in advance of choosing a camera
  - How it will be used
  - What tradeoffs are acceptable
- If transporting, be aware of export regulations and Wassenaar Arrangement
- Above all else – what do you want to see



	DOTCAM	MINIPTZ MK2	C981 / C983	HD-RAD		DOTCAM - HR	SC985	R985	R981 COMPACT	HYPERION COMPACT	R93	R941	R942
Total Dose	100 Gy (1 x 10^4 rad)	100 Gy (1 x 10^4 rad)	100 Gy (1 x 10^4 rad)	500 Gy (5 x 10^4 rad)	500 Gy (5 x 10^4 rad)	1k Gy (1 x 10^5 rad)	10kGy (1 Mrad) [^{137}Cs]	100k Gy (1 x 10^7 rad)	1 MGy (1 x 10^8 rad)	1 MGy (1 x 10^8 rad) Cobalt-60	2 MGy [60Co] (2 x 10^8 rads) Cobalt-60	2 MGy [60Co] (2 x 10^8 rads) Cobalt-60	2 MGy [60Co] (2 x 10^8 rads) Cobalt-60
Dose Rate	100 Gy/h (1 x 10^4 rad/h)	100 Gy/h (1 x 10^4 rad/h)	100 Gy/h (1 x 10^4 rad/h)	100 Gy/h (1 x 10^4 rad/h)	100 Gy/h (1 x 10^4 rad/h)	300 Gy/h (3 x 10^4 rad/h)	1kGy/h (100k rad/h)	1kGy/h (1 x 10^5 rad/h)	1 kGy/h (1 x 10^5 rad/h) Chalnicon	1 kGy/h (1 x 10^5 rad/h)	1 kGy/h (1 x 10^5 rad/h) Chalnicon	1 kGy/h (1 x 10^5 rad/h) Chalnicon	1 kGy/h (1 x 10^5 rad/h) Chalnicon
On-Board Lighting	6 x LED Ring (internal)	LED - 4 x Wide & 4 x Spot (internal)	Optional (external)	4 x LED (internal)	2 x LED (external)	6 x LED Ring (internal)	Optional (external)	No	Optional (external)	Optional (external)	Optional	No	No
Key Options	Optional variable lighting	• 1 x 20 W (in air) • 1 x 50 W (underwater) • 19" rack or pelicase controller	• 100 W (in air) • 300 W (underwater) • High Power LED • Microphone • 19" rack controller	19" rack or pelicase controller	19" rack or pelicase controller	Optional variable lighting	• Optional variable LED lighting • 19" rack controller • HR variant available: 50kGy (5Mrad)	• Simple cable 11.5-15VDC in, video out • C-mount, D-mount, or CS-mount lenses • Integrates with existing pan/tilt units • Auto-iris support	• 100 W (in air) • 300 W (underwater) • High Power LED • Microphone • 19" rack controller	• 2 x 50 W • 19" rack controller	• Optional lighting heads • 19" rack controller	19" rack controller	19" rack controller
Operating U/W Depth	60 m (200 feet)	60 m (200 feet)	60 m (200 feet)	60 m (200 feet)	60 m (200 feet)	60 m (200 feet)	60 m (200 feet)	*Does not operate under water*	60 m (200 feet)	60 m (200 feet)	60 m (200 feet)	50 m (165 feet)	50 m (165 feet)
Max Temperature	• 50 °C (122 °F) underwater • 40 °C (104 °F) in air	• 50 °C (122 °F) underwater • 40 °C (104 °F) in air	• 50 °C (122 °F) underwater • 40 °C (104 °F) in air	40 °C (104 °F) underwater only	• 45 °C (113 °F) in air • 50 °C (122 °F) underwater	• 60 °C (140 °F) underwater • 50 °C (122 °F) in air	55 °C (131 °F)	50 °C (122 °F)	• 70 °C (158 °F) underwater • 50 °C (122 °F) in air	• 0-62.5 °C (without lights) • 0-55 °C (with lights)	• 70 °C (158 °F) underwater • 55 °C (131 °F) in air	• 70 °C (158 °F) underwater • 55 °C (131 °F) in air	• 70 °C (158 °F) underwater • 55 °C (131 °F) in air
CCD/Solid State	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No	No
Pan & Tilt	No	Yes	Optional	Yes	Yes	No	Yes	Optional	Optional	Optional	No	No	Compatible with pan and tilt unit
Lens Options	• 1.9 mm (no LED lights) • 3 mm, 3.7 mm, 4.3 mm • 8 mm, 12 mm, 16 mm	10 x Optical Zoom (4 x Digital Zoom)	18 x Optical Zoom (4 x Digital Zoom)	10 x Optical Zoom (4 x Digital Zoom)	10 x Optical Zoom (4 x Digital Zoom)	• 3.9 mm f/2.8 • 3.0 mm f/2 • 6 mm f/2.8	6.5 - 65 mm f/2 Non browning zoom	Fixed and zoom available (2/3" format)	• 12-72 mm f/1.8 Non browning zoom • 24-144 mm f/3.6 Non browning zoom	17.5 - 105 mm f/2.4-f/16 Non browning zoom	• 6 mm, 9 mm, 25 mm Fixed Non browning • 8-24 mm f/2.8 Non browning zoom	8 - 24 mm f/2.8 Non browning zoom	• 12 - 72 mm f/1.8 Non browning zoom • 24 - 144 mm f/3.6 Non browning zoom
Overall Size	29 mm diameter x 109 mm long (1.14 x 4.3 inches)	63.5 mm diameter x 371 mm long (2.50 x 14.6 inches)	162 mm wide x 221 mm high x 220 mm long (6.4 x 8.7 x 8.7 inches)	110 mm wide x 307 long (4.3 x 12 inches)	155 mm wide x 311 mm long (6.1 x 12.2 inches)	29 mm diameter x 79 mm long (1.14 x 3.1 inches)	206 mm wide x 292 mm high x 224 mm long (8.1 x 11.5 x 8.8 inches)	72 mm diameter x 165 mm long (2.83 x 6.5 inches)	162 mm wide x 229 mm high x 220 mm long (6.4 x 9 x 8.7 inches)	172 mm wide x 267 mm long (with lights)	40.5 mm diameter x 250 mm long (1.6 x 9.8 inches)	55 mm diameter x 269 mm long (2.16 x 10.6 inches)	76.2 mm diameter x 390 mm long (3 x 15.4 inches)
Weight Range	192 g (6.8 oz)	2.4 kg (5.3 lbs)	3.2 kg (7 lbs) without lights or microphone	3.4 kg (7.5 lbs)	3.4 kg (7.5 lbs)	95 g (3.4 oz)	10 kg (22 lbs)	1 kg (2.2lbs)	4.7 kg (10.4 lbs) without lights or microphone	3.5 kg (7.7 lbs) fixed, no lights 7.5 kg (16.6 lbs) pan/tilt, lights	1.3 kg (2.8 lbs)	1.8 kg (4 lbs)	3.7 kg (8.2 lbs)

