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Calcine Retrieval Project

June 2022
CRP Technology
Radiation Testing Report

Kevin L. Young

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SUMMARY

On June 1, 2, 6, and 7, 2022 Calcine Retrieval Project engineers completed radiation tolerance testing on four targets: 1) Elios 3 confined space inspection drone, 2) iSHOT weld observation camera, 3) LED light module, and 4) several EPDM U-cup seals. The purpose of the radiation testing was to help ensure these components will function as intended when exposed to radiation fields during calcine retrieval operations. All testing occurred at the Idaho Accelerator Center on the Idaho State University campus in Pocatello, Idaho using a high-powered 450keV X-ray tube to generate the ionizing radiation fields.

The drone, weld camera, and LED module were irradiated while operating to evaluate their performance while exposed to varying radiation field strengths. An employee from Flyability, the drone vendor, was onsite during the drone testing to pilot the drone and provide technical assistance as needed.

All targets except for the EPDM U-cup seals exceeded minimum radiation tolerance test objectives. The drone operated successfully in a 10,000 R/h with up to 4,000 R of accumulated dose after which a fault with the drone’s on-board computer prevented further testing. The minimum test objectives for the drone required successful operation in a 1,000 R/h field with an accumulated dose of 1,000 R. The iSHOT weld camera operated successfully in a 2,000 R/h field with up to 7,119 R of accumulated dose and did not fail. The minimum test objectives for the iSHOT camera required successful operation in a 2,000 R/h field with an accumulated dose of 6,000 R. The LED module operated successfully in a 91,700 R/h field with an accumulated dose of at least 241,969 R and did not fail. The minimum test objectives for the LED module required successful operation in a 2,000 R/h field with an accumulated dose of 2,000 R.

Test objectives for the EPDM U-cup seals were to irradiate four packages of two seals each to dose levels of 1,000,000 R, 5,000,000 R, and 10,000,000 R, and 50,000,000 R and then have those seals functionally tested with results compared to a set of non-irradiated seals. Available testing time only allowed for each package to be irradiated to an average dose of 584,721 R. These seals will be subjected to additional radiation dose in future rounds of testing.

Based on test results, the Elios 3 drone, iSHOT weld camera, and LED light module for the surface cleaning tool are all considered acceptable for use in calcine retrieval operations. Additional radiation testing and performance evaluations on the EPDM seals must be completed before these seals are considered acceptable for use in calcine retrieval operations.

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ACRONYMS

Ø	Diameter
3D	Three-Dimensional
ANSI	American National Standards Institute
CRP	Calcine Retrieval Project
CSSF	Calcined Solids Storage Facility
D to S	Distance-to-Source
EPDM	Ethylene Propylene Diene Monomer
Gy	Gray
Gy/h	Gray per Hour
H	Hour
HD	High Definition
IAC	Idaho Accelerator Center
IEC	Idaho Environmental Coalition, LLC
keV	Kilo Electron Volt
kg	Kilo gram
LED	Light Emitting Diode
LiDAR	Light Detection and Ranging
R	Roentgen
R/h	Roentgen per Hour

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1. INTRODUCTION

The Calcine Retrieval Project (CRP) team at the Idaho National Laboratory recently completed radiation tolerance testing on four targets.

1. A confined space inspection drone.

2. A weld observation camera.

3. An LED light module.

4. EPDM U-cup seals.

All these components are intended to support the CRP mission of removing granulated calcine, a high-level waste, from storage bins at Calcined Solids Storage Facility 1 (CSSF-1). The purpose of the radiation testing was to help ensure these components will function as intended when exposed to radiation fields during calcine retrieval operations.

Calcine is a granular byproduct of a process called calcining used at the site from 1963 to 2000 to convert high-level radioactive liquid waste from spent nuclear fuel reprocessing to a stable solid. It is stored in large stainless-steel bins inside six concrete vaults known as bin sets at the Idaho Nuclear Technology and Engineering Center. The team is tasked with transferring approximately 220 cubic meters of material from an old bin set to a new one and closing the old bin set under the Resource Conservation and Recovery Act.

2. EXPERIMENTAL DETAILS

All radiation testing occurred at the Idaho Accelerator Center (IAC) in Pocatello, Idaho using a high-powered X-ray generator to irradiate the components. Testing occurred over four days. The high-level testing schedule is shown in Table 1 below.

Table 1. High-level radiation testing schedule

			Thursday, 19 May
			Test Prep. PTZ camera, range extender, support stand. (IEC and IAC only)
Wednesday, 1 June	**Thursday, 2 June**	**Monday, 6 June**	**Tuesday, 7 June**
Elios 3 Drone Testing Flyability on site. LED Module Testing EPDM Seal Testing	Elios 3 Drone Testing Flyability on site. LED Module Testing EPDM Seal Testing	iSHOT Camera Testing LED Module Testing EPDM Seal Testing	iSHOT Camera Testing LED Module Testing EPDM Seal Testing

2.1 Test Facility

The Idaho Environmental Coalition (IEC) contracted with the IAC to provide the facility and ionizing radiation source needed to conduct the testing. The IAC is a unique research facility operated by Idaho State University located in southeast Idaho. It provides opportunities for scientists and engineers from the University, the private sector, and the national laboratories to utilize specialized nuclear facilities. It serves as a principal investigating conduit for research and development in nuclear physics applications in materials science, biology, homeland and national security. Testing CRP components at the IAC using an X-ray generator is more convenient, cost effective, and safer than testing with ionizing sources.

Figure 1 shows CRP engineer Kevin Young and Flyability drone vendor Gaël Brésolin preparing the Elios 3 drone for radiation testing inside the X-ray vault at the IAC.

Figure 1. Kevin Young (IEC) and Gaël Brésolin (Flyability, Inc.) preparing the Elios 3 drone for radiation testing at IAC

2.2 Radiation Source

Ionizing radiation was produced using a water-cooled Yxlon MGC41 450keV constant potential X-Ray generator capable of operating at a maximum power settings of 10mA at 450keV and is shown in Figure 2. The 450keV X-ray generator produces gamma radiation with an energy level comparable to that of the primary gamma energy level in the calcine which is 662keV.

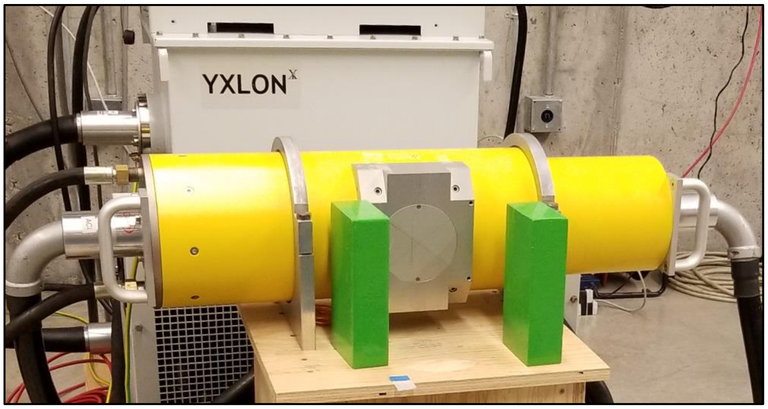

Figure 2. 450keV X-Ray generator used to produce ionizing radiation for testing

The X-ray source and radiation targets are safely controlled and monitored from the primary control room at the IAC. The IAC X-ray vault control room is shown in Figure 3.

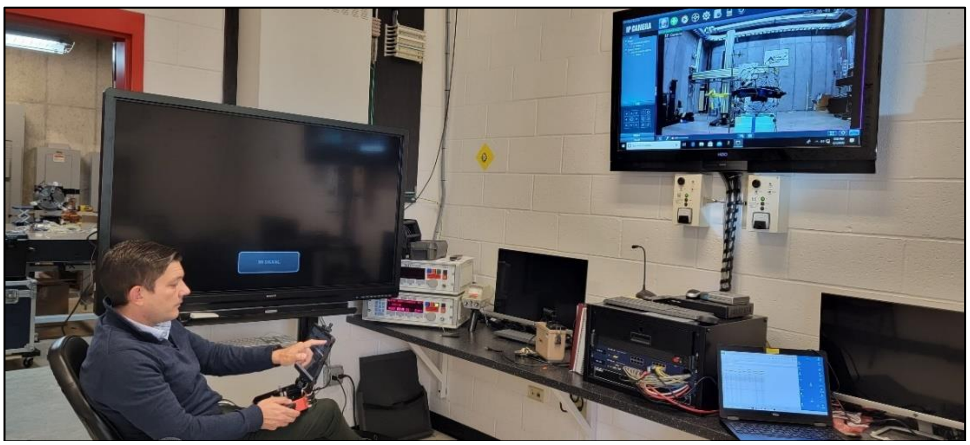

Figure 3. IAC X-ray vault control room

The cone angle of the beam in the horizontal plane was approximately 40 degrees. Changes in dose rate were accomplished by adjusting the distance between the X-ray generator and the targets. Based on the 40-degree angle of the cone and an operating power of 450keV at 10mA, a calculated dose rate and target size versus distance-to-source chart is represented in Figure 4.

