Conceptual Design of the Advanced Test Reactor Non-Destructive Examination System

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Presented in Partial Fulfillment of the Requirements for the
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with a
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By
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AUTHORIZATION TO SUBMIT THESIS

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ABSTRACT

The Advanced Test Reactor is one of the most capable research reactors in the world. Despite its world-class irradiative capabilities, on-site post-irradiation examination is limited to temporary, program-specific non-destructive examination needs, or non-existent altogether. Currently, fueled experiments and other fissile material are stored in the adjacent canal for cooling prior to shipment for comprehensive post-irradiation, reinsertion or disposal. This presents an opportunity for poolside post-irradiation examination to collect intermediate information about irradiated specimens only possible shortly after removal from the reactor. Idaho National Laboratory has funded the conceptual design of the Advanced Test Reactor Non-Destructive Examination System (ANDES), which conducts non-destructive post-irradiation examination on multiple types of specimens to assist reactor operations and further nuclear materials research. This thesis presents a design methodology driven by stakeholder and facility requirements for formulating the ANDES conceptual design. The individual subsystems of the ANDES conceptual design are discussed in detail, including enhanced videography and poolside gamma spectroscopy. Challenges and opportunities facing the development and deployment of ANDES are also discussed. If fully developed and deployed, the combined ANDES capabilities would provide an unparalleled post-irradiation examination approach for advancing nuclear energy science and technology.

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Finally, I would like to express my gratitude to the Thesis Committee for providing their time and granting me the opportunity to defend.

DEDICATION

First, I would like to thank God for blessing me with a passion for engineering and a work ethic for pursuing my studies. Lastly, I dedicate this to my wife Nora, son Otto and my loving family, whom have all given me the motivation and encouragement to pursue my passion. Without them all, this would not have been possible.

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LIST OF ACRONYMS

ADACS	ANDES Data Acquisition and Control System
AFC	Advanced Fuel Cycle
AFIP	ATR Full-size Plate in Center Flux Trap Position
ANDES	ATR Non-Destructive Examination System
ATF-2	Accident-Tolerant Fuel Experiment, Phase 2
ATR	Advanced Test Reactor
ATRC	ATR Criticality Facility
BR	Beryllium Rod
BR2	Belgium Reactor 2
CT	Computed Tomography
CAD	Computer-aided Design
DE	Destructive Examination
DDE	Design Demonstration Experiments
DOE	Department of Energy
HBWR	Halden Boiling Water Reactor
HEU	Highly Enriched Uranium
HFIR	High Flux Isotope Reactor
HPGe	High-Purity Germanium
INL	Idaho National Laboratory
LDW	Low-pressure Demineralized Water
LEU	Low-Enriched Uranium
LWR	Light Water Reactor
LVDT	Linear Variable Differential Transformer
MCNP	Monte Carlo N-Particle
MFC	Materials and Fuels Complex
MITR-II	MIT Nuclear Research Reactor
MP-1	Mini-Plate Experiment Series
MTR	Materials Test Reactor
MURR	University of Missouri Research Reactor
NaI	Sodium Iodide

NBSR	National Bureau of Standards Reactor
NDE	Non-Destructive Examination
NRTS	National Reactor Testing Station
PEEK	Polyether Ether Ketone
PCS	Primary Coolant System
PIE	Post-Irradiation Examination
PTZ	Pan-tilt-zoom
PWR	Pressurized Water Reactor
RERTR	Reduced Enrichment for Research and Test Reactors
SME	Subject Matter Expert
SR	Safety Rod
SST	Stainless Steel
TUGS	The Underwater Gamma System

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1 CHAPTER 1: IDAHO NATIONAL LABORATORY'S ADVANCED TEST REACTOR AND POST-IRRADIATION EXAMINATION

1.1 Nuclear Research Reactors

The dawn of the nuclear power industry in the 20th century required new materials with well-established safety margins. This resulted in the need for research reactors that could simulate material performance[1-2]. Since then, research reactors have reached outside the nuclear industry by studying and characterizing non-nuclear materials at the atomic level, producing isotopes for the medical industry[3] and processing industrial materials[4].

