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Radiation Testing at Sandia National Laboratories
Sandia – JPL Collaboration for Europa Lander

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Sandia National Laboratories (SNL) is assisting Jet Propulsion Laboratory in undertaking feasibility studies and performance assessments for the Planetary Protection aspect of the Europa Lander mission. The specific areas of interest for this project are described by task number. This white paper presents the evaluation results for **Task 2, Radiation Testing**, which was stated as follows:

> Survey SNL facilities and capabilities for simulating the Europan radiation environment and assess suitability for:
>
> A. Testing batteries, electronics, and other component and subsystems
> B. Exposing biological organisms to assess their survivability metrics.

Sandia Radiation Testing Facilities

Sandia operates several facilities, which provide different environments for radiation testing. Of those facilities, two were selected as potential candidates for supporting radiation testing for the Europa Lander Project: the Ion Beam Laboratory (IBL) and the Gamma Irradiation Facility (GIF).

Radiation environment the Europa Lander will encounter on route and in orbit upon arrival at its destination consists primarily of charged particles, energetic protons and electrons with the energies up to 1 GeV. The spacecraft, its payload and ancillary equipment will also experience relatively high doses. The Design Reference Mission (DRM) Total Ionizing Dose (TID) was defined as 3 Mrad(Si).

The charged particle environments can be simulated using the accelerators at the IBL. The description of the facility and its capabilities follows this introduction. The facility can provide the charged particle environments with the energies up to 4.5 MeV. However, there is a size restriction for the test objects. The IBL can accommodate samples as large as 6” wafers with thickness on the order 3”.

The GIF and it annex, the Low Dose Rate Irradiation Facility (LDRIF), offer irradiations using Co-60 gamma sources (1.17 and 1.33 MeV), as well as Cs-137 gamma (0.661 MeV) AmBe neutron (0-10 MeV) sources. The test cells at the GIF are large and could accommodate, not only the parts and subsystems, but also the entire lander. The GIF can deliver the required total dose using gamma radiation as a surrogate.

The IBL and the GIF can handle biological materials with biosafety level 1 (BSL-1).

The links to the sections of this document describing the IBL and the GIF are provided below.

Ion Beam Laboratory

Gamma Irradiation Facility

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Ion Beam Laboratory

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I1. General Capability Selection

The IBL is a new (25000 ft^2, $40M) state of the art accelerator facility that opened in June 2010. The facility is currently utilized to elucidate fundamental questions in particle physics, solid-state physics, device physics, and materials science through the use of ion beam analysis, ion beam modification, radiation effects microscopy, and in-situ TEM studies in radiation environments. Although the IBL has a broad range of experimental capabilities, the following four are thought to be of the greatest interest to the DOE-NE community:

1. In-situ ion irradiation transmission electron microscope (described in detail below)
2. High-energy light- or heavy-ion irradiation at elevated temperature and/or applied mechanical load [1]
3. Deep, high-dose-rate, light-ion irradiation experiments at temperatures from 77K to 1073 K
4. Calibrated neutron production through D-D or D-T reactions