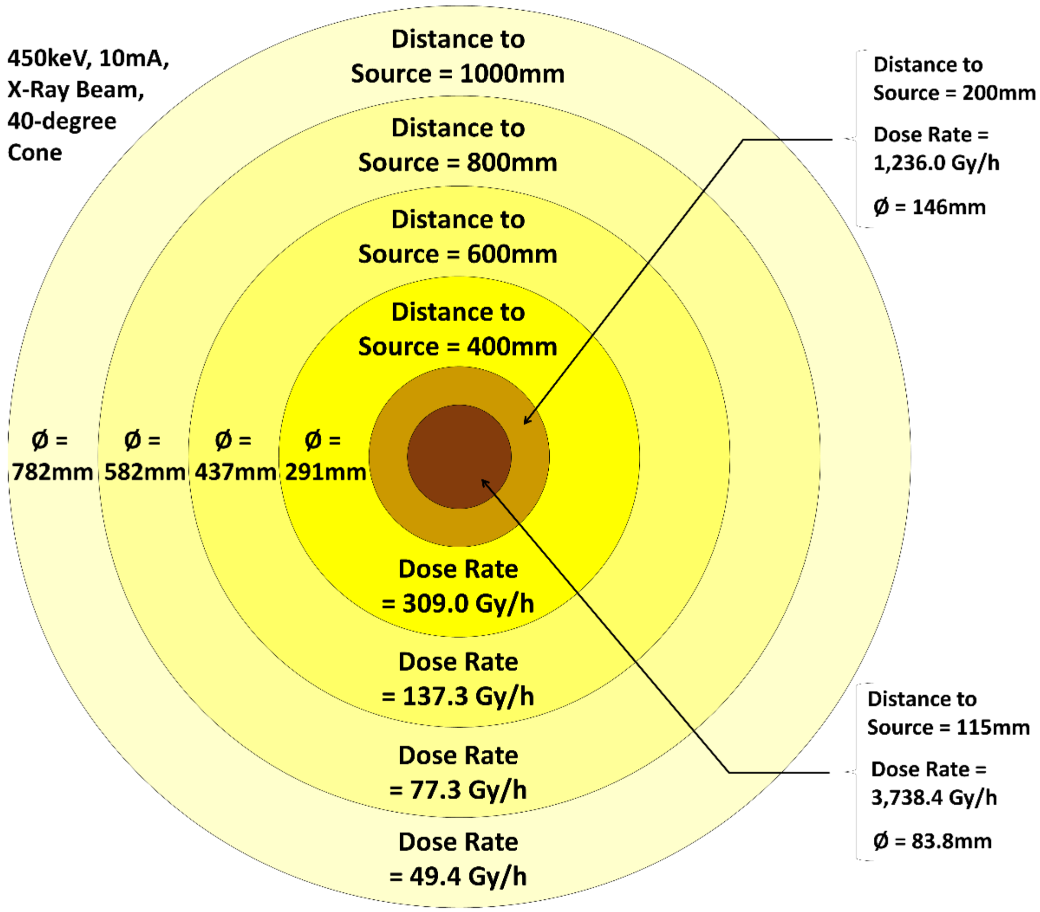

Figure 4. Chart depicting dose rate versus distance to source for 450keV X-ray generator

2.3 Radiation Targets

As indicated in the Introduction above, four different CRP components were irradiated during this round of radiation testing at the IAC.

1. Elios 3 drone, by Flyability.
2. iSHOT weld camera, 625-HD, by Intertest.
3. surface cleaning tool LED light module, SP-01-T9 ANSI white, by Luxeon Star LEDs.
4. EPDM U-cup seals, 6226-16 U-Cup Seal EPDM 70, by www.theoringstore.com.

A brief description of each target and how it is intended to be used during calcine retrieval operations is provided below.

2.3.1 Elios 3 Confined Space Inspection Drone

The Elios 3, made by Flyability, is a 2.5kg ducted fan quadrotor drone contained in a protective cage that is roughly 50cm in diameter. The protective cage enables the drone to tolerate collisions without damaging critical components. The drone is equipped with the OS0-32 Beam Sensor light detection and ranging (LiDAR) unit from Ouster and a 12.3-megapixel image sensor optimized for low light. A custom, highly reactive control system, allows the drone to recover quickly from collisions without a loss of stability. The combination of these two technologies enables the Elios 3 to operate in confined and cluttered environments without risk to the drone structure. Elios 3 has been operated underground on multiple occasions including in caves and mines. The use of an optional, remote antenna which is lowered into the underground flight area allows for reliable wireless communication and flight control during the mission.

Prior to retrieval operations, the Elios 3, drone equipped with LiDAR, will be used to create a 3D map of all obstructions above the bin set within the CSSF-1 storage vault. This 3D map is necessary for accurately placing the calcine retrieval equipment.

The drone will launch above ground and be remotely piloted down into the CSSF-1 vault area where it will collect the LiDAR data necessary to build the 3D map of obstructions. The estimated flight paths will take the drone to each of the four corners of the vault at a height of approximately three feet above the tallest bin top. The drone will then return up and out of the vault to its original launch location. The worst-case radiation field the drone will encounter is expected to be 2,000 R/h at the surface of the storage bins. It is estimated that up to three 6-minute flights will be required to collect all the necessary data. Drone flights are limited to 6 minutes of flight time due to battery limitations. Figure 5 shows the Elios 3 drone and the intended flight path into and out of the CSSF-1 vault.

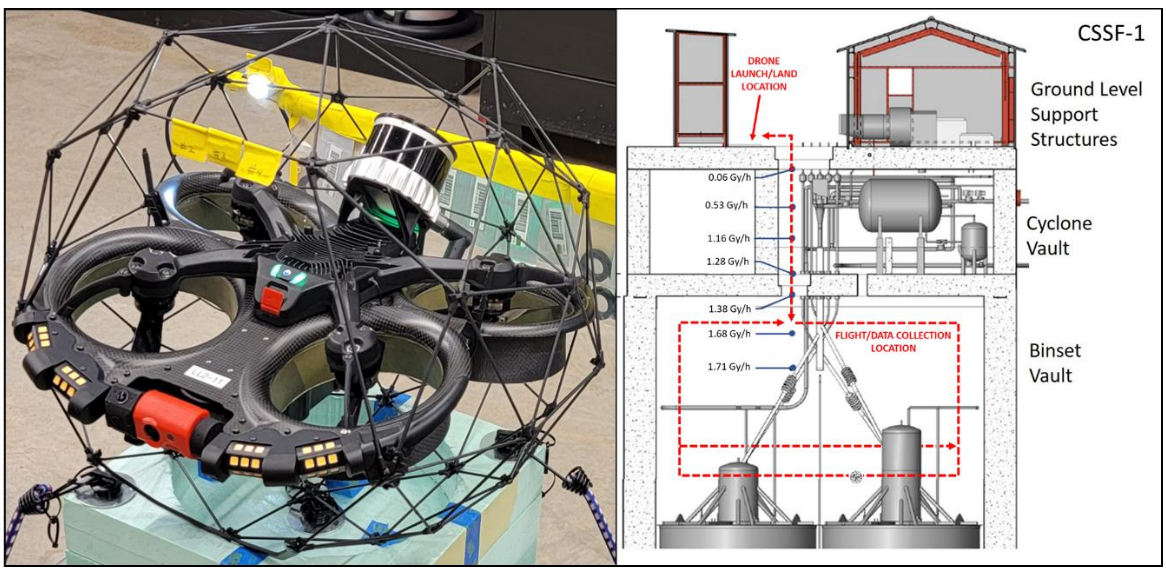

Figure 5. Flyability Elios 3 inspection drone with LiDAR (left) and proposed drone flight path within CSSF-1 vault (right)

Engineering position paper M-1509, *CRP CSSF-1 Vault Mapping Technology Position Paper* [1] and engineering report RPT-1988, *CRP Retrieval Project FY2021 Inspection Drone Demonstration Test Report* [2] document the decision-making process for identifying a drone as the best method for collecting the 3D data from the CSSF-1 vault and for selecting the Elios series of drone by Flyability as the best drone for this application.

2.3.2 iSHOT Weld Camera

The iSHOT weld camera, from Intertest, is designed to provide remote viewing of welding operations and the ability to conduct remote, visual inspection of welds. The camera head and lamp will be part of a custom designed robotic welding machine. The calcine removal process includes robotic welding of twenty-foot long, 8-inch diameter steel pipes to the top of the calcine storage bins. The expected worst-case radiation field at this location is 2,000 R/h. It is estimated to take approximately 20-minutes to complete a robotic weld and visual inspection. Figure 6 shows the weld camera head and integrated lamp along with an image captured from the camera view during a mechanical test of the system.

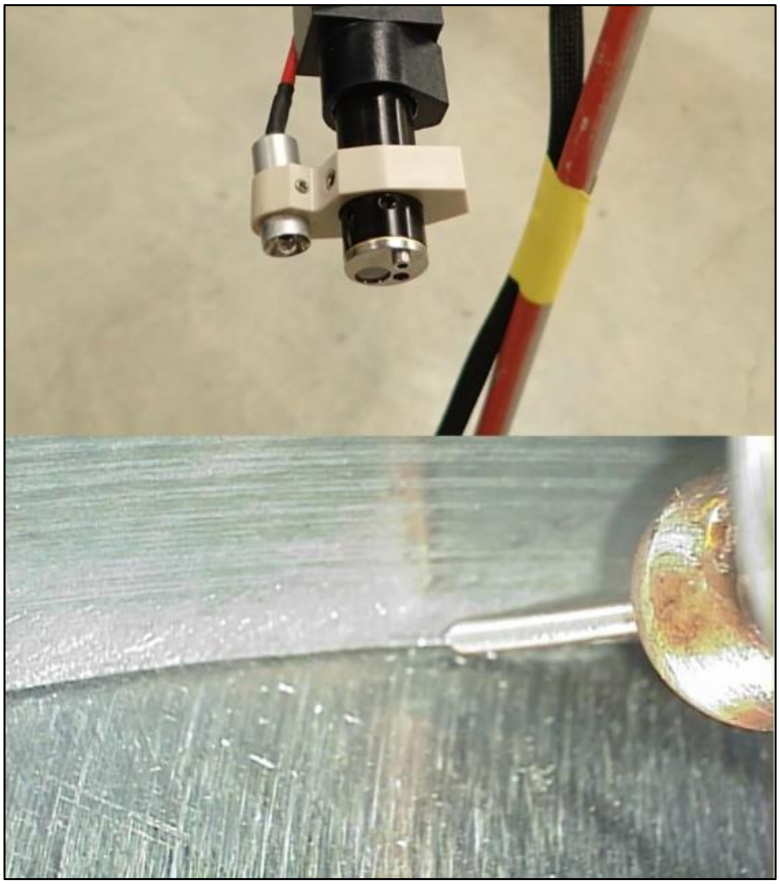

Figure 6. iSHOT weld camera and integrated lamp (top) and pre-weld test image (bottom)

2.3.3 LED Light Module for Surface Cleaning Tool

The robotic welding operation described in the section above will be preceded by a process to clean the surface of the bin top to ensure an acceptable weld. The remotely operated surface cleaning tool includes rotating steel brushes, compressed air nozzles, a camera, and an LED light module. The camera head and light module will allow engineers to remotely view the bin top surface to verify it is clean prior to welding operations. The camera head, made by AXIS, had previously passed radiation testing. But the LED module with the SP-01-T9 ANSI white LED assembly made by LuxeonStarLEDs had not yet passed radiation testing. The estimated amount of time needed to properly clean the bin top surface prior to welding will depend on the condition of the bin surface. It is reasonable to assume the surface cleaning tool may have to operate for three hours to properly clean the bin top surface. It is expected the surface cleaning tool will operate in a worst-case radiation field of 2,000 R/h. Figure 7 shows the LED light module mounted on the surface cleaning tool and an image captured by the camera during a mechanical test of the system.