As of December 2018, 226 research reactors operate worldwide across 227 countries[5]. The missions for these reactors vary considerably. In February 2017, the U.S. Nuclear Energy Advisory Committee released a report that assessed irradiation capabilities needed to further advanced non-light water and light water reactor technologies. The report considered five U.S. research reactors as primary candidates for irradiation testing of nuclear materials[6]:

- Advanced Test Reactor – Idaho National Laboratory, ID
- High Flux Isotope Reactor (HFIR) – Oak Ridge National Laboratory, TN
- Massachusetts Institute of Technology Research Reactor, MS
- University of Missouri Research Reactor (MURR), MO
- National Bureau of Standards Reactor, National Institute of Standards and Technology, MD

While these reactors differ considerably across design, operating mission and capabilities, they all provide in-core irradiation for specimens under different test conditions. Of these reactors, Idaho National Laboratory's (INL's) Advanced Test Reactor (ATR) is the largest and most capable in terms of power and irradiation test positions. For comparison, select U.S. and international research reactor characteristics are provided in Table 1.1.

Table 1.1: International and U.S. research reactor characteristics[6-8]

Reactor	**ATR**	**BR2**	**HBWR***	**HFIR**	**MITR-II**	**MURR**
Location	Idaho Falls, USA	Mol, Belgium	Halden, Norway	Oak Ridge, USA	Cambridge, USA	Columbia, USA
Core Height (cm)	122	80	91	61	61	61
Power, MW_{th}	250	100	20	85	6	10
Maximum Thermal Flux, n/cm^2-s	5.0E+14	1-5E+13	1.5E+14	1.0E+15	1.7E+14	1.0E+14
Irradiation Locations (Loops)	75 (6)	81 (1)	55 (10)	42 (0)	9 (1)	15 (0)

Halden Boiling Reactor Project is in the process of permanent shutdown, but is presented here for comparison.

1.2 INL's Advanced Test Reactor

ATR is one of the largest and most advanced nuclear research reactors in the world. At INL, which was established as the National Reactor Testing Station (NRTS), historical research reactors such as the Materials Test Reactor (MTR) and Experiment Test Reactor (ETR) could only test a few fuel samples at a time, making results slow to obtain[9]. Furthermore, homogenous neutron flux for experiments in MTR and ETR was inhibited by the vertical movement of control rods during reactor operation. The U.S. Navy, one of the largest customers of the NRTS at the time, required homogenous irradiation for their increasingly complex fuel systems.

Through brilliance by Deslonde deBloisblanc and other NRTS scientists, the ATR serpentine design was conceived in 1959 to provide this homogenous neutron flux[9]. ATR is a pressurized water reactor comprised of 40 plate assemblies arranged in a serpentine configuration (Figure 1.1). This configuration, combined with semi-circular beryllium reflectors, gives ATR a unique capability of simultaneously providing a variety of neutron fluence for up to 75 individual testing locations. These irradiation experiments can include both fuel and other materials. This serpentine design gave ATR the ability to accommodate and discretely control thermal, hydraulic, nuclear and geometric conditions in irradiation experiments. Today, ATR's irradiation capabilities continue to be applied to further nuclear science and technology, serving customers across academia, the commercial nuclear power sector and international governments.