Radiation Tolerance Level: LOW › › › MEDIUM › › › HIGH › › ›

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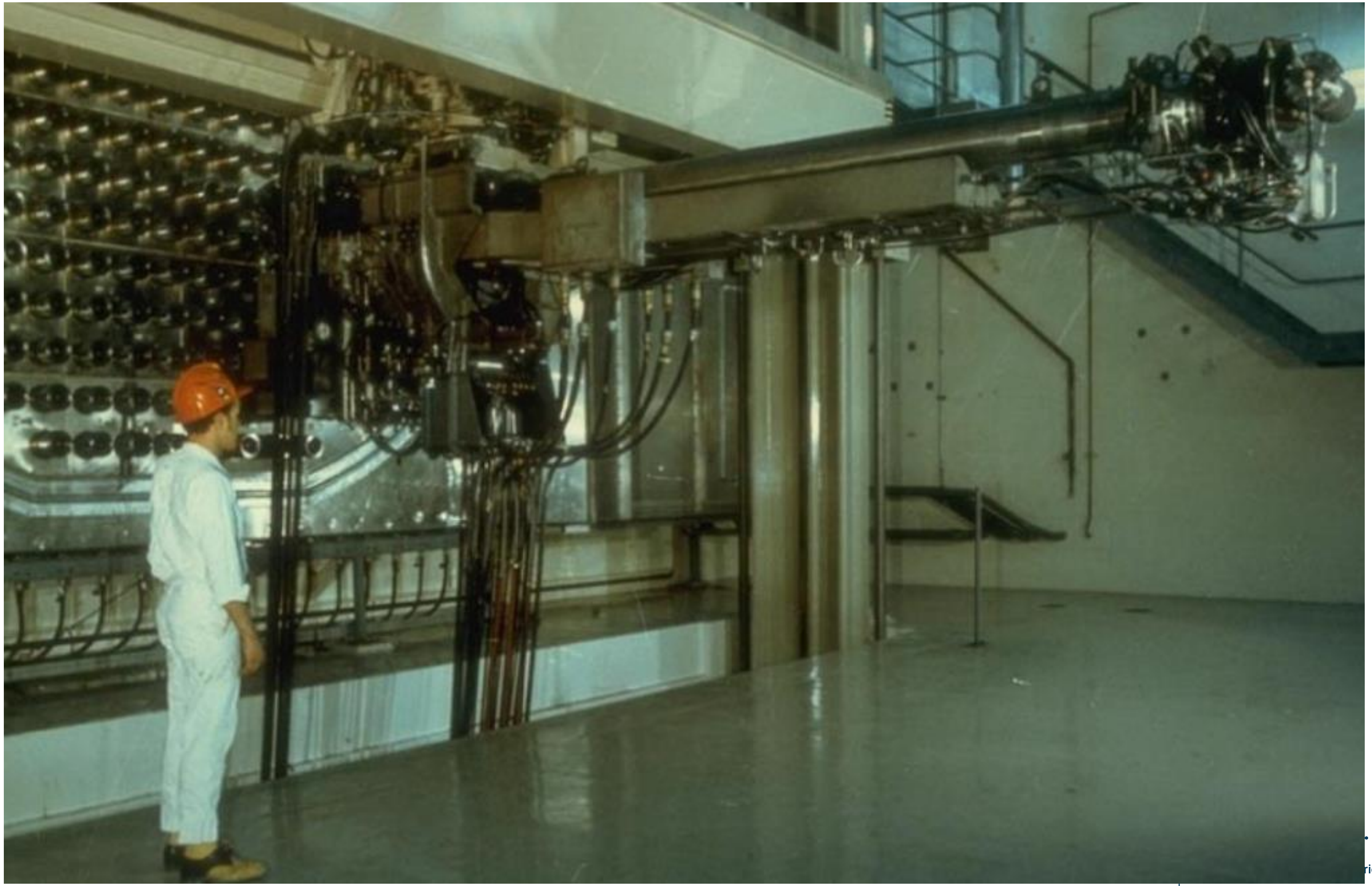
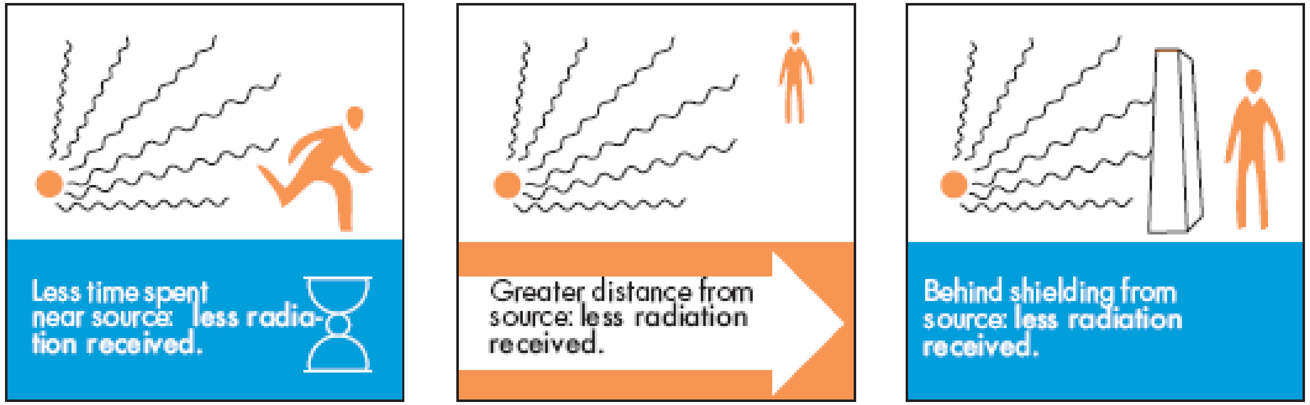
What Do You Want to See



Time, Distance, and Shielding

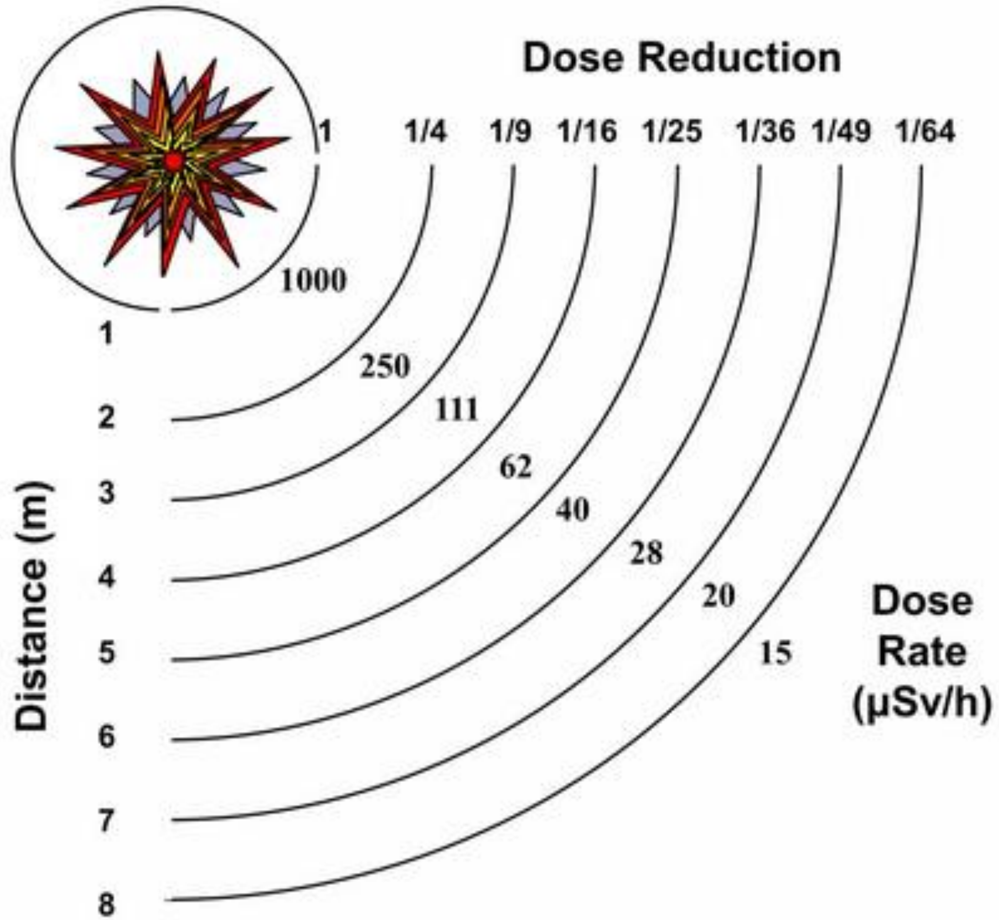
Time, Distance, Shielding

- Applies to people and cameras, but how?
- Quicker to deploy/retrieve
- Image from a greater distance
  - Remember 2x the distance = ¼ the radiation
  - **BUT** can you still see what is needed?
- Shielding of cameras can allow greater tolerance



Distance

- Distance tradeoffs
  - May result in thermals for underwater applications and some in-air applications
  - Vibration and image instability prevalent in air as distance from pan/tilt increases
- Compensate with lenses (but at a cost)
  - Zoom needed
  - Narrow Angle
- But remember: double the distance will quarter the radiation



Time

- In addition to consideration for rapid deployment, other benefits to utilize temporal benefits exist
- At low to modest levels of radiation, for non-radiation tolerant cameras
  - Gamma photons impacting the detector may appear as saturated pixels
  - Typically long term damage is cumulative and the pixel will return to function
- Near real-time software analysis can identify these pixels and replace with prior and subsequent image data
- Result is in effective noise removal