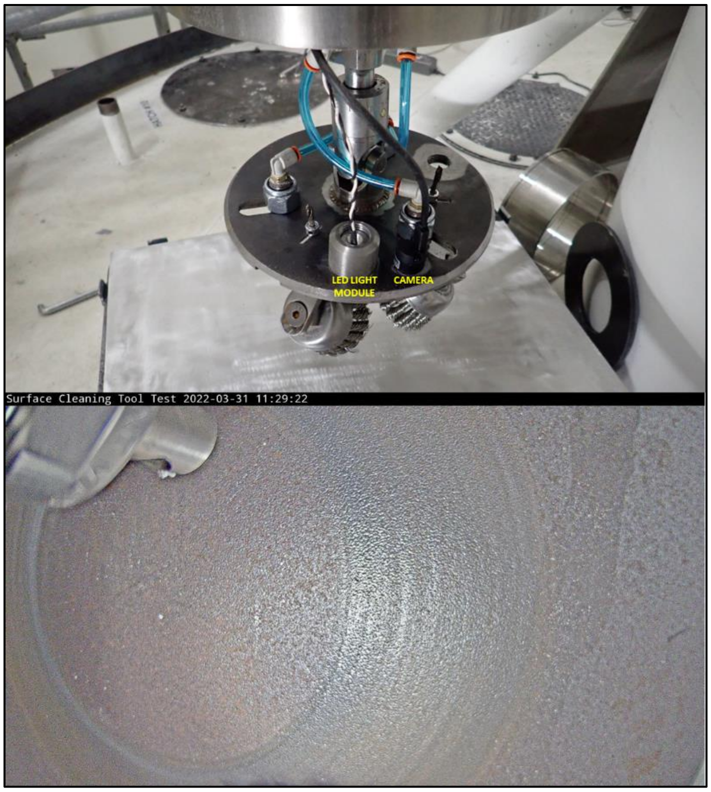

Figure 7. LED light module mounted on surface cleaning tool (top) and image from the camera captured during a mechanical test

2.3.4 EPDM U-cup Seals

The EPDM U-cup seals will be used in custom designed pneumatic equipment used to retrieve the calcine. The seals are a critical component for preventing radioactive calcine material from escaping the pneumatic equipment. Once calcine retrieval operations begin, these seals will be very difficult to replace and must perform properly in radiation fields as high as 2,000 R/h for several months. Figure 8 shows two EPDM U-cup seals with a GAFChromic dosimetry film strip during testing.

Figure 8. Two EPDM U-cup seals with dosimetry film

2.4 Test Objective and Setup

2.4.1 Test Objectives

The primary test objective was to determine if each target continued to function as designed for the given minimum radiation field and with the minimum amount of accumulated dose as listed in Table 2. A secondary test objective was to determine the level of accumulated dose at system failure for the Elios 3 drone and LED light module. The threshold of acceptable image quality for the Elios 3 and iSHOT weld cameras would be determined qualitatively by the CRP team based on the images collected during test.

Table 2. Minimum dose rate and accumulated dose values for test targets

Item	**Model/Manufacturer**	**Quantity**	**Req. Minimum Dose Rate (Rad/hr)**	**Req. Minimum Cumulative Dose (Rad)**
Surface Cleaning Tool LED Module	SP-01-T9 / LuxeonStarLEDs	1	2000	2000 Then Test to Failure
iSHOT Camera and Light	625-HD / Intertest	1	2000	6,000
Elios 3 Drone	Elios 3 / Flyability	1	1000	1000 Then Test to Failure
EPDM Seals	6226-16 U-Cup Seal EPDM 70 / www.theoringstore.com	8	2000	1,000,000 5,000,000 10,000,000 50,000,000

2.4.2 Test Setup

For this testing, the radiation field strength was determined by two factors, the power output of the X-ray generator which was controlled by the current setting for the 450keV X-ray tube and the distance the target was placed from the source. The intensity of the radiation field dissipates inversely to the square of the source-to-target distance. Table 3 provides estimated field strengths at several current settings and source-to-target distances used during testing.

Table 3. Estimated radiation field strength for a given current setting and source-to-target distance

X-ray Tube Current (mA)	**Source-to -Target Distance (mm)**	**Estimated Radiation Field (R/h)**
2.35	1750	440
3.15	1750	590
2.35	1500	600
3.95	1750	739
3.15	1500	800
3.95	1500	1000
7.85	1750	1470
7.85	1500	2000
10.00	1695	2000
10.00	1260	3611

X-ray Tube Current (mA)	Source-to -Target Distance (mm)	Estimated Radiation Field (R/h)
10.00	970	6093
10.00	900	7078
10.00	640	10000
10.00	260	84800
10.00	250	91700

Figure 9 provides a simple layout of how targets were placed in front of the X-ray tube during testing along with the locations of support equipment which was located safely to the side of the X-ray beam.

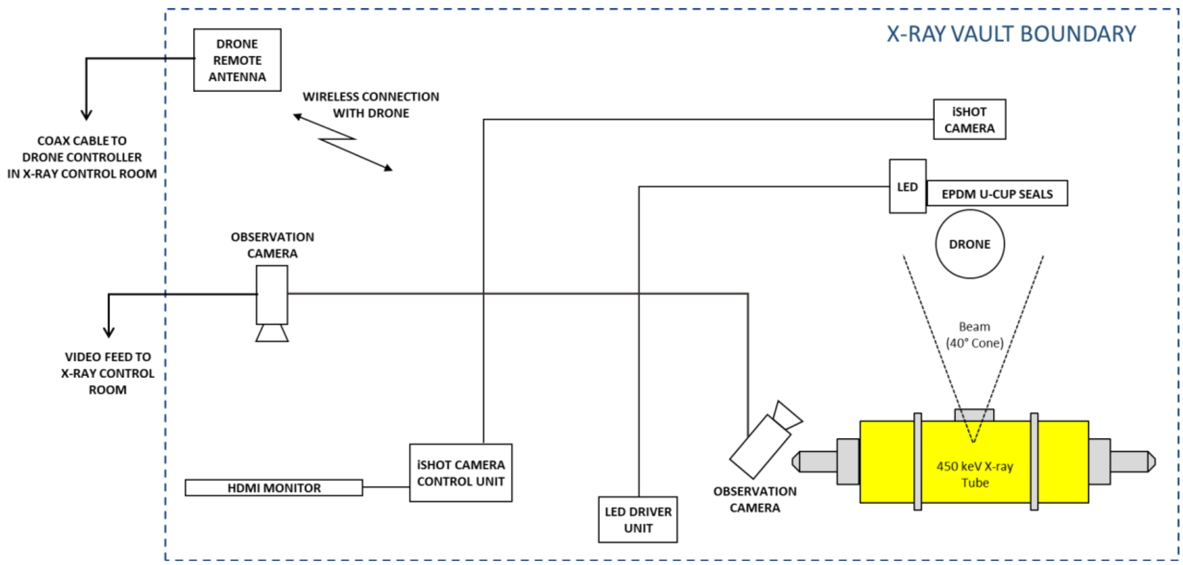

Figure 9. Simplified layout of targets and support equipment for radiation testing

The actual targets are shown in Figure 10 with associated dosimetry film strips.

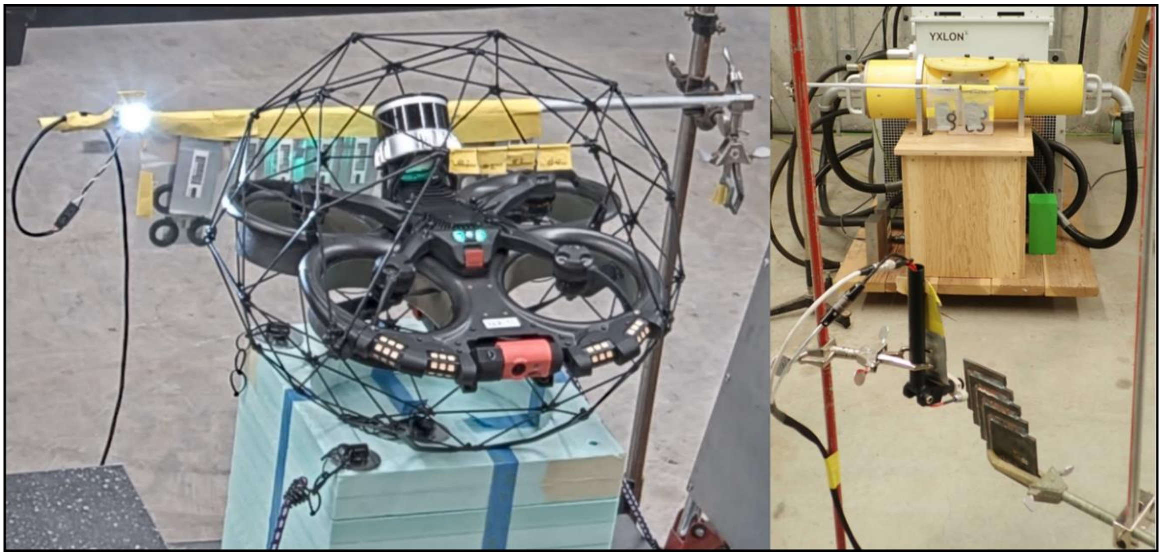

Figure 10. Radiation targets shown with attached dosimetry, Elios 3 drone, LED, and seals (left) iSHOT weld camera (right)

2.4.3 Dosimetry Film

To obtain the most accurate indication of absorbed dose possible for each target, dosimetry detectors were attached to the targets. The two types of dosimetry used were nanoDots by Landauer with a maximum dose value of 1300 R and GAFChromic HD-V2 film strips with a maximum dose value of 100,000 R. Figure 11 shows a closeup view of nanoDots and GAFChromic HD-V2 film.

Figure 11. Dosimetry used during radiation testing. nanoDots (left) and GAFChromic HD-V2 film (right)

3. RESULTS

All targets remained functional at the minimum dose rates and accumulated doses identified in the test objectives. Due to limitations of allotted beam time, the EPDM U-cup seals only received roughly

600,000 R of dose. These seals will be included in a future round of radiation testing to increase the accumulated dose received. Dosimetry readings for the GAFChromic film and nanoDots are provided in Appendix A. Detailed results for each target are given below.

3.1 Elios 3 Radiation Test Results

Per Table 2 above, the Elios 3 drone test objectives were to remain functional in a minimum radiation field of 1,000 R/h and continue to function after an accumulated dose of 1,000 R. Test results indicated the drone successfully operated in a 10,000 R/h field and continued to function after an accumulated dose of approximately 4,000 R, greatly exceeding the minimum test objectives for this target.