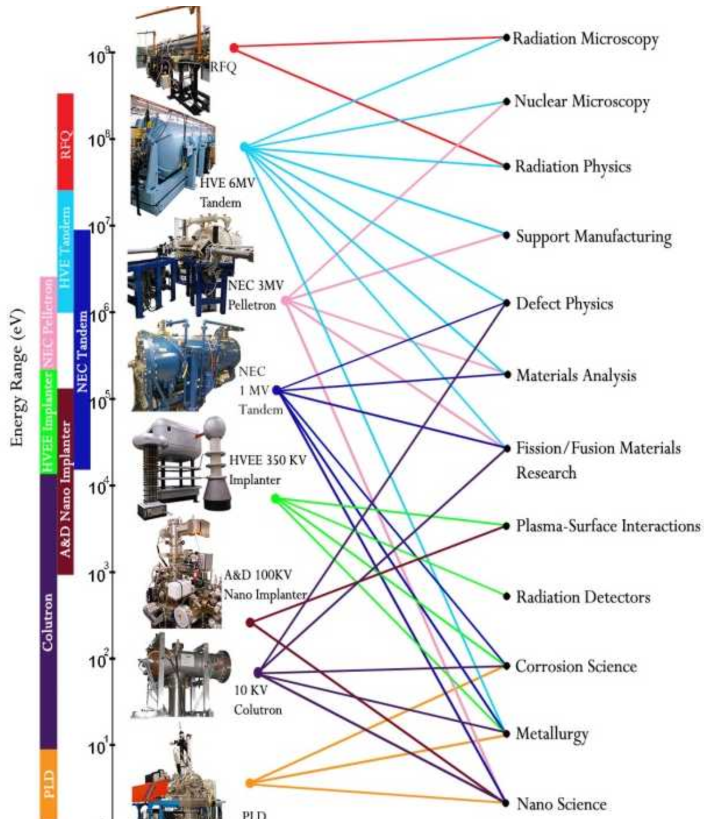

Figure 1. The seven accelerators and pulsed laser deposition systems currently at the IBL. The energy ranges from a few eV to 100s of MeV, which permit a range of particle physics, solid-state physics, and materials science studies to be performed.

The IBL has significant capabilities that make it a premier facility for studying materials response to extreme environments (Fig. 1). In addition to Sandia's expertise in applying ion beam accelerators to materials science dates back to the 1950's, the new facility incorporates seven accelerators including: a 10 kV Colutron, 100 kV A&D Nanoimplanter (Mass separated FIB), a 350 kV HVEE implanter, a 1 MV NEC Tandem Pelletron, a 3 MV NEC Pelletron, a 6 MV HVE EN Tandem, and a Radio Frequency Quadrapole booster attached to the 6 MV Tandem.

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I2. Expected Relevant Capabilities

I2.1 Proton irradiation

Combined use of the Colutron, HVEE Implanter, NEC Pelletron, and HVE Tandem permits proton irradiation over an energy range from 10 eV to 4.5 MeV. All of the accelerators have at minimum one end station that can accommodate samples as large as 6" wafers with thickness on the order 3". The following table obtained from JPL's interoffice memorandum 5132-16-006 Project: Europa March 21, 2016 demonstrate the expected electron and proton radiation environments of the mission. The highlighted values are those that we expect to be able to reproduce in a controlled lab environment utilizing IBL facilities at Sandia.

Table I1. Proton and Electron Fluence by Energy for the Design Reference Mission (RDF = 1)

Energy	Trapped Electrons		Trapped Protons	
	Integral	Differential	Integral	Differential
(MeV)	(cm^{-2})	(cm^{-2} MeV^{-1})	(cm^{-2})	(cm-2 MeV-1)
0.0001	2.783E+17	3.895E+20	1.188E+15	2.163E+17
0.0003	2.033E+17	3.646E+20	1.147E+15	1.962E+17
0.0005	1.472E+17	2.210E+20	1.118E+15	1.090E+17
0.001	8.632E+16	6.845E+19	1.093E+15	2.303E+16
0.003	4.333E+16	6.564E+18	1.077E+15	2.853E+15
0.005	3.375E+16	3.569E+18	1.070E+15	3.717E+15
0.01	2.164E+16	1.709E+18	1.045E+15	6.236E+15
0.03	8.891E+15	2.480E+17	8.831E+14	9.610E+15
0.05	5.739E+15	1.011E+17	7.063E+14	8.226E+15
0.1	3.013E+15	2.991E+16	4.576E+14	3.111E+15
0.2	1.523E+15	7.415E+15	2.842E+14	9.888E+14
0.3	1.029E+15	3.372E+15	2.137E+14	5.057E+14
0.5	6.172E+14	1.266E+15	1.479E+14	2.173E+14
1	2.912E+14	3.338E+14	8.289E+13	7.583E+13
2	1.255E+14	8.110E+13	3.920E+13	2.453E+13
3	7.247E+13	3.349E+13	2.207E+13	1.176E+13
5	3.450E+13	1.054E+13	8.457E+12	3.696E+12
10	1.036E+13	2.083E+12	1.434E+12	4.044E+11
20	2.151E+12	2.610E+11	1.826E+11	2.722E+10
30	7.942E+11	6.519E+10	5.343E+10	5.298E+09
50	2.263E+11	1.106E+10	1.154E+10	6.754E+08
100	4.167E+10	1.011E+09	1.490E+09	4.256E+07
200			2.027E+08	2.834E+06
300			6.519E+07	5.948E+05
500			1.602E+07	8.569E+04
1000			2.475E+06	6.474E+03