Distance

- More prevalent in underwater inspections
- Causes “waving” distortion across video image
- Can significantly “hide” fine details
- Contributes to viewer fatigue
- Very specialist software exists
  - Cost
  - Latency
  - Training

Shielding

- Various methods for shielding
  - Embedded imager and optics within a shielded housing ("dog leg")
  - Imager in shielded housing with right angle viewing mechanism
  - Utilize shielded material (i.e. fused quartz silica blocks) with electronics located outside radiation area
- Primary tradeoff is weight
- Throughwall devices have significant cost of ownership benefits, but high capital

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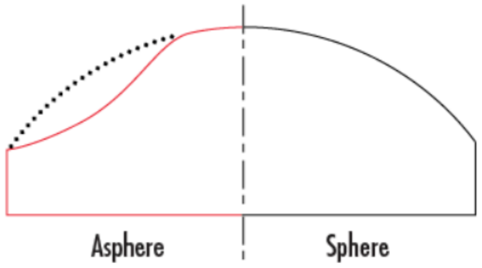
Shielding

- Shielding is not as simple as placing a camera in the center of high-Z material
- The camera is often directed at the source for most of its useful acquisition
- Requires either
  - Shielded optical components (i.e. fused quartz silica blocks
  - The camera to self shield by “turning around”
  - A “pop out” camera
- If moderate to high radiation source is neutron, require hydrogen shield material (i.e. poly)
- High energy Beta consider x-ray production

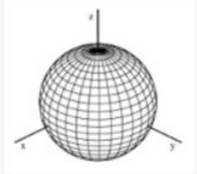
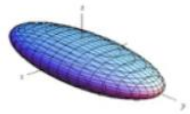
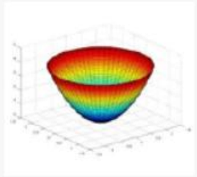
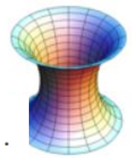
Cost and Weight

Optics

Optics



- The lens is often the mostly costly portion of a camera
- Compact optics can be manufactured using aspheric lens design techniques
- High volume is normally produced through a combination of molding and polishing
  - Materials are not typically radiation stable
  - Typical of “block” imagers and cell phones
- Low volume requires precision micro-polishing one lens at a time

Conic Constant	Conic Surface	
$k = 0$	Sphere	
$k > -1$	Ellipse	
$k = -1$	Parabola	
$k < -1$	Hyberbola	

$$Z(s) = \frac{Cs^2}{1 + \sqrt{1 - (1+k)\,C^2 s^2}} + A_4 s^4 + A_6 s^6 + A_8 s^8 + \ldots$$

Where:

Z: sag of surface parallel to the optical axis

s: radial distance from the optical axis

C: curvature, inverse of radius

k: conic constant

$A_4,\ A_6,\ A_8,\ \ldots$: 4th, 6th, 8th... order aspheric coefficients

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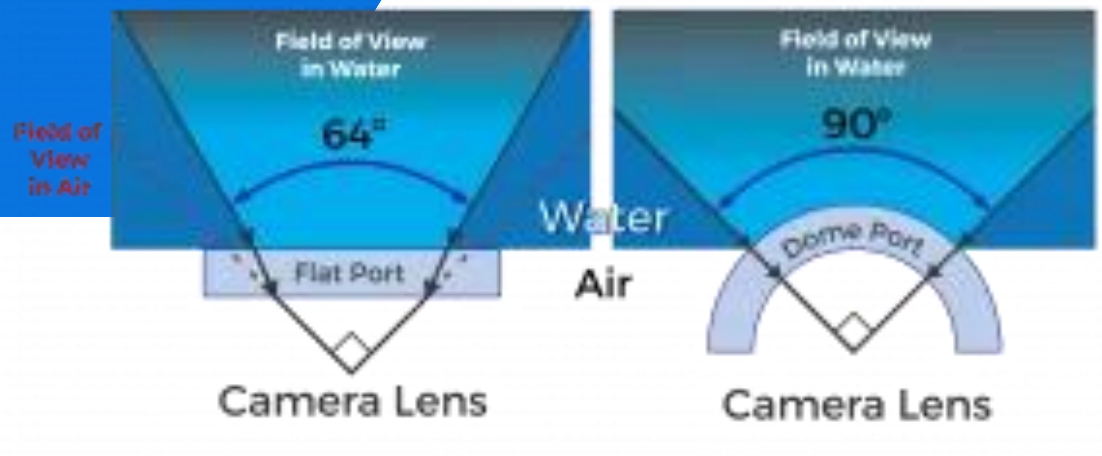
Optics – Radiation Impacts Design

- Radiation tolerant lens materials
  - Limited range of refractive indices
  - Result in larger lenses (particularly zoom)
- Non-browning
  - Typically achieved through Cerium Oxide doping
  - Non-color corrected lenses appear brown and reduce the response to blue light
  - Color corrected non-browning lenses can be produced, but are often higher cost
- Limited materials often result in larger optics

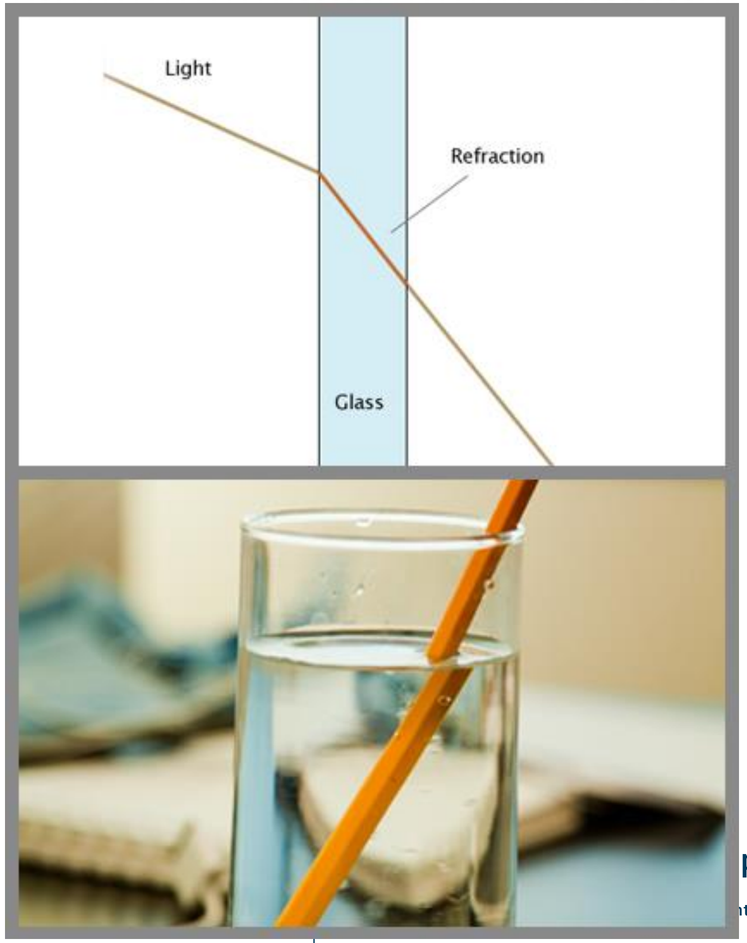
Optics – Radiation Impacts Usage

- Radiation induced discoloration caused by impurities and amorphous non-crystalline structure of the glass
- Multiple lens elements in a single lens resulting in significant reduction of light
- Also impacts lenses on the front of lights
- Impacts micro lenses on LEDs
- Some plastic coated reflectors can deteriorate as well