When preparing for the second 10,000 R/h irradiated flight, the drone failed to initialize indicating a problem with data storage on the on-board computer (OBC). This error could not be cleared and prevented any further radiation testing on the drone. A detailed assessment by Flyability engineers is planned to determine if this error was caused by radiation or if it was due to some other problem. This OBC error was the only issue observed by the test team. All other systems on the drone, including the LiDAR and high-resolution camera, continued to function as designed.

The drone was subjected to increasing radiation field strengths in a stepped fashion ranging from 600 R/h up to 10,000 R/h. The drone was irradiated while in a controlled hover in line with the X-ray beam. The drone was tethered to ensure it did not damage itself or other equipment in the X-ray vault should a control system failure occur. Figure 12 shows the drone in a controlled hover while exposed to a radiation field of 10,000 R/h.

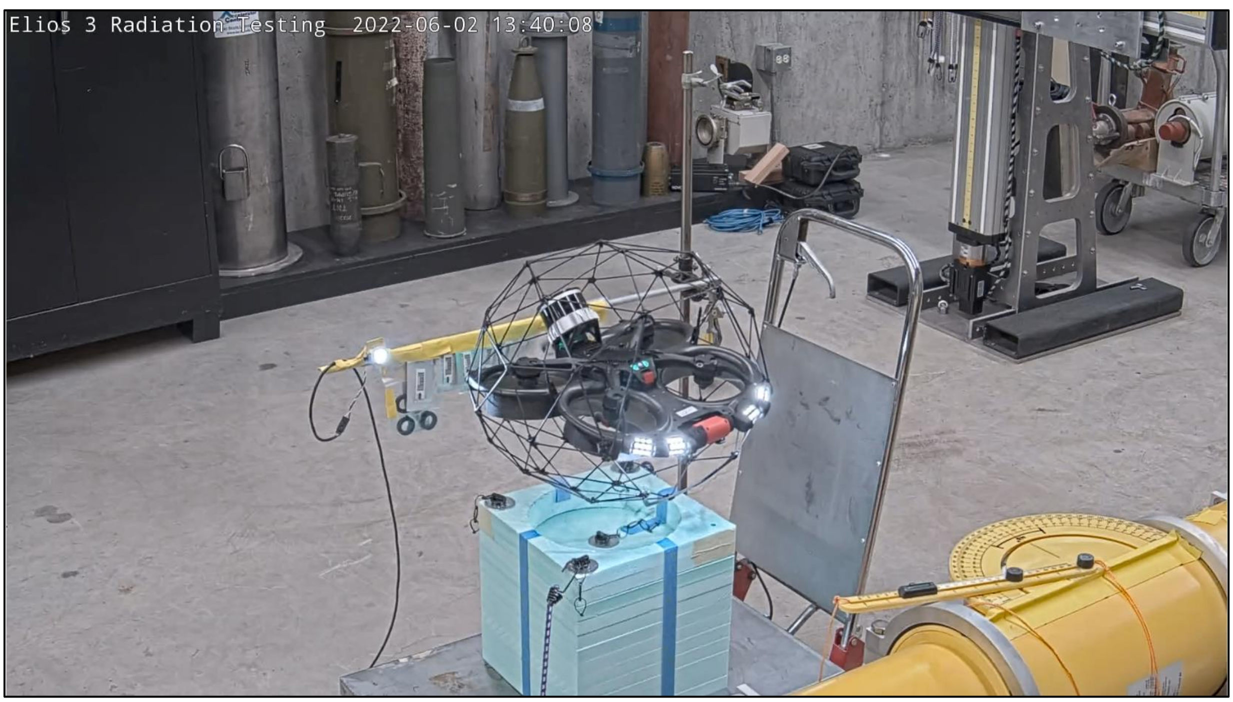

Figure 12. Elios 3 drone in stable flight during a 10,000 R/h radiation exposure

The drone successfully completed 19, six-minute flights while exposed to radiation. During each irradiation, the drone was flown in a controlled hover by a Flyability expert using the ground control station attached to the remote antenna link. During each six-minute irradiated flight the following functions were exercised and/or monitored:

- Visible camera feed.
- Flight control.
- LiDAR function.
- Gimbal control.
- Smart lighting control.
- Transmitter status.
- Battery voltage.

At the end of each six-minute irradiated flight, the X-ray source was shut off. The pilot then landed the drone on the test stand and placed it in standby mode. Test personnel entered the vault and removed the tether from the drone. The pilot then conducted a two-minute test flight within the X-ray vault to verify all systems on the drone were still functioning correctly and to collect LiDAR data. Figure 13 shows the Elios 3 drone conducting a successful, untethered test flight following a six-minute irradiation at 10,000 R/h.

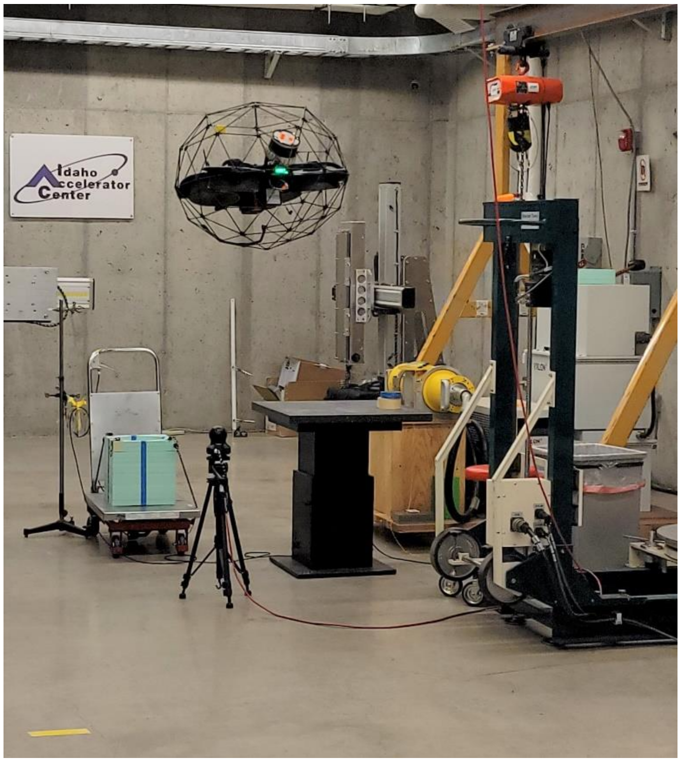

Figure 13. Elios 3 drone conducting a successful, untethered test flight after 10,000 R/h irradiation

After the untethered test flight, the pilot powered down the drone, replaced the battery with a fully charged battery, and downloaded LiDAR, imagery, and flight log data. The drone was then ready for the next six-minute irradiated flight.

Table 4 and the chart in Figure 14 provides a detailed summary of the stepped radiation profile the Elios 3 drone was subjected to. The actual dose values shown are derived from the average value of dosimetry readings placed directly in front of and behind the drone during test. The estimated dose values are calculated using an estimated field strength at a point directly at the center of the drone.

Table 4. Stepped radiation test results for Elios 3 drone

Test Run ID	Target Dose Rate (R/hr)	Duration (mm:ss)	Cum. Time (min.)	X-ray Energy (keV)	X-ray Current (mA)	Source to Target Distance (mm)	Estimated Dose (R)	Estimated Cumulative Dose (R)	Actual Cumulative Dose (R)
0			0					0	0.0
600-1	600	6.00	6.00	450	2.35	1500	60.0	60.0	
600-2	600	6.00	12.00	450	2.35	1500	60.0	120.0	152.4
800-1	800	6.00	18.00	450	3.15	1500	80.0	200.0	
800-2	800	6.00	24.00	450	3.15	1500	80.0	280.0	
800-3	800	6.00	30.00	450	3.15	1500	80.0	360.0	458.5
800-4	800	6.00	36.00	450	3.15	1500	80.0	440.0	
800-5	800	6.00	42.00	450	3.15	1500	80.0	520.0	
800-6	800	6.00	48.00	450	3.15	1500	80.0	600.0	745.8
1000-1	1000	6.00	54.00	450	3.95	1500	100.0	700.0	
1000-2	1000	6.00	60.00	450	3.95	1500	100.0	800.0	
1000-3	1000	6.00	66.00	450	3.95	1500	100.0	900.0	
1000-4	1000	6.00	72.00	450	3.95	1500	100.0	1000.0	1256.3
1000-5	1000	6.00	78.00	450	3.95	1500	100.0	1100.0	
1000-6	1000	6.00	84.00	450	3.95	1500	100.0	1200.0	
2000-1	2000	6.00	90.00	450	7.85	1500	200.0	1400.0	
2000-2	2000	6.00	96.00	450	7.85	1500	200.0	1600.0	2090.0
6000-1	6000	6.00	102.00	450	10.00	970	600.0	2200.0	
6000-2	6000	6.00	108.00	450	10.00	970	600.0	2800.0	
10000-1	10000	6.00	114.00	450	10.00	640	1000.0	3800.0	4778.9

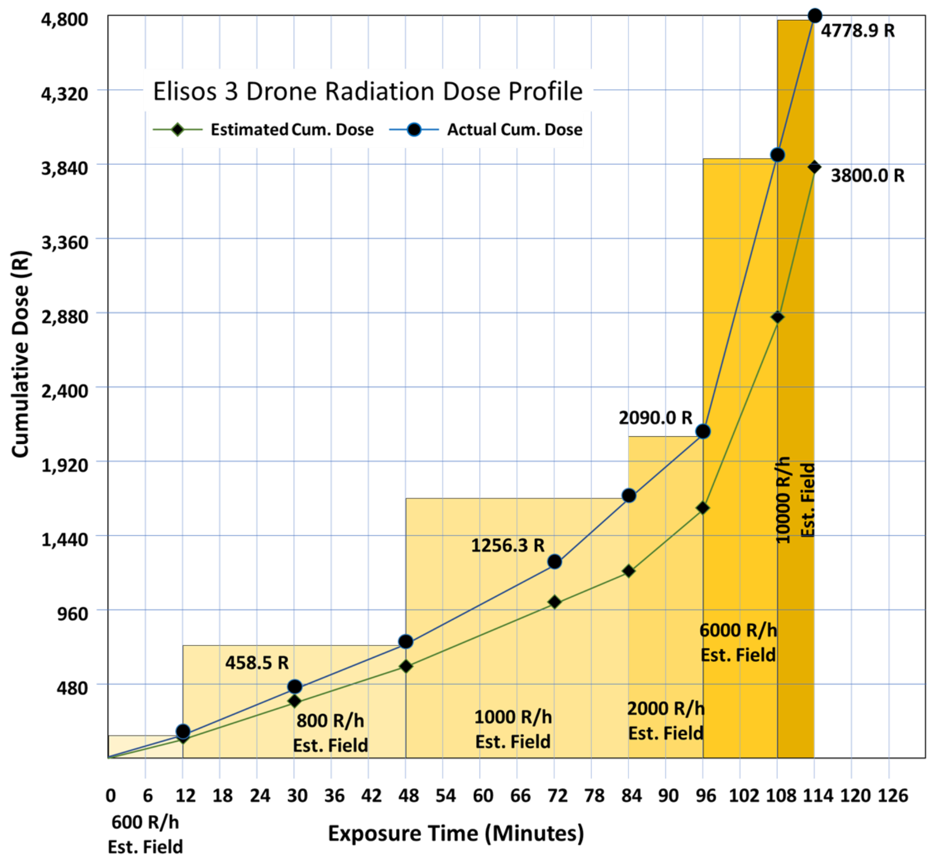

Figure 14. Graph representing the stepped radiation test results for the Elios 3 drone

The downloaded 4K imagery and LiDAR data indicated that these systems performed well throughout the radiation testing profile shown above. Images pulled from the downloaded drone video show an increase in radiation induced noise on the camera sensor as the radiation field strength increased. But, after the X-rays were shut off, there appeared to be no permanent damage to the camera sensor. Figure 15 provides a comparison of drone camera images taken while operating in different radiation field strengths. Even at 10,000 R/h, the image quality is very good. Figure 16 shows an expanded section of the 10,000 R/h image to show the amount of radiation induced noise compared to an image with no radiation.