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I2.2 In-situ concurrent electron and proton irradiation

The I[3]TEM currently combines a modern 200 kV, JEOL 2100 high-contrast TEM with a 10 kV Colutron and a 6 MV Tandem accelerator [2]. *This new in-situ TEM with two integrated accelerators and third being installed has a wealth of capabilities to understand the fundamental physics governing the microstructural evolution that occurs in materials exposed to extreme radiation environments and subsequently provide input into advanced models.* A sample can be exposed to 200 kV electron and protons ranging from 10 eV to 10 keV and 800 keV to 40.5 MeV sequentially or concurrently and over a range of dose rates. Samples would have to be limited to a ~10 mm^2.

Extensive ion optic design and development allowed simultaneous collinear entry of both high energy ions from the Tandem and low energy light ions from the Colutron to irradiate and implant a TEM sample, respectively. Images of the major components of the facility can be seen in Figure 2.

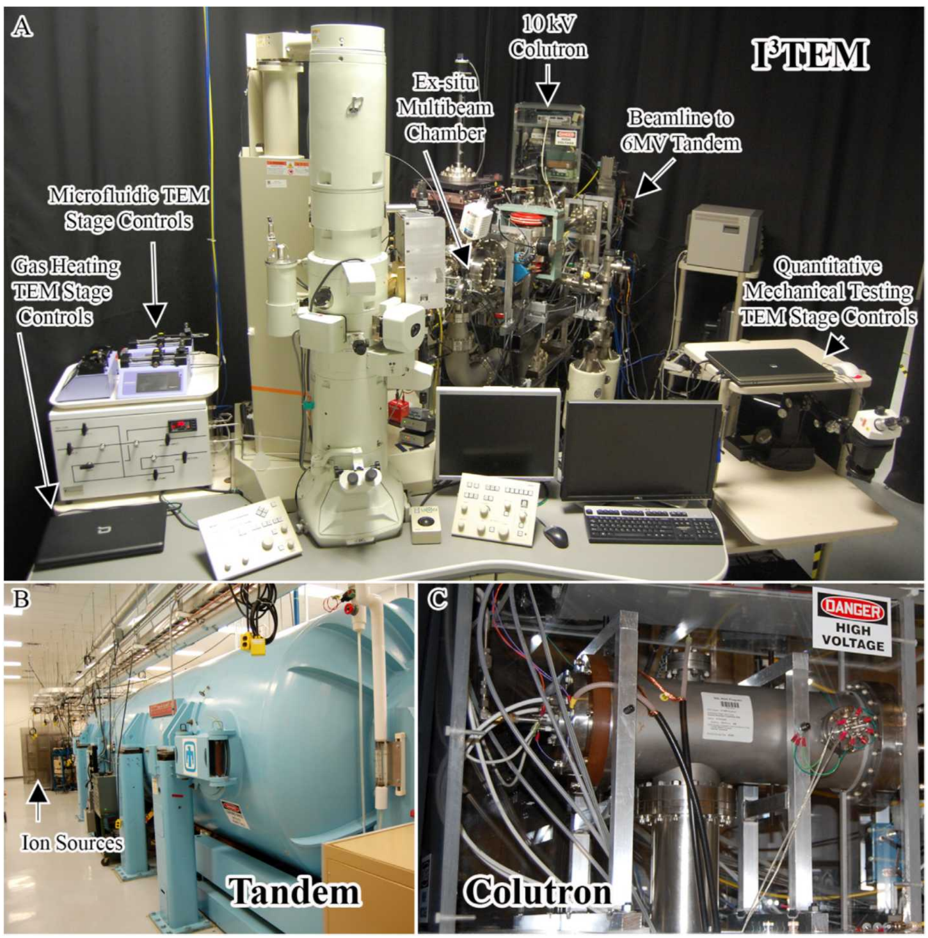

Figure I2. I[3]TEM facility (A) JEOL 2100 TEM with key beamline and stage capabilities identified. (B) 6 MV EN Tandem Accelerator with the location of the ion sources identified. (C) 10 kV Colutron [2].