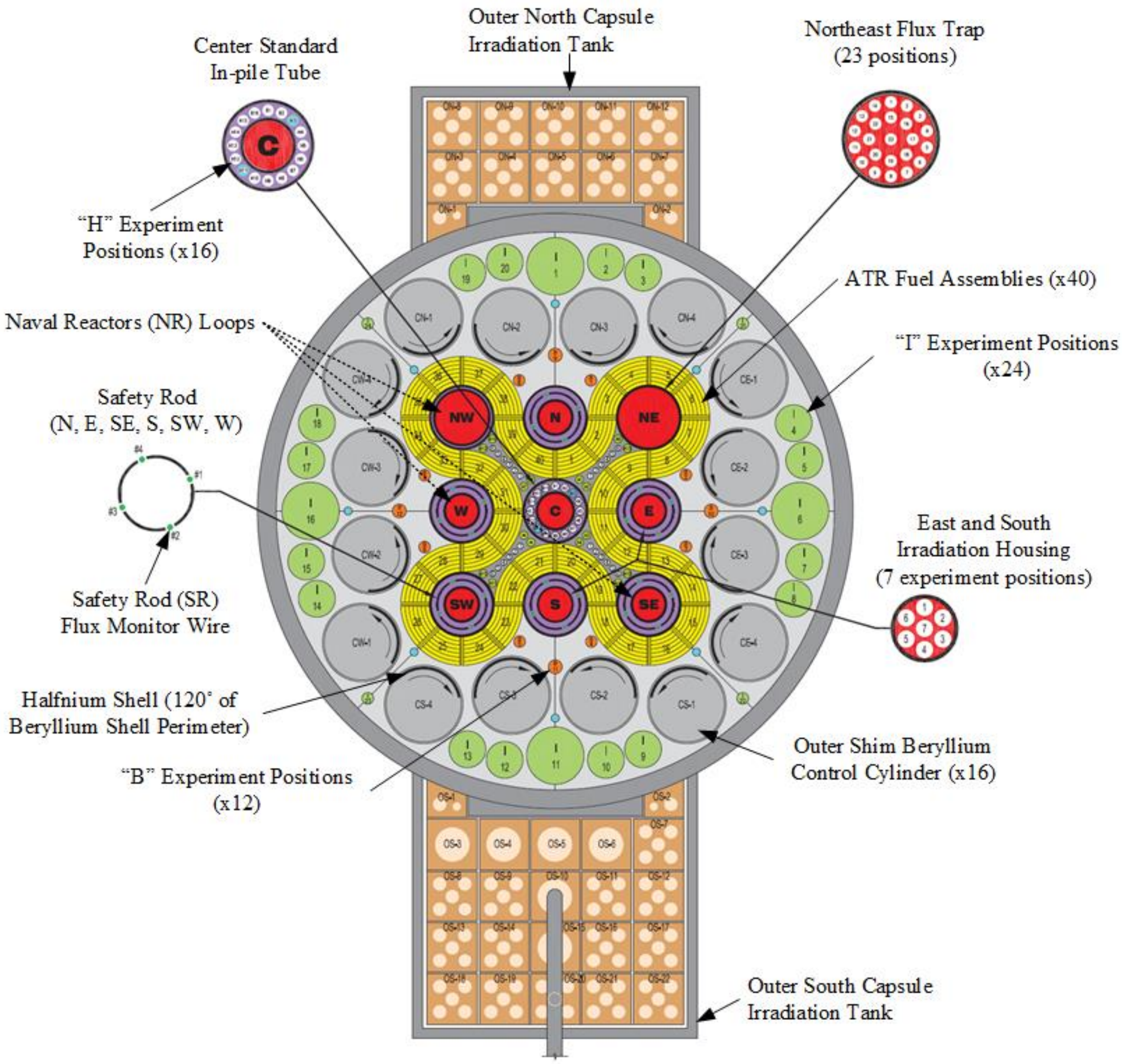

Figure 1.1: Cross-section of Advanced Test Reactor core[10]

1.3 Types of ATR Experiments

ATR's primary function is to irradiate state-of-the-art nuclear material systems in the form of experiments. These experiments are often not characterized until long after irradiation due to cooling and shipping prior to disassembly and analysis of experiment samples, known as post-irradiation examination (PIE). ATR experiments generally fall into three categories: static experiments, instrumented experiments and loops. Furthermore, the instrumentation included in these categories are classified as active and passive.