Optics – Imaging Underwater



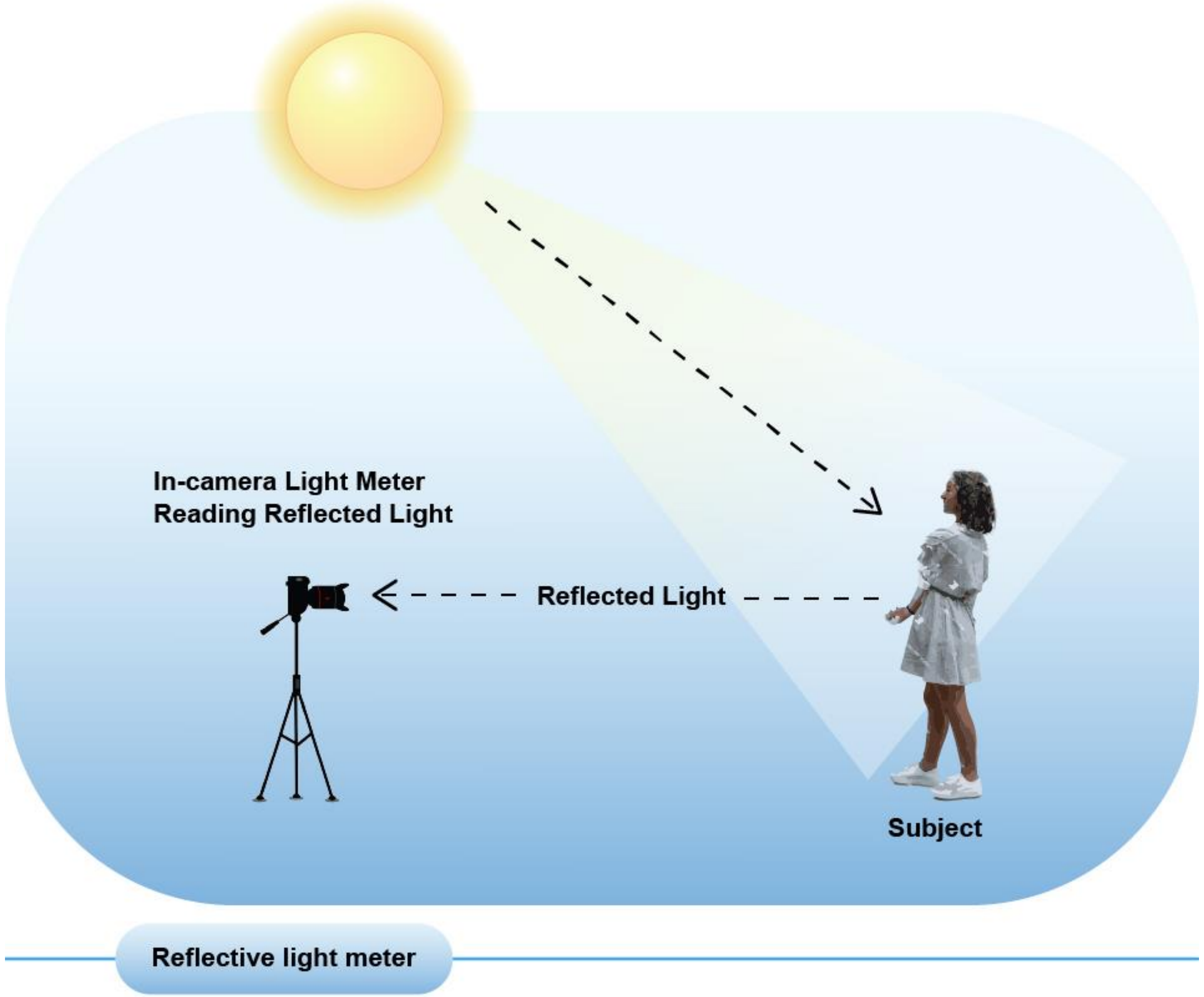
- When using a camera underwater, it is important to remember that the refractive index is different
- The angle of view will be different
  - Typically 1.33x for radiation stable windows
  - Must be considered when choosing lens focal length for use underwater
- Windows that are "shaped" to adjust for the change in refractive index can be manufactured (water corrected window)
- Water corrected windows will distort images when used in air



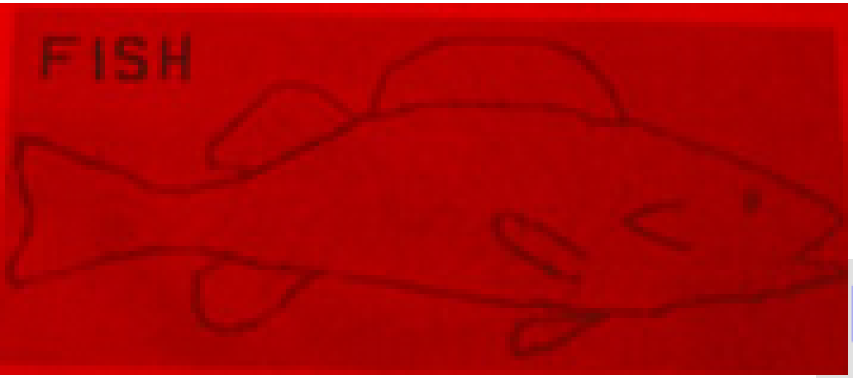
Lighting

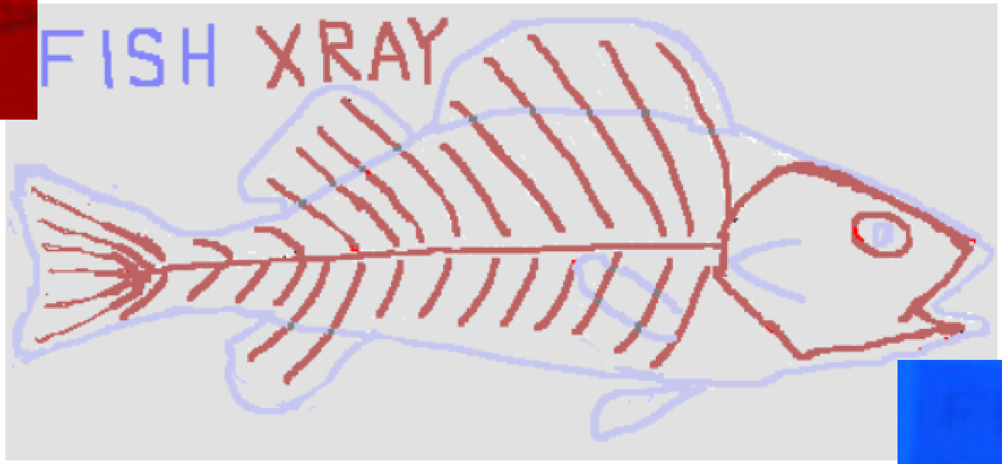
Lighting Physics

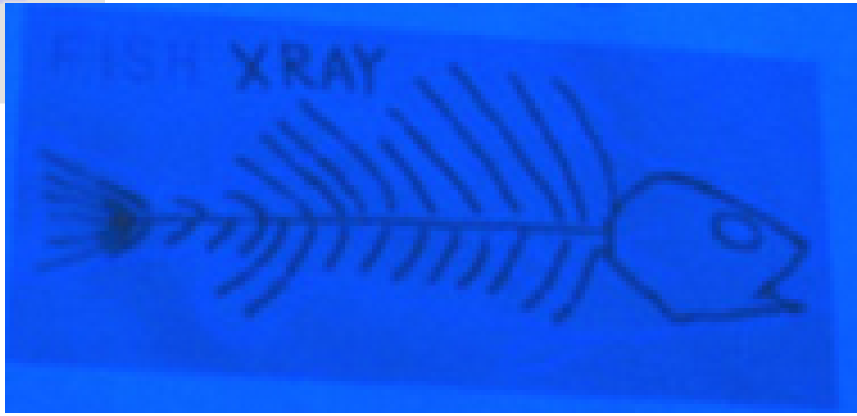
- Cameras image reflected light
- Can aid in dusty or turbulent environments if the light is closer to the object of interest (need only transmit one direction)
- Polarizing filters can assist with glare – remember result in ~1.5 stop reduction