The attention to detail in the design and construction has permitted the TEM to maintain a 2.5 Å point resolution during real time observation of the TEM sample during ion irradiation, implantation, or both concurrently. The ability to simultaneously image and irradiate enables unique fundamental studies into the synergistic role. In addition to evaluating radiation effects at room temperature in a vacuum, the use of modern TEM stages permits the evaluation of the materials when exposed to:

1) Both high and low energy ion beams concurrently at elevated temperatures up to 1000 ˚C,
2) Liquid environments including some corrosive environments [4],
3) Gas environments at both room and temperatures up to 1000 ˚C [5], and
4) Quantitative straining environments at temperatures as high as 400 ˚C.

Significantly more detail regarding the facility and its capabilities (as of August 2014), including the large rang e of ion species and energies, can be found in reference [2].

Additionally, several upgrades have been or are currently being made to further enhance the capabilities of the I^{3}TEM. The following details the added capabilities and the associated upgrade:

1) Completed energy range and increased beam time availability by the addition of a 1 MV NEC Tandem accelerator (in progress).
2) Greater evaluation of ion track formation and other high energy events through an upgrade of the last major bending magnet to increase the beam rigidity that can be bent into the TEM (in progress).
3) Increased temporal resolution to complement the high spatial resolution by upgrading the JEOL 2100 to a dynamic TEM permitting (in progress).
4) Detailed 3D tomographic reconstructions of crystalline samples are obtained using the addition of a Gatan 925 DT double tilt-rotate stage to permit.
5) Classical TEM straining experiments using the addition of a Gatan 654 ST qualitative strain stage.
6) Detailed orientation imaging microscopy of texture and grain boundary information from large regions of the sample via the addition of the Precession Electron Diffraction (PED) capability from Nanomegas and ASTAR.

I2.3 In-situ concurrent electron and proton irradiation.

Heavy ion irradiation of a large range of ion species is possible over an energy range from 45 keV to 100 MeV. However, further details are not included based on the expected radiation environment of the mission.

I3. Capability Location

The I^{3}TEM is an operational suite of instruments located at the Ion Beam Lab (IBL) at Sandia National Laboratories (SNL) in Albuquerque, NM. The IBL is located outside the limited area of SNL, but within a property protected area (PPA) on Kirtland Air Force Base (KAFB). The placement of this facility at SNL permits the initial multimillion dollar development cost, and a fraction of the maintenance cost, to be covered by NNSA relevant projects. The institutional support available in the national laboratory environment ensures the continued operation of the I^3TEM. Furthermore*, location of the facility at an NNSA site leverages the weapons complex funding to continually modernize the facility*. Users do not require a security clearance to access the facility, but will be subject to SNL and KAFB badging and training requirements. Currently, US citizens can obtain badges typically in 1-5 days, most foreign nationals in less than 30 days, and sensitive country foreign nationals in less than 60 days. Access for foreign nationals is not guaranteed.

The regional location of the facility in Albuquerque, NM is central to the major universities located on either coast. In addition, it provides increased convenience for National Lab users in the mountain states including Los Alamos National Laboratory and Idaho National Laboratory. Albuquerque International Sunport is an easy to use, *major domestic airport that is only a 15-minute drive from the IBL*.

I4. References

[1] "Anisotropic radiation-induced segregation in 316L austenitic stainless steel with grain boundary character," C. M. Barr, G. A. Vetterick, K. A. Unocic, K. Hattar, X.-M. Bai, and M. L. Taheri, Acta Materialia, vol. 67, pp. 145-155, Apr 2014.

[2] "Concurrent in situ ion irradiation transmission electron microscope," K. Hattar, D. C. Bufford, and D. L. Buller, Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms, vol. 338, pp. 56-65, Nov 2014.

[3] "In Situ TEM Concurrent and Successive Au Self-Ion Irradiation and He Implantation," C. Chisholm, K. Hattar, and A. M. Minor, Materials Transactions, vol. 55, pp. 418-422, Mar 2014.

[4] "Studying localized corrosion using liquid cell transmission electron microscopy," S. W. Chee, S. H. Pratt, K. Hattar, D. Duquette, F. M. Ross, and R. Hull, Chemical communications (Cambridge, England), vol. 51, pp. 168-71, 2015-Jan-4 2015.