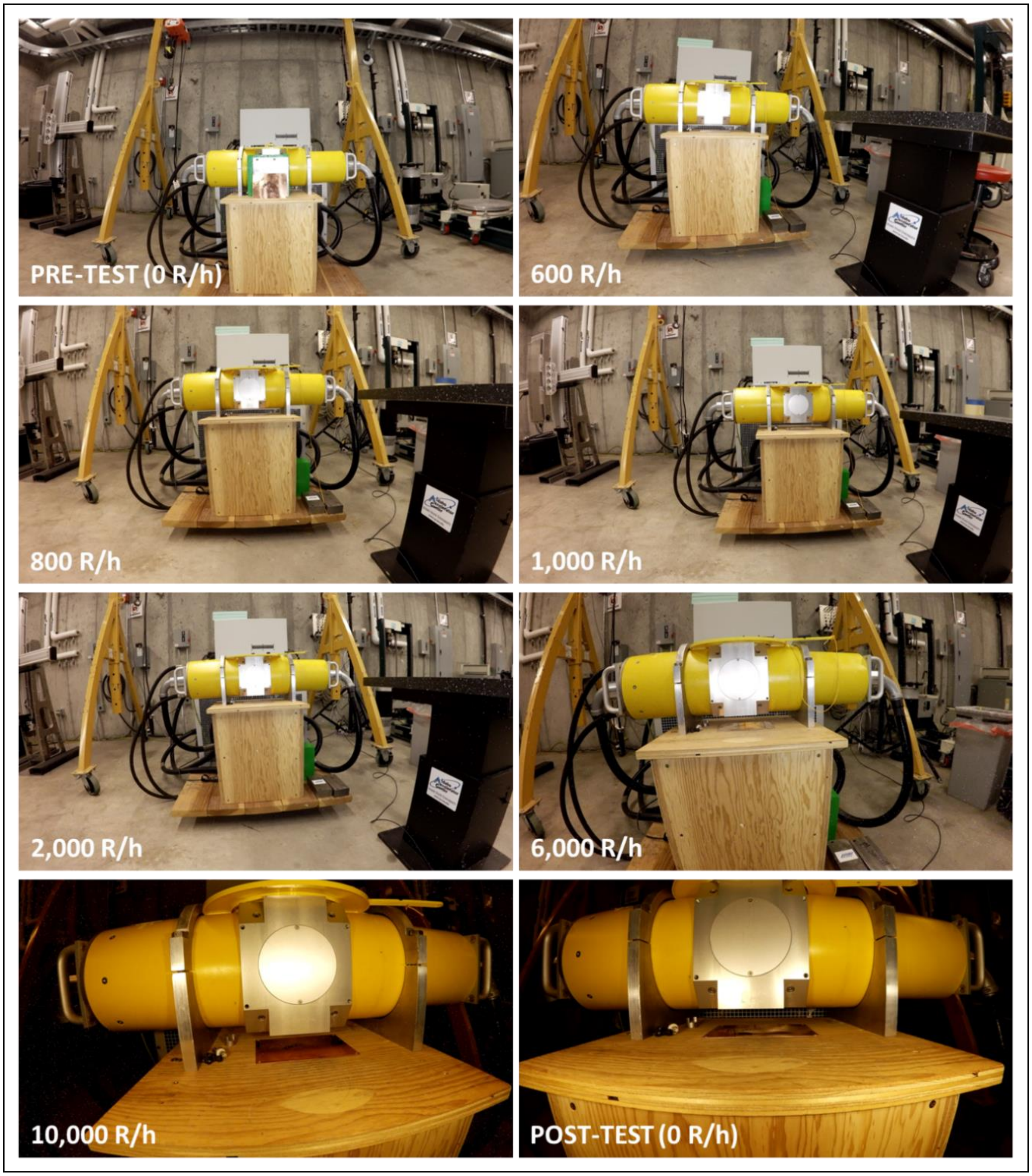

Figure 15. Comparison of drone camera images taken in varying radiation fields

Figure 16. Expanded sections of drone image captured in 10,000 R/h radiation field showing radiation induced noise compared to an image captured in a 0 R/h field

The Elios 3 drone’s LiDAR payload is a critical subsystem that will be used to collect the 3D map data within the CSSF-1 vault. During radiation testing of the drone the LiDAR payload continued to operate as designed throughout the radiation exposure profile indicated above. Figure 17 provides a low-resolution rendering of the X-ray vault created from LiDAR data collected during the test flight after the 10,000 R/h radiation exposure along with a photo of the vault for reference. This low-resolution point cloud image was rendered using CloudCompare, an open-source software package. This software was used only to provide a rough verification of the LiDAR data collected by the Elios 3 drone during radiation testing.

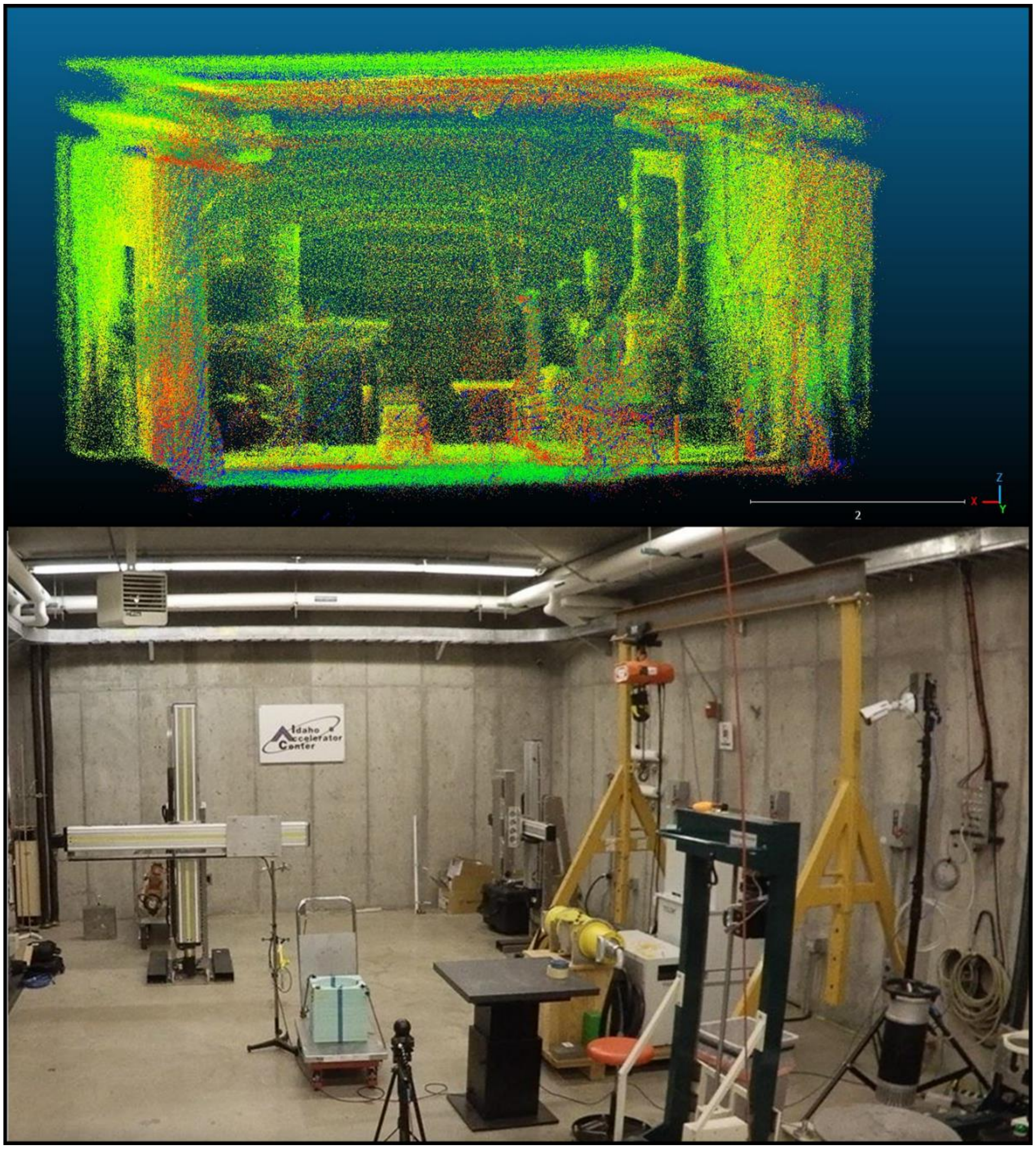

Figure 17. Low-resolution point cloud image (top) collected by Elios 3 drone LiDAR during test flight after 10,000 R/h exposure. X-ray vault image (bottom) provided for reference

CRP engineers will continue to work with Flyability engineers to obtain information regarding on-board computer fault.

3.2 iSHOT Camera Radiation Test Results

Per Table 2 above, test objectives required the iSHOT camera to be functional in a minimum radiation field of 2,000 R/h and continue to function after an accumulated dose of 6,000 R. Test results indicated the iSHOT camera successfully operated in a 2,000 R/h field and continued to function after an accumulated dose of approximately 7,119 R, exceeding the minimum test objectives for this target.

The iSHOT camera was exposed to a 2,000 R/h field for 3.6 hours while the camera operated. The camera did not fail during testing. An observation camera inside the X-ray vault was used to record and monitor images from the iSHOT camera that were displayed on a high-definition video monitor as shown in Figure 18.