Static experiments, sometimes referred to as drop-in capsules, are passive. They do not include hardware that directly collect in-situ specimen performance data (e.g., temperature, gas composition), such as melt wires to indicate peak temperature[11]. In other words, specimen performance in static experiments is typically determined after the experiment has been irradiated, cooled and transported to a lab for PIE.

Instrumented experiments include active instrumentation for in-situ data acquisition and specimen environment control, including thermocouples for temperature measurement or gas lines for controlling specimen temperature. These complex experiments are capable of collecting information and controlling their environment during irradiation, but still require PIE.

Loop experiments are valuable for testing single or multiple fuel and/or material specimens under prototypic pressurized-water reactor (PWR) conditions. These tests are particularly valuable for qualifying fuels and materials for commercial use. In addition to temperature measurement devices, pumps and flow measurement devices are often included to provide in-situ specimen monitoring and control.

1.4 Post-Irradiation Examination of ATR Experiments

Typically, ATR experiments are irradiated for several cycles and removed during outages. This means that experiments are removed and reinserted into ATR many times over the course of several months or years. Depending on the experiment, the condition of the material or fuel being tested might be completely unknown until the experiment is dismantled and the specimens are removed and analyzed. This analysis, known as PIE, comprises of a multitude of measurement and examination techniques. Following irradiation, most ATR experiments are shipped in shielded casks to INL's Materials and Fuels Complex (MFC) for PIE.

Depending on the experiment, many different PIE activities are conducted for characterizing and testing irradiated fuel and material specimens. These capabilities cover a wide range of techniques, and are conducted at several facilities within MFC. A summary of these capabilities is provided below[12].

- Visual examination
- Dimensional examination (profilometry, oxide thickness measurement)
- Neutron radiography/tomography
- Gamma spectroscopy/gamma computed tomography (CT) (collimated high-purity germanium (HPGe) detector)
- Chemical/radiochemical characterization (mass spectroscopy)
- Thermal analysis (calorimetry, dilaometry)
- Visual characterization (optical and electron microscopy)
- Machining, disassembly of experiment hardware (shielded hot cells)
- Physical testing (remote tensile load frame for irradiated specimens)
- Fission-gas release measurement (gas assay, sample and recharge system)

Many of these techniques can be conducted without destroying the specimen, which are referred to as non-destructive examination (NDE). Some of these techniques, such as tensile testing and mass spectroscopy, require deforming the entire or a portion of the specimen to gather measurements or prepare samples of the specimen, and are referred to as destructive examination (DE). Finally, many of these specimens are highly radioactive when PIE is needed. This requires heavily shielded chambers, known as hot cells, to house the equipment and experiment for most of these PIE techniques.

While PIE at MFC has been invaluable for the success of previous industrial and government nuclear experiment programs, these processes have the disadvantage of taking place long after experiments have cooled down, been shipped to and received at MFC. While allowing experiments to cool increases the schedule and cost of experiment programs, it also potentially loses valuable experiment information (e.g., short-life isotopes for determining fuel performance). One undercapitalized opportunity with this process is “poolside” NDE in the ATR canal.

1.5 Poolside NDE

The ATR canal is a large cooling pool located adjacent to the reactor core. It contains ~350,000 gallons of demineralized water, but all regions of the canal are frequently utilized for various reactor and experiment operations. This entire volume of water is considered the primary coolant system (PCS). The entire canal is lined with a stainless steel sheet. The edge above is surrounded by 3-ft-tall concrete and/or metal walkways, or parapets, where operators stand to use long-handled tools for various canal activities.

While the ATR canal facility is large and supports many operations, including reactor unloading, experiment assembly and fuel storage, it is seldom used to support experiment or operational NDE. The most obvious reason is that most experiments are not designed for submerged, or poolside, disassembly and/or NDE. Elsewhere in the industry, poolside NDE has long been favored as an examination technique of nuclear fuel and material specimens[13-14].