[5] "Synthesis of mesoporous palladium with tunable porosity and demonstration of its thermal stability by in situ heating and environmental transmission electron microscopy," P. J. Cappillino, K. M. Hattar, B. G. Clark, R. J. Hartnett, V. Stavila, M. A. Hekmaty, B. W. Jacobs, and D. B. Robinson, Journal of Materials Chemistry A, vol. 1, pp. 602-610, 2013.

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Gamma Irradiation Facility

Maryla A Wasiolek

G1. General Description

Gamma Irradiation Facility provides a wide range of experimental gamma radiation environments using cobalt-60 sources. The facility has three large irradiation cells for dry irradiations and an 18-foot deep pool for submerged irradiations. The facility is used mainly for radiation certification of satellite and weapon systems electronic components, dosimetry calibration, and studies on radiation damage to materials.

The facility offers gamma dose rates from 10^{-3} rad/s to over 10^{3} rad/s. This range is further expanded in the low dose rate region by three orders of magnitude at the Low Dose Rate Irradiation Facility (LDRIF), which is operated by the GIF staff. The dose rate ranges are shown in Figure G1. The facility will be deploying in the near future a new array called the shutter (variable aperture) array capable of dose rates up to 5×10^{3} rad/s. All source arrays are reconfigurable and can be loaded to meet the specific experiment conditions. The available source array geometries are circular (cylindrical), linear (planar), and point (line).

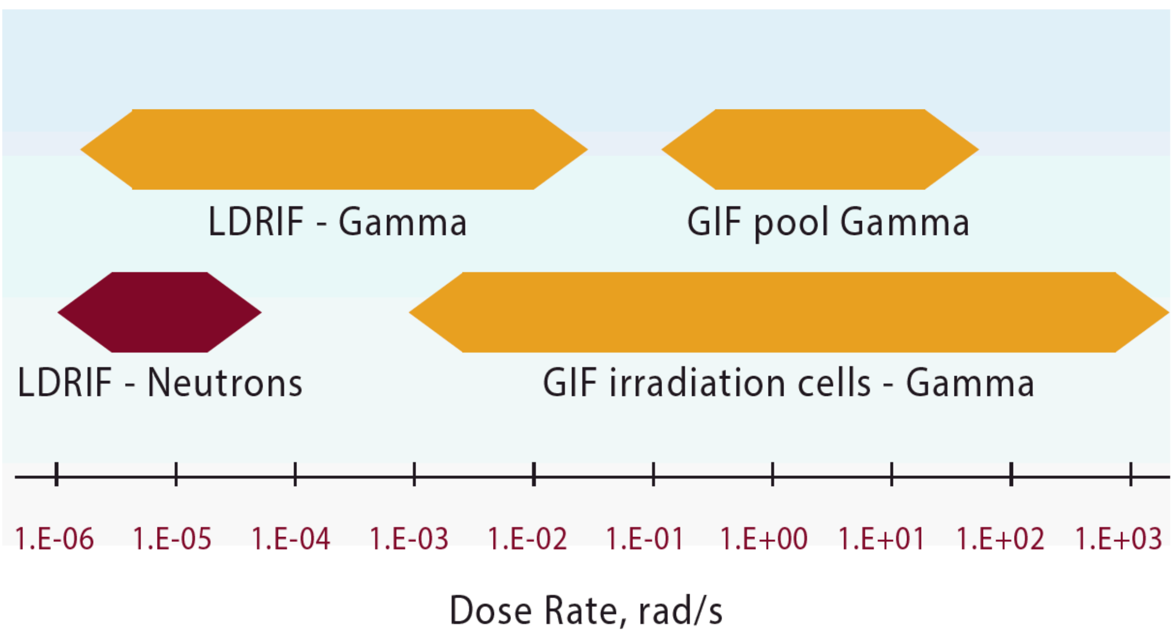

Figure G1. Dose rate ranges offered at the GIF and LDRIF. The GIF uses Co-60 gamma sources; the LDRIF uses Cs-137 gamma and AmBe neutron sources.