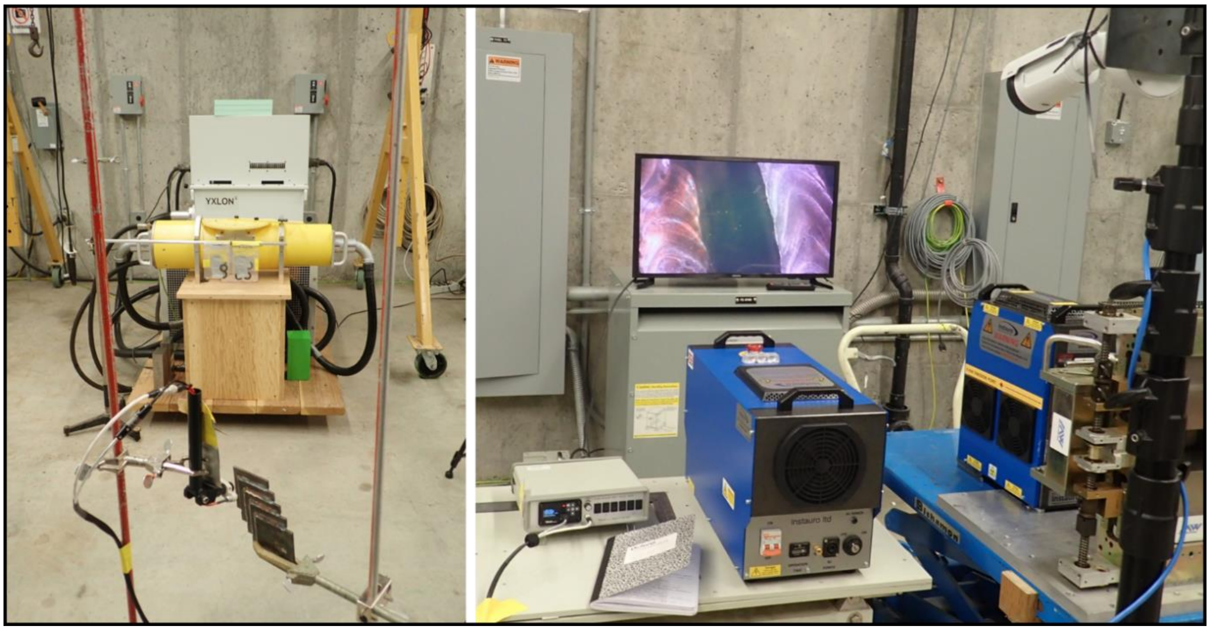

Figure 18. iSHOT camera head and weld test specimen (left) and iSHOT camera control unit, high-definition monitor, and observation camera (right)

The iSHOT camera image contained observable radiation induced noise when exposed to the 2,000 R/h radiation field but did not show any indication of permanent sensor degradation after 7,119 R of accumulated dose.

Figure 19 provides a comparison of the iSHOT camera image captured with no radiation and while operating in a 2,000 R/h field.

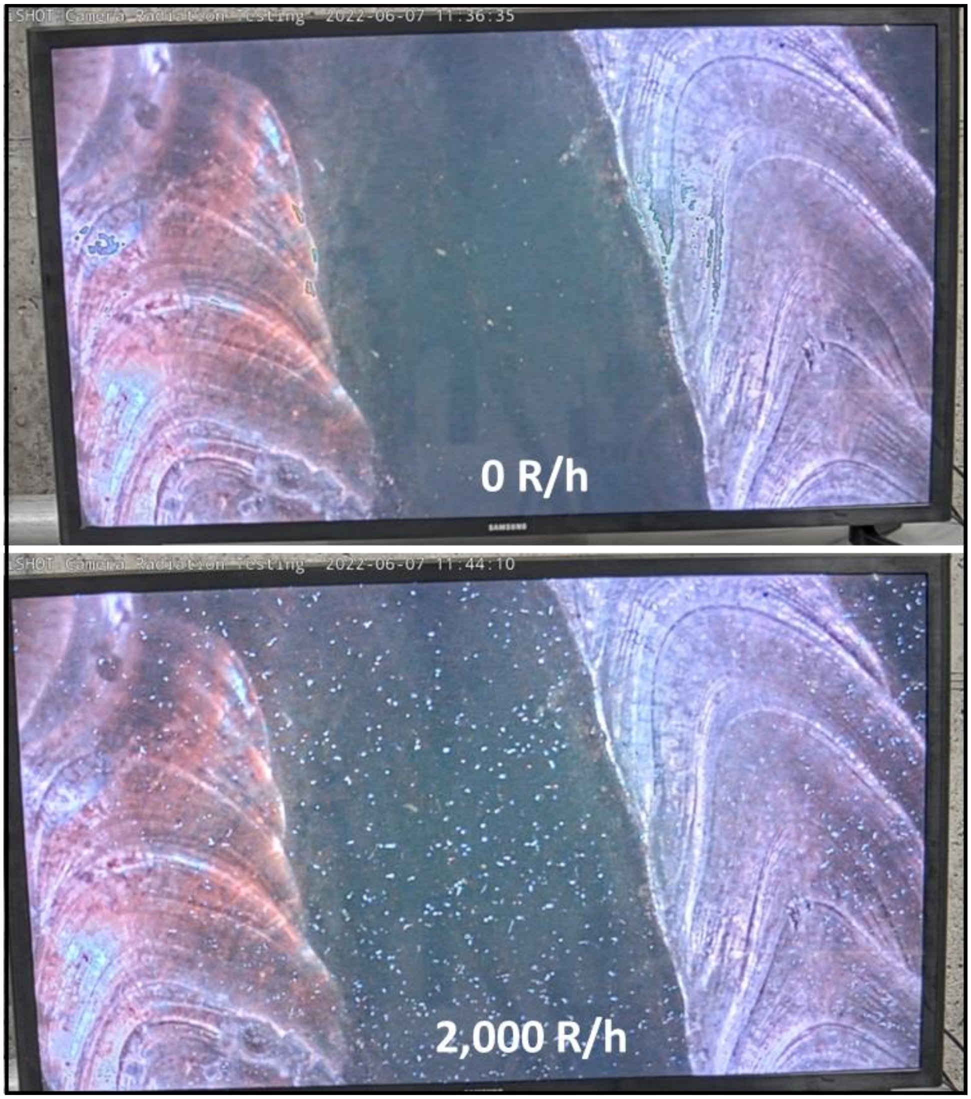

Figure 19. iSHOT camera image of weld sample taken with no radiation (top) and while operating in a 2,000 R/h field

The graph showing the iSHOT camera head radiation exposure profile is provided in Figure 20. The lamp function on the camera head was turned on several times throughout the 3.6 hours of exposure. There was no visibly detectable degradation of the lamp performance due to radiation exposure.

Although, the iSHOT camera control unit was located approximately 25 feet to the side of the X-ray tube, well outside the 40-degree beam, a GAFChromic dosimetry tag placed on the control unit prior to test indicated a total dose of 1,126 R received over the 3.6 hours of camera head exposure. This means the iSHOT control unit operated successfully in a radiation field of approximately 313 R/h with a total accumulated dose of 1,126 R.

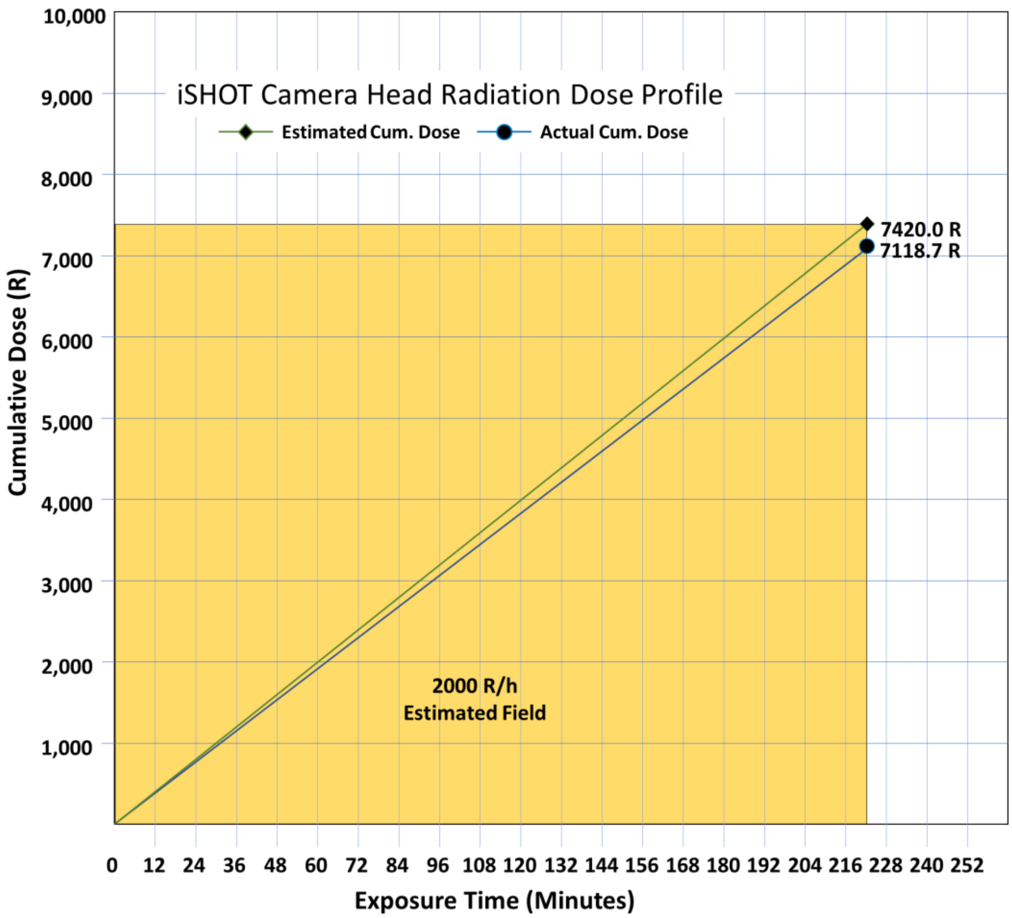

Figure 20. Graph representing the stepped radiation test results for the iSHOT weld camera head

3.3 Surface Cleaning Tool LED Module Radiation Test Results

According to Table 2 above, the test objectives for the Surface Cleaning Tool LED module indicated it must function in a minimum radiation field of 2,000 R/h and continue to function after an accumulated dose of at least 2,000 R. Test results indicated the Surface Cleaning Tool LED module successfully operated in a 91,700 R/h field and continued to function after an accumulated dose of at least 241,969 R, significantly exceeding the minimum test objectives for this target. The LED module did not fail during radiation testing.