Historically, ATR poolside NDE has been limited to supporting specific programs or specimens. Figure 1.2 shows a poolside NDE system specifically purposed for high-resolution gamma spectroscopy of fuel rodlets and flux monitoring wires in the ATR canal. Though this design was never developed or installed at ATR, it still presents opportunities for improving ATR operations even today[15], albeit for a limited set of specimens. Other ATR poolside NDE systems have been developed for experiment programs whose objectives required intermediate poolside inspection of specimens prior to reinsertion for more irradiation or shipment for PIE[16]. This has included ultrasonic scanning for measuring fuel plate thickness and coolant channel spacing measurements[17]. Figure 1.3 shows a similar poolside NDE system, which provided fully submerged control of ATR Full-size Plate in Center Flux Trap Position (AFIP) experiments for measuring channel gap thickness and profiles.

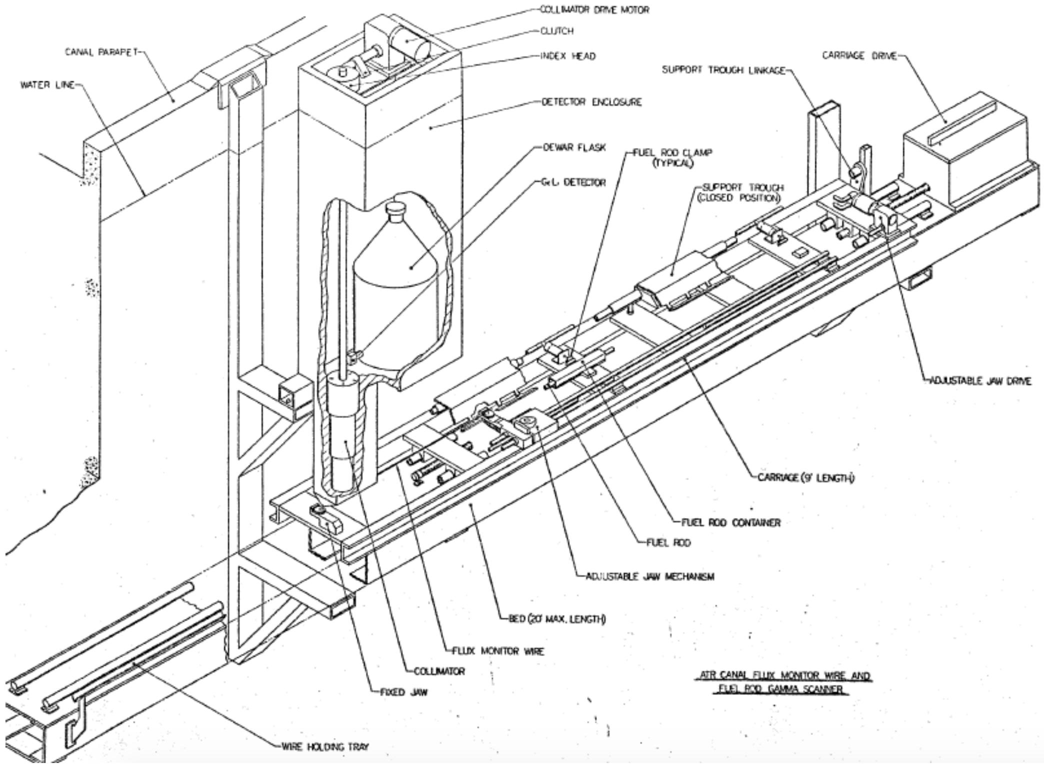

Figure 1.2: 1978 Conceptual design of an ATR canal high-resolution flux wire monitor and fuel rod gamma scanner[15]