Lighting Filters, Color, and Contrast







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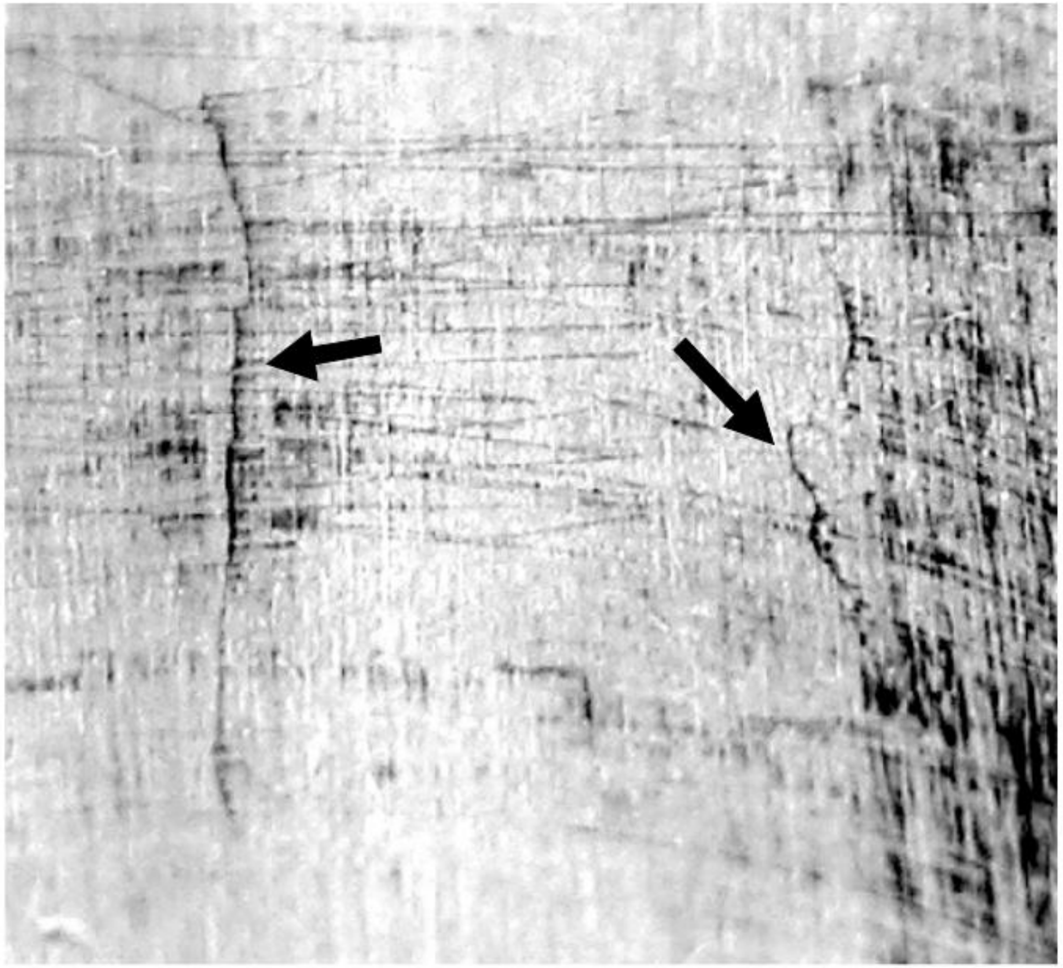
Lighting Filters, Color, and Contrast

- Intended as an extreme example, but…
- Simple filter changes for highlighting
  - Heat effected zone
  - Oxidation/formation
  - Area of interest
- Suppression of background information
  - Show anything that's unexpected
  - Particularly good for leak detection
  - Speeds process of assessment

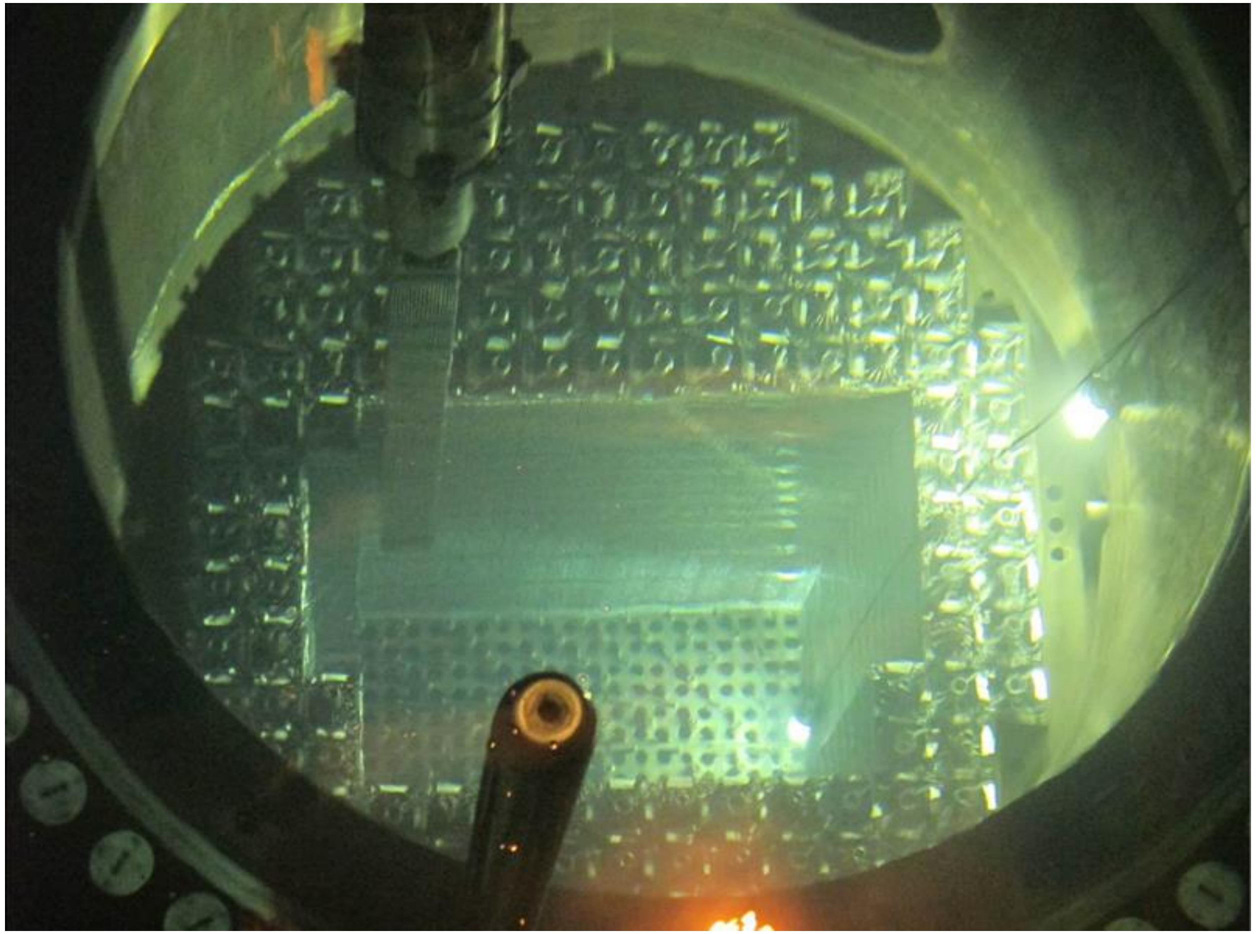
Lighting Angle

- In line lighting beneficial for:
  - Compact deployment areas
  - Minimal high reflective surfaces
- Offset angle lighting beneficial for:
  - Highlighting depth of any imperfections
  - Providing an alternate "view" without re-positioning the camera
  - Ideally independent control
- Offset lighting highlights crack paths
- Just above right arrow, however, "hides" lateral portion of crack migration