The test cells for in-air irradiations are dry, shielded, rooms with 6-ft thick walls, where irradiations are performed with a high intensity gamma ray source. When irradiations are not being performed, the

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radioactive sources are stored below the cells in the GIF pool. Three test cells are available. The cell specifications are presented in Table G1. Figure G2 shows the linear and the circular source arrays in the storage configuration.

Table G1. Test Cell Specifications

Test Cell	Dimensions
Test Cell 1 (west small cell)	3.0 m x 3.0 m (~9.9 ft. x ~9.9 ft.)
Test Cell 2 (east small cell)	3.0 m x 3.0 m (~9.9 ft. x ~9.9 ft.)
Test Cell 3 (large cell with moveable wall)	5.5 m x 9.1 m (~18 ft. x ~29.9 ft.)

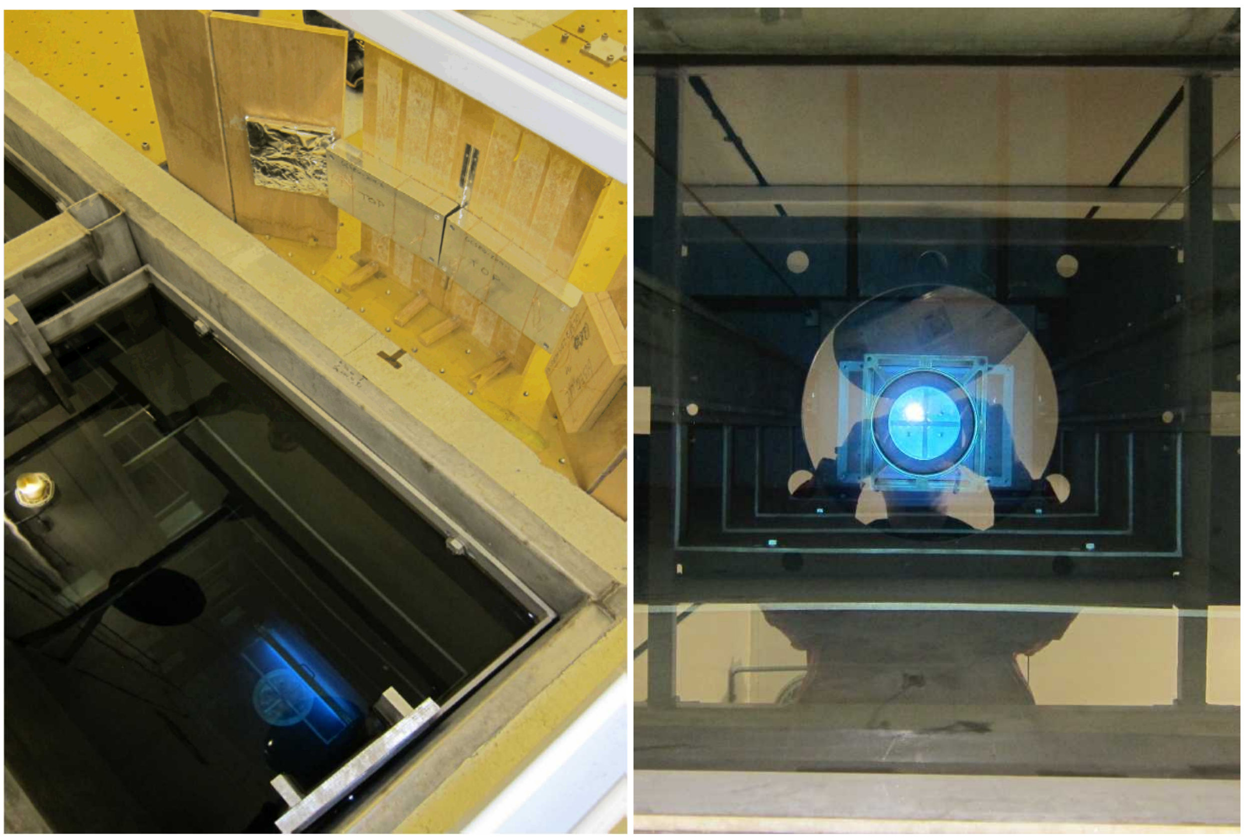

Figure G2. 30-Pin Linear Array and 40-Pin Circular Array at the GIF. The arrays are shown in their storage configuration (when not in use), at the bottom of the GIF pool.