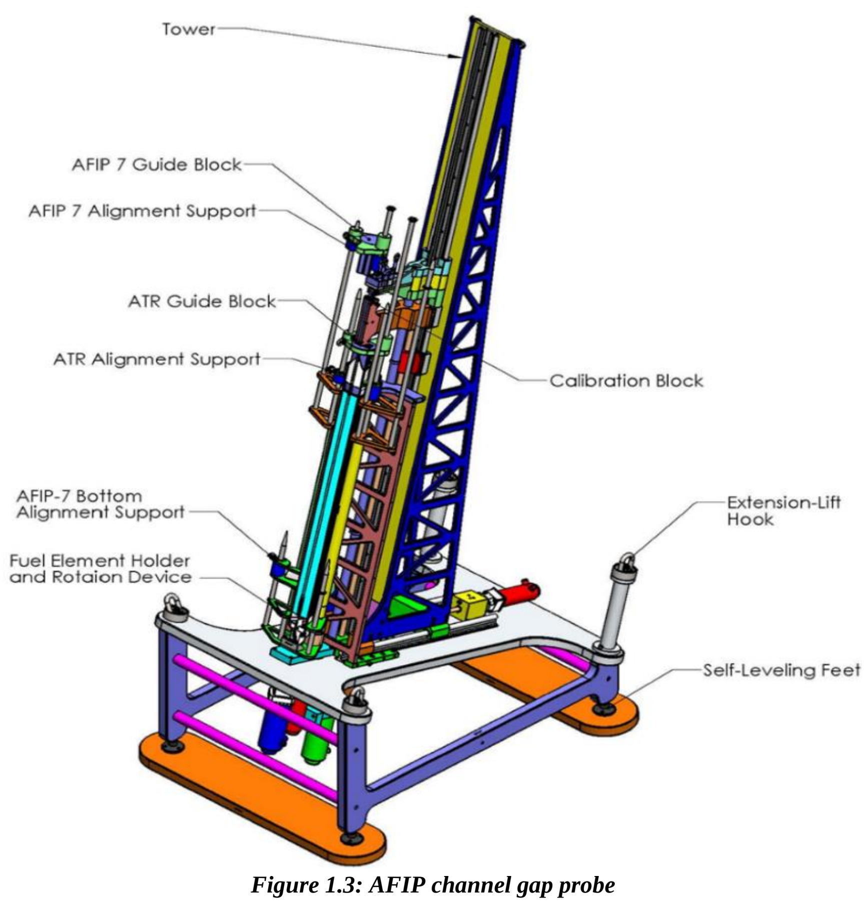

Figure 1.3: AFIP channel gap probe

ATR experiments are not typically examined at MFC in between irradiation cycles because transportation and examination time is prohibitively long when compared to the duration of ATR outages. Instead, experiments are irradiated in ATR for a given number of cycles, and placed in the ATR canal for cooling during outages before reinsertion. At the end of irradiation, the experiment is transferred to the canal where it awaits cask transport to INL's MFC. At MFC, any number of the previously mentioned NDE and DE techniques are used to characterize the specimen of interest in shielded hot cells, glove boxes and/or other facilities or instruments. However, this traditional sequence could pose an issue with certain fueled experiments. For example, static experiments or drop-in capsules could have experienced fuel failure in one of the several ATR irradiation cycles. It would be extremely difficult to ascertain which cycle caused the failure unless some sort of intermediate PIE was conducted, or if an instrumented experiment provided in-situ measurements. If some type of an examination system were available in the ATR canal that provided a host of NDE capabilities, then mid-irradiation examinations of experiments could be provided that otherwise would not be determined without MFC PIE or complex in-situ instrumentation.

Beginning in 2016, INL funded a laboratory-directed research and development project tasked with designing an ATR Non-Destructive Examination System (ANDES) that could conduct poolside PIE of irradiated specimens in the ATR canal. With input from both experiment programs and ATR Operations, ANDES would be the first poolside PIE system that would accommodate a multitude of irradiated specimens from ATR. The following chapter presents the completion of the ANDES conceptual design.