The LED module was co-located with the drone during the first 114 minutes of radiation exposure. Once radiation testing on the drone concluded, the LED module was moved to within 250mm of the source to greatly increase the rate of dose accumulation for the remainder of test time. The intent was to irradiate the LED module until it failed or until we ran out of allotted testing time. The LED module remained functional until the end of allotted test time. There was no visible degradation of light output from the LED module over the entire 7.8 hours of radiation exposure.

Figure 21 shows the radiation exposure profile for the Surface Cleaning Tool LED module. The difference in estimated total dose and actual total dose at 468 minutes of exposure time is most likely due to overexposure of the GAFChromic dosimetry film. Although the dosimetry indicates a total dose of 241,969 R, it is appropriate to assume the true dose is significantly higher and closer to the estimated total dose of 546,296 R. At 114 minutes of exposure time, the estimated dose and actual dose as determined using the nanoDots dosimetry are in alignment.

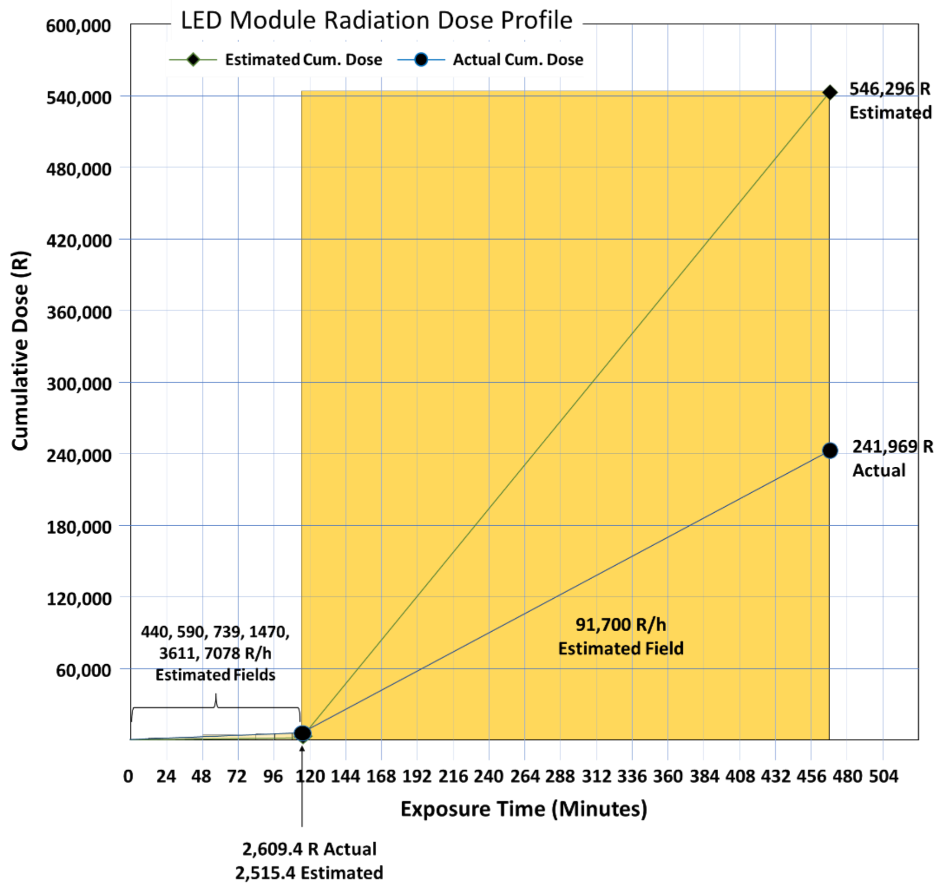

Figure 21. Radiation test profile for the surface cleaning tool LED module

3.4 EPDM U-cup Seals Radiation Test Results

The test plan for irradiating the EPDM U-cup seals called for packages of two seals each to be irradiated to doses of 1,000,000 R, 5,000,000 R, 10,000,000 R, and 50,000,000 R. Due to a change in allotted test time from two weeks to one week, CRP engineers modified the test requirements to applying as much dose as test time permits.

GAFChromic dosimetry film indicates the four EPDM U-cup seal packages received total doses of 641,867 R, 461,168 R, 648,513 R, and 587,337 R.

The EPDM U-cup seals were co-located with the drone during the first 114 minutes of radiation exposure. Once radiation testing on the drone concluded, the seals were moved to within 260mm of the source to greatly increase the rate of dose accumulation for the remainder of test time. Figure 22 shows the four packages of EPDM U-cup seals and the Surface Cleaning Tool LED module during radiation testing.

Figure 22. EPDM U-cup seals and Surface Cleaning Tool LED module during radiation testing

Figure 23 provides the radiation exposure profile for the EPDM U-cup seals. The difference in estimated total dose and actual total dose at 14.7 hours of exposure time is most likely due to overexposure of the GAFChromic dosimetry film. Although the dosimetry indicates an average total dose of 584,721 R for the four packages of seals, it is more likely the true dose is significantly higher and closer to the estimated total dose of 1,088,049 R. At 114 minutes of exposure time, the estimated dose and actual dose as determined using the nanoDots dosimetry are in better alignment.

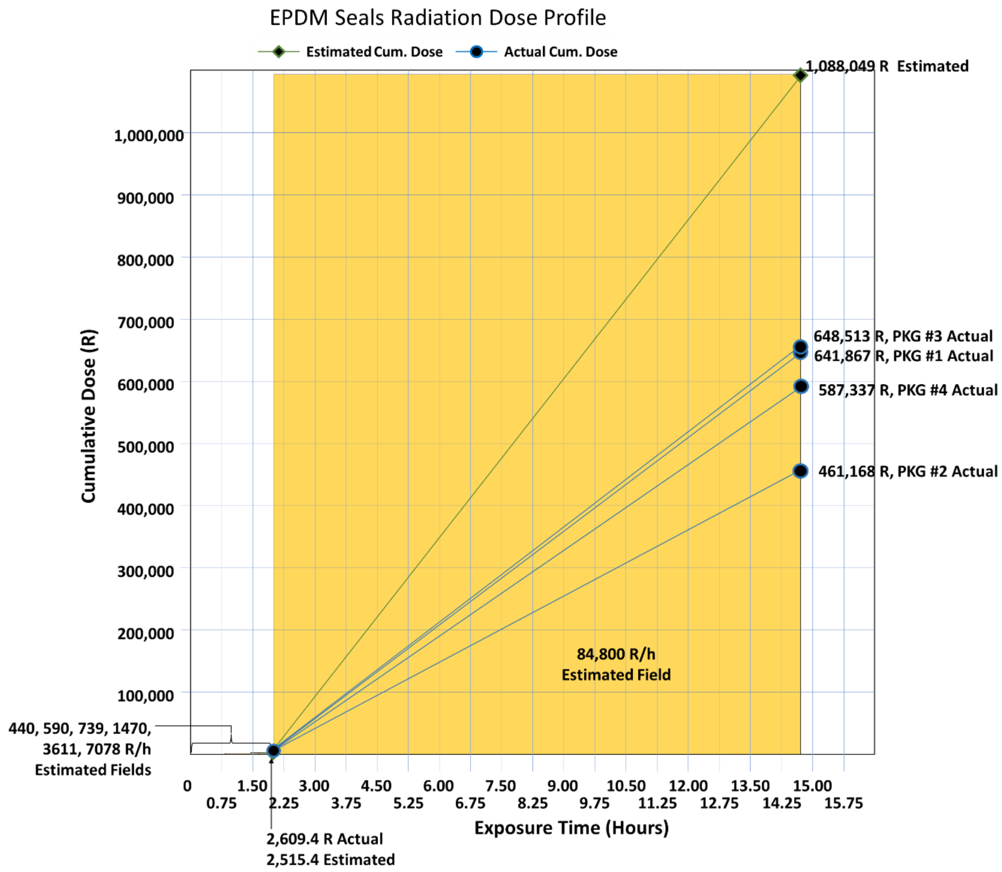

Figure 23. Radiation exposure profile for EPDM U-cup seals testing

Future radiation testing will subject the EPDM U-cup seals to additional radiation dose to meet the original test objectives. The radiated seals will then be compared to a set of non-radiated seals. Future testing will also consider irradiating the EPDM seals while under compression to more closely test per intended use.

4. CONCLUSIONS

All test targets except for the EPDM U-cup seals met minimum radiation tolerance test objectives. Additional irradiation time is needed for the seals to obtain the accumulated dose levels indicated in the test objectives. The cause of the OBC failure associated with the Elios 3 drone is unknown at this time. But the drone performed well above the minimum radiation tolerance level prior to the failure and is considered suitable for collecting the 3D data within the high-radiation area of the CSSF-1 vault. The iSHOT weld camera and the surface cleaning tool LED light module also performed well above the minimum acceptable radiation tolerance levels established in the test objectives and are considered suitable for use in calcine retrieval operations.

CRP engineers will continue to work with Flyability engineers to determine the cause of the OBC failure on the drone and then determine if additional radiation testing on the drone is needed. This information will be documented in a follow-on report.