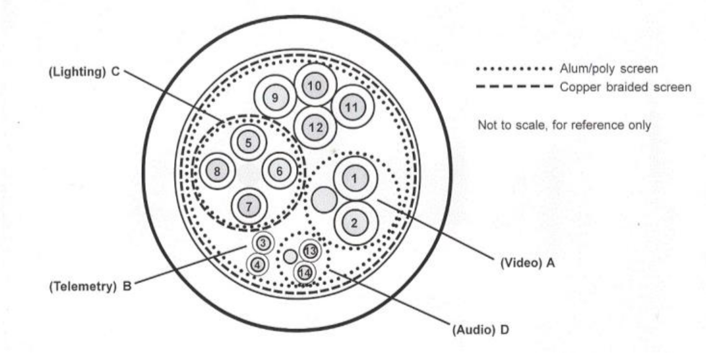
Access

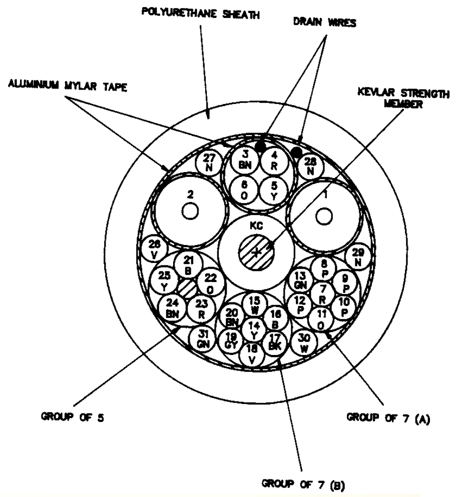
How Do You Deploy and Retrieve

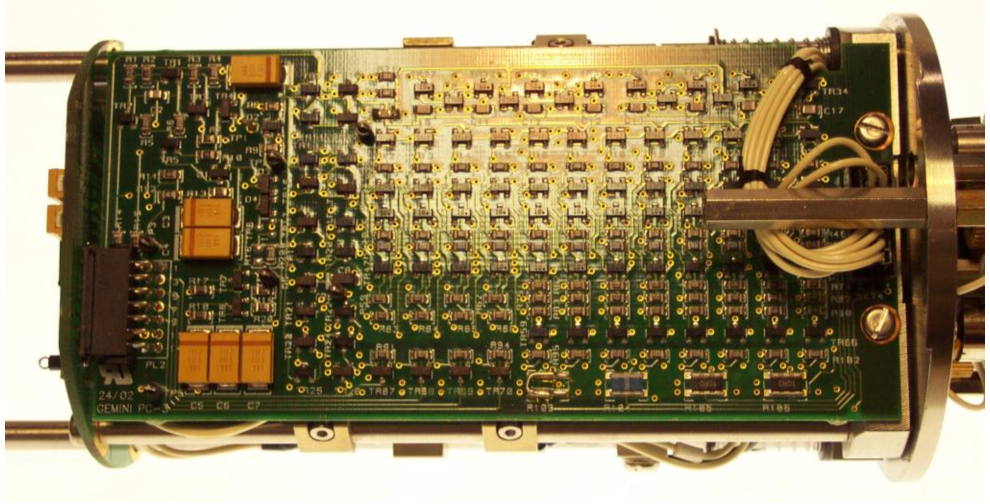


- Some camera deployments are well known, well planned, and well optimized
  - Reactor inspection underwater deployed from the refuel bridge
  - Linear accelerator treatment vault
- Others are more difficult
  - Limited access hot cell with air lock telemanipulator positioning
  - Limited access glovebox without cabling support
- ALL cameras are sacrificial in radiation

Connectivity







- Through wall penetrations
- Dog leg penetrations
- Telemanipulator connectors
- Complex cables v. radiation tolerant telemetry
- Distance of cabling v. degradation

- Wireless can be a consideration
  - most wireless transmitters are very susceptible to radiation damage
  - power is still required

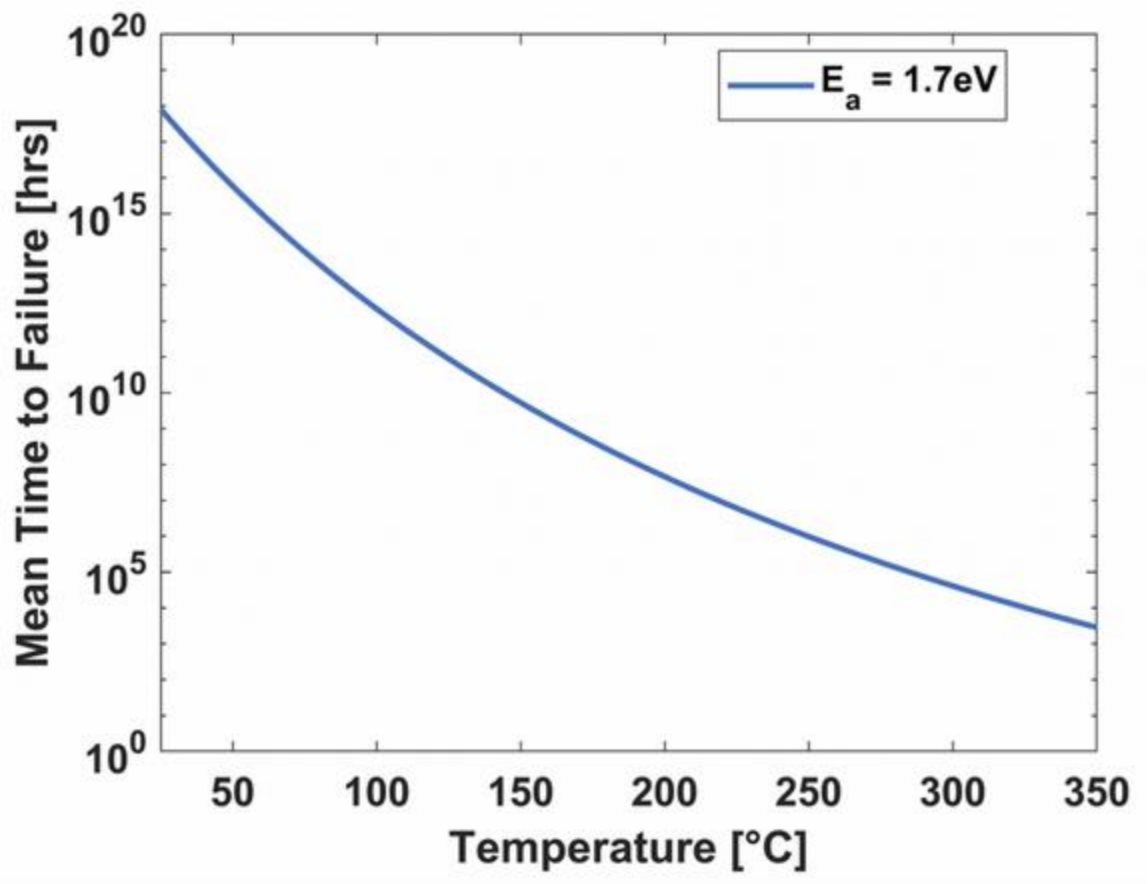
Deployment/Retrieval

- Decontamination
  - In air
  - Underwater
  - Fixed v. removable
- Activation of materials (dependent on deployed environment)
- Serviceability of camera v. discard
- Lifting hooks, lifting eyes, telemanip grip handles
  - Often hotcell equipment dependent