2 CHAPTER 2: FORMULATION OF THE ATR NON-DESTRUCTIVE EXAMINATION SYSTEM (ANDES) MISSION

2.1 Design Methodology

The ANDES conceptual design process was grounded heavily in continuous stakeholder engagement by the ANDES design team. The process used for formulating the ANDES conceptual design began with defining the problem statement. As previously mentioned, no consistent poolside NDE capability exists for providing rapid PIE data between cycles for either ATR specimens (i.e., flux wires, driver fuel) or experiments (e.g., rodlets, plate experiments). ANDES stands to improve data quality, increase operational efficiency and transform irradiation testing at ATR. This problem statement guided the ANDES conceptual design.

Following the definition of the problem statement, the ANDES design team analyzed different examination systems, followed by generating requirements, trade studies and concept development[18]. Several examination techniques were considered and excluded for consideration from ANDES as discussed below (Section 2.3). Stakeholders from both ATR Operations and nuclear irradiation experiment programs were engaged to define the scope of the ANDES system (Section 2.2). These discussions established functional requirements for ANDES. Trade studies were then conducted using these requirements as metrics for ranking the efficacy of certain NDE techniques. Finally, the team generated and down-selected individual NDE subsystem concepts based on their compliance with the applicable requirements (Chapter 3).

2.2 Scope

There are opportunities for ANDES to benefit both ATR experiments and reactor operations. ATR Operations conduct numerous activities that require, or would benefit from, poolside NDE, including cobalt (Co) source assembly, ATR fuel assembly inspection and radiological contamination screening. Similarly, ATR experiments have included gas loops, water loops and drop-in capsules containing different specimens, including metallic fuels, ceramic fuels and structural materials (e.g., stainless steel), that require NDE. When designing ANDES, it is important to be explicit in the portfolio of specimens that ANDES will support. Furthermore, the PIE techniques employed by ANDES must provide the most value from a research perspective, while not comprising existing operational capabilities.

Early in the design process, the ANDES design team held focus group discussions with approximately 40 stakeholders who represented ATR Operations, NDE/instrumentation experts and different ATR experiment programs. From these discussions, the ANDES specimen portfolio and most-attractive and viable PIE capabilities were established. It was determined that the ANDES specimen portfolio should be comprised of (1) ATR Mark-VII fuel assemblies, (2) flux-monitoring wires, (3) drop-in capsules, (4) fuel rodlets with cladding directly exposed to coolant and (5) plate-type capsules and assemblies. General information about each specimen is provided in Table 1.1. Each of these specimens, and the reason for their selection, are briefly described below.

Table 2.1: General ANDES specimen information

Specimen	Specimen Activity (Ci)	Specimen Length (in.)	Specimen Width or Outside Diameter (in.)	Specimen Thickness (in.)	Dry Weight (lb)
ATR Mark-VII Fuel Assembly	2.30E+04 – 3.00E+06	48	4.2	0.045-0.145	40
AFC-4 Fueled Capsule	7.00E+01 – 5.75E+02	8.5	Ø 0.284	NA	< 5 lb
ATF-1 Fuel Rodlet	1.11E+03 – 4.18E+03	6.8	Ø 0.374	NA	< 5 lb
MP-1 Plate Experiment	1.47E+03 – 5.78E+04	8.4	1.0	0.049	< 5 lb
Nickel Flux Wire	5E-03 – 8.1E-01	50-81	Ø 0.020	NA	< 5 lb
Cobalt Flux Wire	5E-03 – 8.1E-01	50-81	Ø 0.040	NA	< 5 lb

Specimen activity is immediately after removal from ATR (i.e., t=0 decay). Flux wire specimen weight reflects SR and BR flux wire holder dry weight.

2.2.1 ATR Mark-VII Fuel Assemblies

The 40 driver fuel assemblies that make up the ATR core are called the Mark-VII fuel assemblies. These assemblies are comprised of 19 concentrically stacked plates, which are cladded in 6061-aluminum around uranium oxide fuel. A cross-section schematic and picture of the Mark-VII fuel assembly is shown in

Figure 2.1.