5. REFERENCES

1. M-1509 - *CRP CSSF-1 Vault Mapping Technology* – ICP Engineering Position Paper.

2. RPT-1988 - *CRP Retrieval Project FY2021 Inspection Drone Demonstration Test Report, 2021*.

Appendix A

GAFChromic and nanoDots Dosimetry Values

Appendix A

GAFChromic and nanoDots Dosimetry Values

Target	Date/Time Removed	ID Number	Dose (Rad)	Average
Elios 3 - on bar behind	6/2/22 11:46	8151307A	1811.6	
Elios 3 - on bar behind	6/2/22 11:46	8151307B	1811.6	1811.6
Elios 3 - on bar behind	6/2/22 13:48	8151347A	1811.6	
Elios 3 - on bar behind	6/2/22 13:48	8151347B	1672.3	1742.0
Elios 3 - on bar behind	6/2/22 16:34	8151323A	3187.9	
Elios 3 - on bar behind	6/2/22 16:34	8151323B	2669.6	2928.8
Elios 3 - on bar behind	6/2/22 16:34	8151328A	2742.8	
Elios 3 - on bar behind	6/2/22 16:34	8151328B	2523.9	2633.4
Elios 3 - on bar behind	6/2/22 16:34	8151329A	2451.5	
Elios 3 - on bar behind	6/2/22 16:34	8151329B	1951.9	2201.7
Elios 3 - on bar behind	6/2/22 16:34	8151346A	2235.7	
Elios 3 - on bar behind	6/2/22 16:34	8151346B	2022.4	2129.1
LED Module	6/6/22 15:50	8151330A	240314.0	Overexp.
LED Module	6/6/22 15:50	8151330B	238405.0	239359.5
EPDM Seals pkg #1 (set 1 of 5)	6/6/22 16:40	8151322A	230548.0	Overexp.
EPDM Seals pkg #1 (set 1 of 5)	6/6/22 16:40	8151322B	226731.0	228639.5
EPDM Seals pkg #3 (set 1 of 5)	6/6/22 16:40	8151325A	234477.0	Overexp.
EPDM Seals pkg #3 (set 1 of 5)	6/6/22 16:40	8151325B	232905.0	233691.0
EPDM Seals pkg #4 (set 1 of 5)	6/6/22 16:40	8151326A	213935.0	Overexp.
EPDM Seals pkg #4 (set 1 of 5)	6/6/22 16:40	8151326B	211353.0	212644.0
EPDM Seals pkg #2 (set 1 of 5)	6/6/22 16:40	8151517A	94613	Overexp.
EPDM Seals pkg #2 (set 1 of 5)	6/6/22 16:40	8151517B	94501.0	94557.0
EPDM Seals pkg #1 (set 2 of 5)	6/7/22 9:26	8151294A	103593.0	
EPDM Seals pkg #1 (set 2 of 5)	6/7/22 9:26	8151294B	99215.0	101404.0
EPDM Seals pkg #2 (set 2 of 5)	6/7/22 9:26	8151298A	94052.0	
EPDM Seals pkg #2 (set 2 of 5)	6/7/22 9:26	8151298B	92368.0	93210.0
EPDM Seals pkg #3 (set 2 of 5)	6/7/22 9:26	8151299A	101236.0	
EPDM Seals pkg #3 (set 2 of 5)	6/7/22 9:26	8151299B	100226.0	100731.0
EPDM Seals pkg #4 (set 2 of 5)	6/7/22 9:26	8151300A	94613.0	
EPDM Seals pkg #4 (set 2 of 5)	6/7/22 9:26	8151300B	94052.0	94332.5
EPDM Seals pkg #4 (set 3 of 5)	6/7/22 11:38	8151309A	105726.0	
EPDM Seals pkg #4 (set 3 of 5)	6/7/22 11:38	8151309B	102920.0	104323.0
EPDM Seals pkg #3 (set 3 of 5)	6/7/22 11:38	8151312A	108869.0	
EPDM Seals pkg #3 (set 3 of 5)	6/7/22 11:38	8151312B	109430.0	109149.5

Target	Date/Time Removed	ID Number	Dose (Rad)	Average
EPDM Seals pkg #1 (set 3 of 5)	6/7/22 11:38	8151398A	115267.0	
EPDM Seals pkg #1 (set 3 of 5)	6/7/22 11:38	8151398B	106849.0	111058.0
EPDM Seals pkg #2 (set 3 of 5)	6/7/22 11:38	8151557A	101348.0	
EPDM Seals pkg #2 (set 3 of 5)	6/7/22 11:38	8151557B	102022.0	101685.0
iSHOT Control Unit	6/7/22 12:03	8151301A	1059.0	
iSHOT Control Unit	6/7/22 12:03	8151301B	1193.4	1126.2
iSHOT Camera Head	6/7/22 12:03	8151303A	7272.8	
iSHOT Camera Head	6/7/22 12:03	8151303B	7096.5	7184.7
iSHOT Camera Head	6/7/22 12:03	8151314A	7096.5	
iSHOT Camera Head	6/7/22 12:03	8151314B	7008.8	7052.7
EPDM Seals pkg #2 (set 4 of 5)	6/7/22 14:47	8151302A	138391.0	
EPDM Seals pkg #2 (set 4 of 5)	6/7/22 14:47	8151302B	134911.0	136651.0
EPDM Seals pkg #1 (set 4 of 5)	6/7/22 14:47	8151340A	159382.0	
EPDM Seals pkg #1 (set 4 of 5)	6/7/22 14:47	8151340B	156014.0	157698.0
EPDM Seals pkg #4 (set 4 of 5)	6/7/22 14:47	8151348A	142095.0	
EPDM Seals pkg #4 (set 4 of 5)	6/7/22 14:47	8151348B	137605.0	139850.0
EPDM Seals pkg #3 (set 4 of 5)	6/7/22 14:47	8151349A	166902.0	
EPDM Seals pkg #3 (set 4 of 5)	6/7/22 14:47	8151349B	162300.0	164601.0
EPDM Seals pkg #2 (set 5 of 5)	6/7/22 15:30	8151291A	35233.0	
EPDM Seals pkg #2 (set 5 of 5)	6/7/22 15:30	8151291B	34896.0	35064.5
EPDM Seals pkg #4 (set 5 of 5)	6/7/22 15:30	8151293A	35794.0	
EPDM Seals pkg #4 (set 5 of 5)	6/7/22 15:30	8151293B	33998.0	34896.0
EPDM Seals pkg #3 (set 5 of 5)	6/7/22 15:30	8151558A	40284.0	
EPDM Seals pkg #3 (set 5 of 5)	6/7/22 15:30	8151558B	40396.0	40340.0
EPDM Seals pkg #1 (set 5 of 5)	6/7/22 15:30	8151561A	42595.0	
EPDM Seals pkg #1 (set 5 of 5)	6/7/22 15:30	8151561B	43540.0	43067.5

Nano Dots

Target	Read Date/Time	ID Number	Dose (Rad)
Elios 3 - on cage	6/1/22 13:13	00821U	150.9
Elios 3 - on cage	6/1/22 13:13	00748G	153.9
Elios 3 - on cage	6/1/22 15:25	03721V	460.7
Elios 3 - on cage	6/1/22 15:25	31138T	456.3
Elios 3 - on cage	6/1/22 17:44	92616J	745.4
Elios 3 - on cage	6/1/22 17:44	00873L	746.2
Elios 3 - on cage	6/2/22 9:31	03681R	1295.2
Elios 3 - on cage	6/2/22 9:31	02197O	1217.3
LED - on LED	6/6/22 8:45	31325W	2917.8

Target	Date/Time Removed	ID Number	Dose (Rad)	Average
LED - on LED	6/6/22 8:45	03625R	2942.3	
not used		312414		
not used		00711X		
not used		02168P		

Appendix B

CRP Radiation Test Log

Appendix B

CRP Radiation Test Log

Date	Drone Run	Energy (keV)	Current (mA)	X-Ray On Time (hh:mm:ss)	X-Ray Off Time (hh:mm:ss)	Duration (hh:mm:ss)	Elios 3 D to S (mm)	LED D to S (mm)	iSHOT D to S (mm)	Seals #1 D to S (mm)	Seals #2 D to S (mm)	Seals #3 D to S (mm)	Seals #4 D to S (mm)	Notes
6/1/2022	600-1	450	2.35	12:05:45	12:11:45	0:06:00	1500	1750		1750	1750	1750	1750	
6/1/2022	600-2	450	2.35	12:31:46	12:37:46	0:06:00	1500	1750		1750	1750	1750	1750	
6/1/2022	800-1	450	3.15	14:34:38	14:40:38	0:06:00	1500	1750		1750	1750	1750	1750	
6/1/2022	800-2	450	3.15	15:01:44	15:07:44	0:06:00	1500	1750		1750	1750	1750	1750	
6/1/2022	800-3	450	3.15	15:16:54	15:22:54	0:06:00	1500	1750		1750	1750	1750	1750	
6/1/2022	800-4	450	3.15	17:00:37	17:01:56	0:01:19	1500	1750		1750	1750	1750	1750	Had to pause due to drone tablet problem.
6/1/2022	800-4	450	3.15	17:09:24	17:14:05	0:04:41	1500	1750		1750	1750	1750	1750	User error. Resolved.
6/1/2022	800-5	450	3.15	17:22:48	17:28:48	0:06:00	1500	1750		1750	1750	1750	1750	
6/1/2022	800-6	450	3.15	17:35:02	17:41:02	0:06:00	1500	1750		1750	1750	1750	1750	
6/1/2022	1000-1	450	3.95	8:17:47	8:23:47	0:06:00	1500	1750		1750	1750	1750	1750	
6/2/2022	1000-2	450	3.95	8:30:06	8:36:06	0:06:00	1500	1750		1750	1750	1750	1750	
6/2/2022	1000-3	450	3.95	8:42:13	8:48:13	0:06:00	1500	1750		1750	1750	1750	1750	
6/2/2022	1000-4	450	3.95	9:25:25	9:31:25	0:06:00	1500	1750		1750	1750	1750	1750	
6/2/2022	1000-5	450	3.95	9:41:47	9:47:47	0:06:00	1500	1750		1750	1750	1750	1750	
6/2/2022	1000-6	450	3.95	10:34:56	10:40:56	0:06:00	1500	1750		1750	1750	1750	1750	
6/2/2022	2000-1	450	7.85	10:49:51	10:55:51	0:06:00	1500	1750		1750	1750	1750	1750	
6/2/2022	2000-2	450	7.85	11:24:52	11:30:52	0:06:00	1500	1750		1750	1750	1750	1750	
6/2/2022	6000-1	450	10.00	13:26:00	13:32:00	0:06:00	970	1260		1260	1260	1260	1260	
6/2/2022	6000-2	450	10.00	13:38:44	13:44:44	0:06:00	970	1260		1260	1260	1260	1260	
6/2/2022	10000-1	450	10.00	14:17:46	14:23:46	0:06:00	640	900		900	900	900	900	
6/2/2022	10000-2	450				0:00:00	end							Could not get drone to initialize. OBC problem
6/6/2022	n/a	450	10.00	9:34:49	15:31:14	5:56:25		250		260	260	260	260	Film dosimetry overexposed?
6/6/2022	n/a	450	10.00	16:51:26	17:21:26	0:30:00		end	1695	260	260	260	260	Pulled LED
6/7/2022	n/a	450	10.00	8:24:58	9:26:34	1:01:36			1695	260	260	260	260	
6/7/2022	n/a	450	10.00	9:36:24	11:22:17	1:45:53			1695	260	260	260	260	
6/7/2022	n/a	450	10.00	11:38:04	12:03:28	0:25:24			1695	260	260	260	260	
6/7/2022	n/a	450	10.00	12:14:20	14:47:00	2:32:40			end	260	260	260	260	Pulled iSHOT
6/7/2022	n/a	450	10.00	14:52:10	15:30:31	0:38:21				260	260	260	260	
						0:00:00								