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G2. Custom Experiment Set-up

Gamma Irradiation Facility is equipped to provide various experiment setup options. At the GIF, pass-throughs in the shielding walls allow for experiment power and instrumentation cables to penetrate the shield walls. Experiments may be cooled or heated. Irradiation can be conducted at inert gas atmosphere for test object that fit into the cylindrical chamber with the diameter of about 6 inches and the height of about 11 inches. Source arrays are available in three different geometries (with the point, linear, or circular cross-section) and can be configured depending on the experiment. Large cells and flexible cell arrangement allow the irradiated parts to be placed up to 7 m away from the sources or as close as a few cm away from the sources. The large cell can accommodate test objects as large as Abrams M1 tank.

G3. Experiment Support

At the GIF, a movable wall measuring 5.5 m (~18 ft.) wide in the large cell provides access for large components, such as space vehicles or military vehicles. In addition to the moveable wall, removable cell roof plugs provide access to large/massive experiments. An overhead bridge crane spans the facility high bay. Remote manipulators can be installed in the cells to facilitate experiment or source handling. The maze hallway in each cell provides simple, safe entry into the cells and quick egress from the cells to set up test units and connect instrumentation. Radiation shielding windows allow personnel to view the irradiation process. There is one window in each small cell and three windows in the large test cell. Windows consist of multiple, leaded glass panes, optically coupled by transparent oil.) An elevator system lifts sources from the pool into the dry cells with programmable timed termination of the run and to a predetermined position in the cell. Cell 3 has two source elevators.

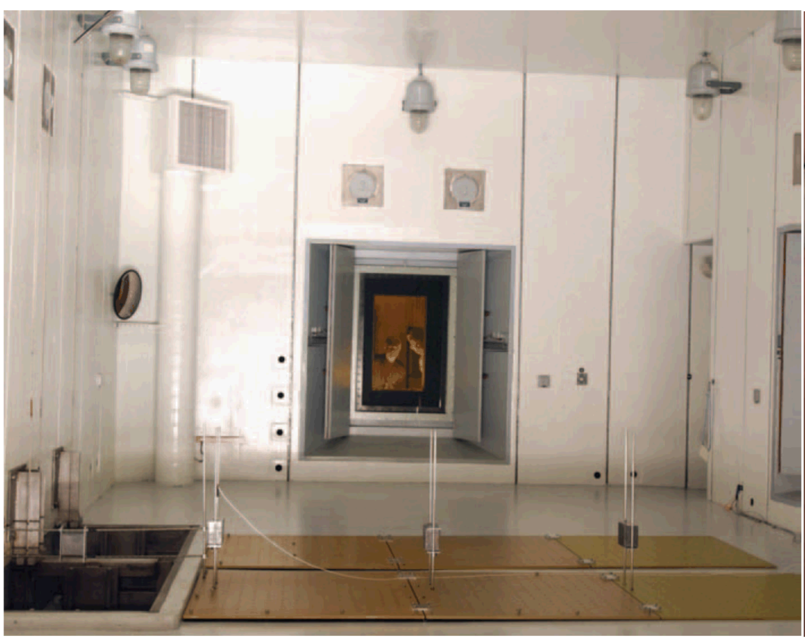

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Figure G3. Shielded windows are used during the irradiation startup and can be used during the experiment.

G4. In-Pool Submerged Irradiation

For the in-pool facilities, radioactive sources are held in a submerged irradiation fixture near the bottom of the 5.5 m (~18 ft.) deep pool of demineralized water. Water is supplied to the GIF pool by a water make-up subsystem to maintain an adequate radiation shielding depth. A recirculation loop maintains the pool water purity.

Dry experiment canisters, which contain test units, are immersed in the pool and positioned in preset locations in the irradiation fixtures. The in-pool irradiation fixtures are custom designed to specific source and test canister configurations. The fixtures are voided of water to provide an unshielded path between the source and the test unit.

The pool can store up to 1.5 megacuries (MCi) of Co-6o. The sources are in the form of pins and can be shared between the in-cell irradiation facilities and the in-pool irradiation facilities.

G5. Dosimetry

The GIF and LDRIF use calibrated ion chambers to measure gamma radiation dose rates. Thermoluminescent dosimeters can also be used to measure gamma radiation dose.