ALARA always a consideration

Temperature

Temperature – Imaging Impacts

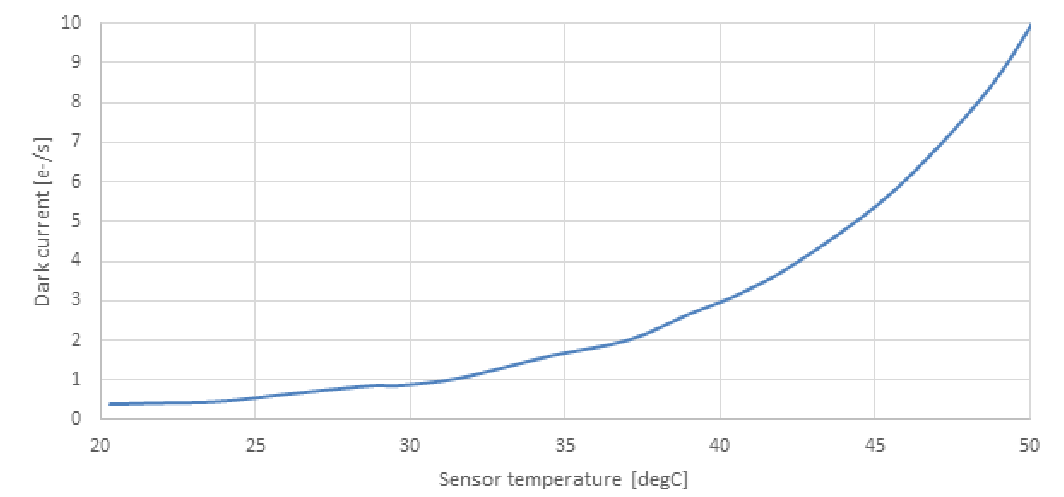


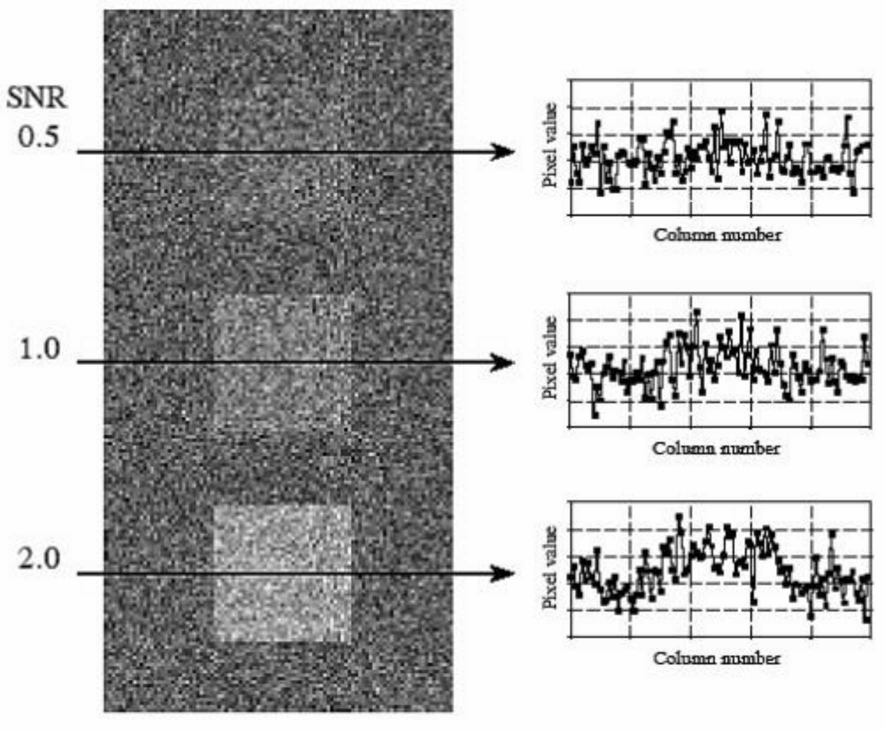
Arrhenius Equation Graph

- Elevated temperature provides several challenges for all cameras
- Component life is shortened
- Many cameras are packaged in stainless steel (15 watts per kelvin per meter)
- General rule of thumb remains 50% reduction in lifetime for every 10˚C rise when discussing semiconductor devices
- Lighting can "self heat" and add to the thermal sources

Temperature – Imaging Impacts

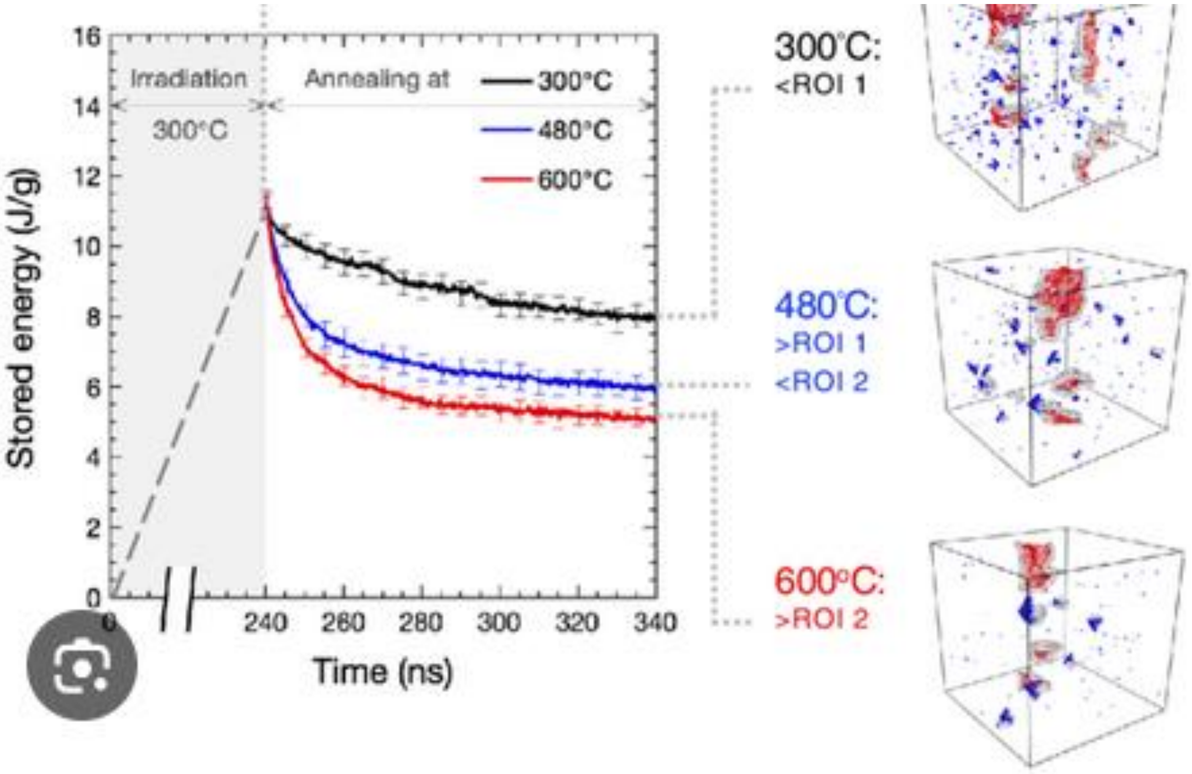
- As temperatures increase in the imaging detector (tube or digital device), the dark current will rise
- Effectively this amounts to a decrease in the signal to noise ratio
- Result to the operator is a decrease in the scene contrast
- At the extreme, the image will appear all "grey" in response with no discernible image
- Why do I care: operating during a LOCA event, a process event, or early images during shutdown





Temperature – Radiation Impacts

- Ordinary optical is not stabilized and will "brown" in a radiation field
- The type of radiation is of little consequence
- Radiation damage is apparent in many IC devices
- The suggested mechanism is charge trapping gate oxide around the impurity centers
- BOTH of these types of damage are reversible through annealing

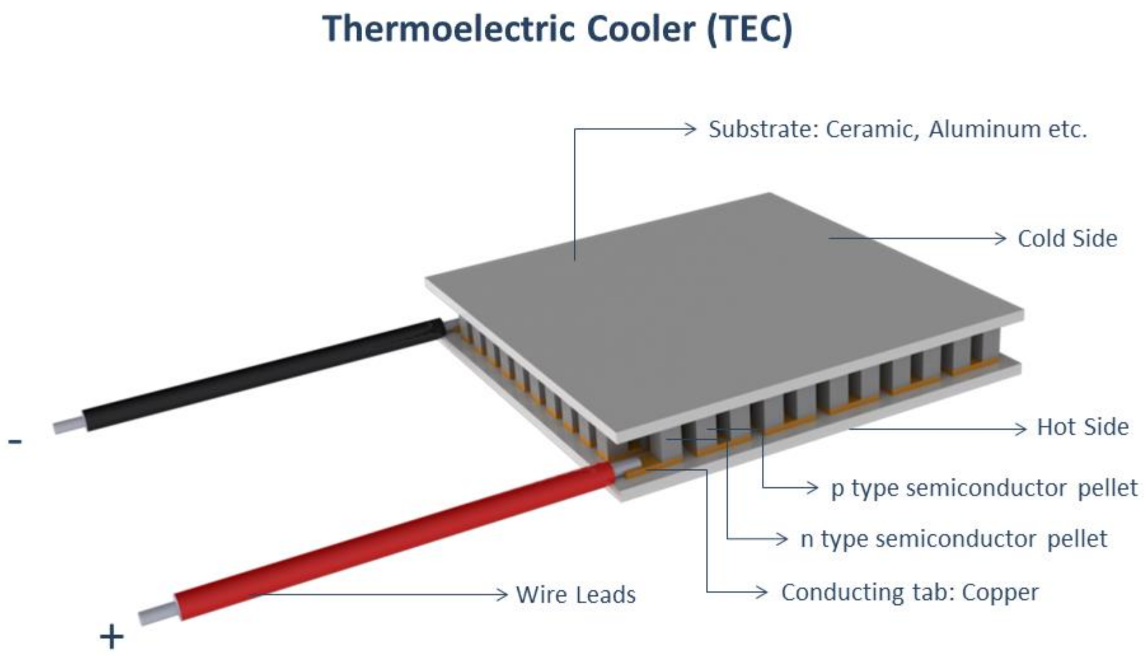


Temperature Benefits

- Annealing is the process of applying an elevated temperature over a period of time
- There are some commercial cameras marketed on this premise
- Online annealing has challenges, however
  - No image is able to be obtained during the annealing cycle
  - A cool down period is required before restart
  - The camera must be positioned in a safe area with allowable elevated temperatures
  - Heating requires power (supplies and conductors)

Temperature Benefits

- Additional design considerations can allow for elevated temperature operations without significant dark current impacts
- Active cooling via a Thermal Electric Cooler or a Stirling Engine have been utilized
- Air cooling/gas cooling have been employed for the protection of optics and dark current
- If protecting from a transient temperature event (i.e. loss of coolant accident)
  - Stainless steel housing is a benefit
  - Thermal mass of areas near the imager
- Water is 23.5x more efficient at transferring heat



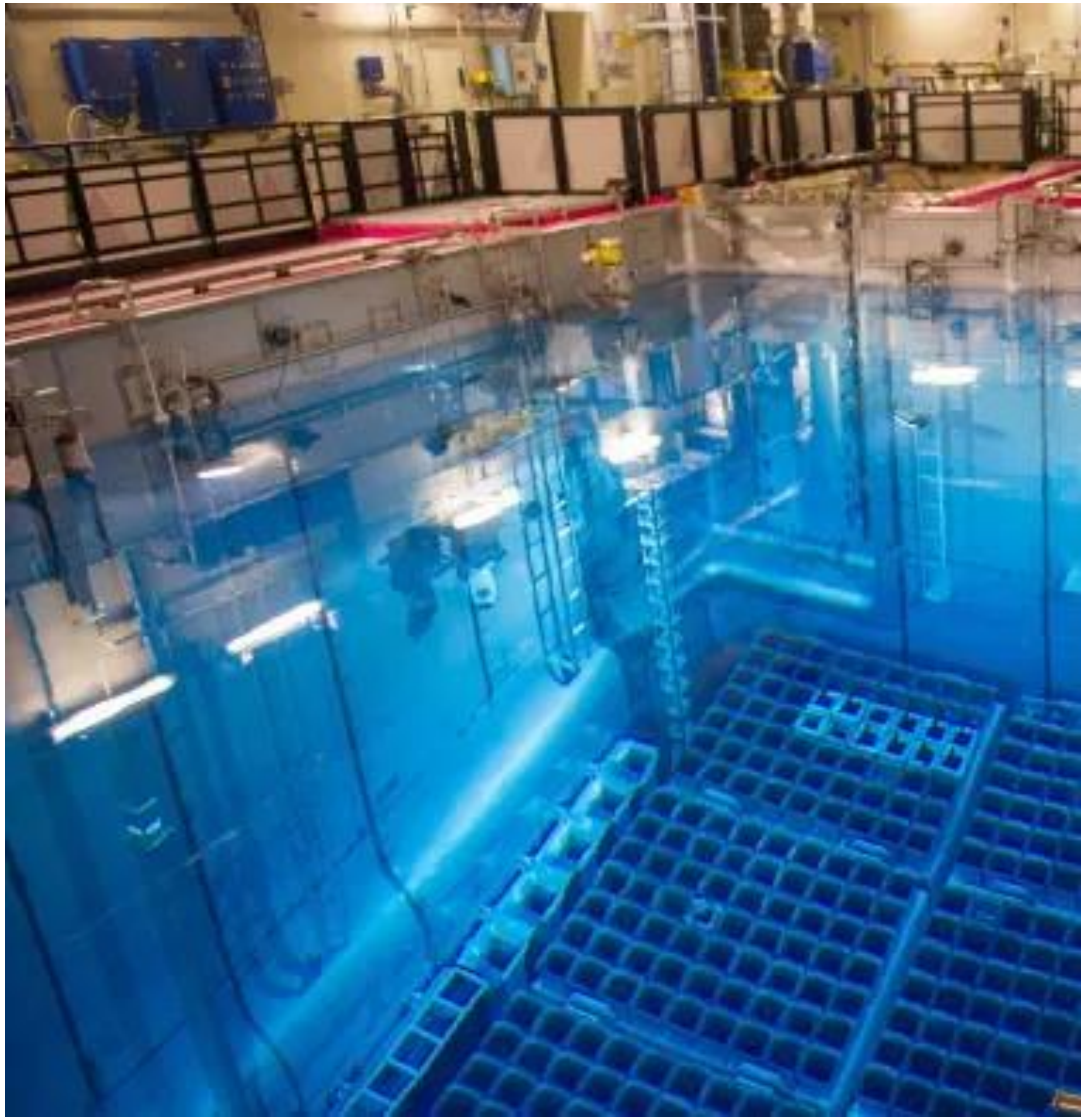
Closing Thoughts

Closing Thoughts

- **Five Questions to ask:**
  - What do you want to see?
    (or, sometimes – What don't you want to see)
  - Expected Dynamic/Cumulative Dose (how much of what and how long)
  - How are you going to get the camera in/out
  - Existing cabling, penetrations, access to the signal
  - What do you want in your control room or operator station and where else do you want to view/archive the video

The questions are easy, the answers are hard

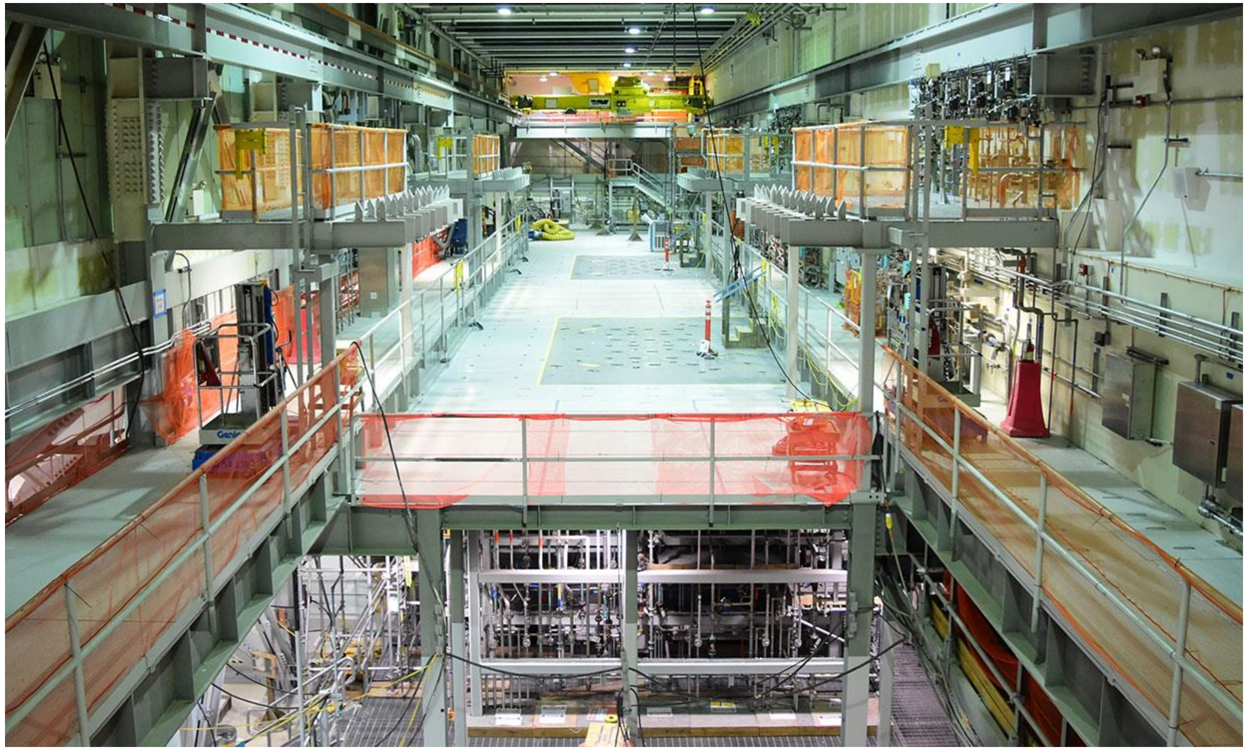
Things You Might Not Know…



- Almost all nuclear cameras are sealed for underwater use (IP68/60m)
- About 30-40% of cameras are customized
  - Based on standard product
  - Most likely changes requested: cable, mounting, connector
- Radiation levels is the easiest way to start choosing (once the tradeoffs are understood)
- Most all radiation tolerant cameras are designed to be readily serviced/reused
- People rarely know what they want to see

Closing Thoughts

- Consider Time, Distance, and Shielding for your cameras in conjunction with what you want to see
- Can utilize optics, camera types (high rad v. low rad), and deployment/retrieval considerations to optimize costs
- Always consider that cameras in a radioactive environment are sacrificial
- Choice of camera needs to also consider facility and operational costs



Thank you