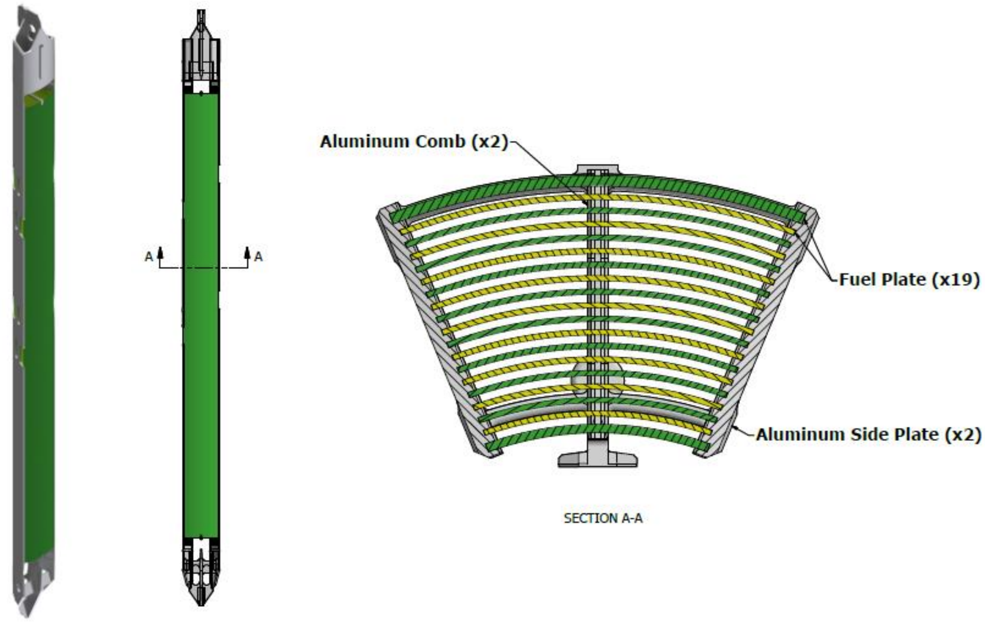

Figure 2.1: Isometric view of Mark-VII fuel assembly (left); Cross-section schematic of Mark-VII fuel assembly (right)

Typically, each ATR fuel assembly is irradiated for one cycle and then placed in the canal for cooling during the next cycle. This repeats until the ATR fuel assembly has been irradiated for several cycles, after which it is placed in the ATR canal for intermediate storage. While ATR Operations do conduct dimensional (i.e., coolant channel gap) and visual inspection of select assemblies, no radioisotopic or burnup characterization is conducted. Furthermore, these existing inspections are unreliable and/or time-consuming.

The maximum use of any ATR fuel assembly is determined by its power. Established burnup thresholds are based on PIE of Mark-VII assemblies from the 1970s[19-22]. However, fabrication techniques and construction materials have changed significantly to the point where mid-irradiation burn-up characterization would be greatly beneficial. The Mark-VII was chosen for the ANDES specimen portfolio to improve the efficiency and quality of ATR fuel assembly inspection.

It should also be mentioned that the Department of Energy (DOE) has listed ATR as one of several research reactors whose fuel will be converted from its 93 wt% ^{235}U highly enriched uranium (HEU) to 19.5 wt% ^{235}U low-enriched uranium (LEU)[23-24]. Intermittent poolside

NDE of ATR fuel could improve confidence in continued irradiation of fuel assemblies and/or inform fuel performance and core models. ANDES would need to accommodate the future LEU version of the Mark-VII assemblies.

2.2.2 Flux-Monitoring Wires

Neutron flux-measuring wires are inserted at various locations throughout the ATR core to monitor its radiation environment. There are two wires that are used to determine the flux levels and axial flux profile. The first wire is a cobalt-aluminum (CoAl) alloy, which is used for measuring thermal neutron flux. The second wire is a nickle (Ni) alloy, which measures fast neutron flux.

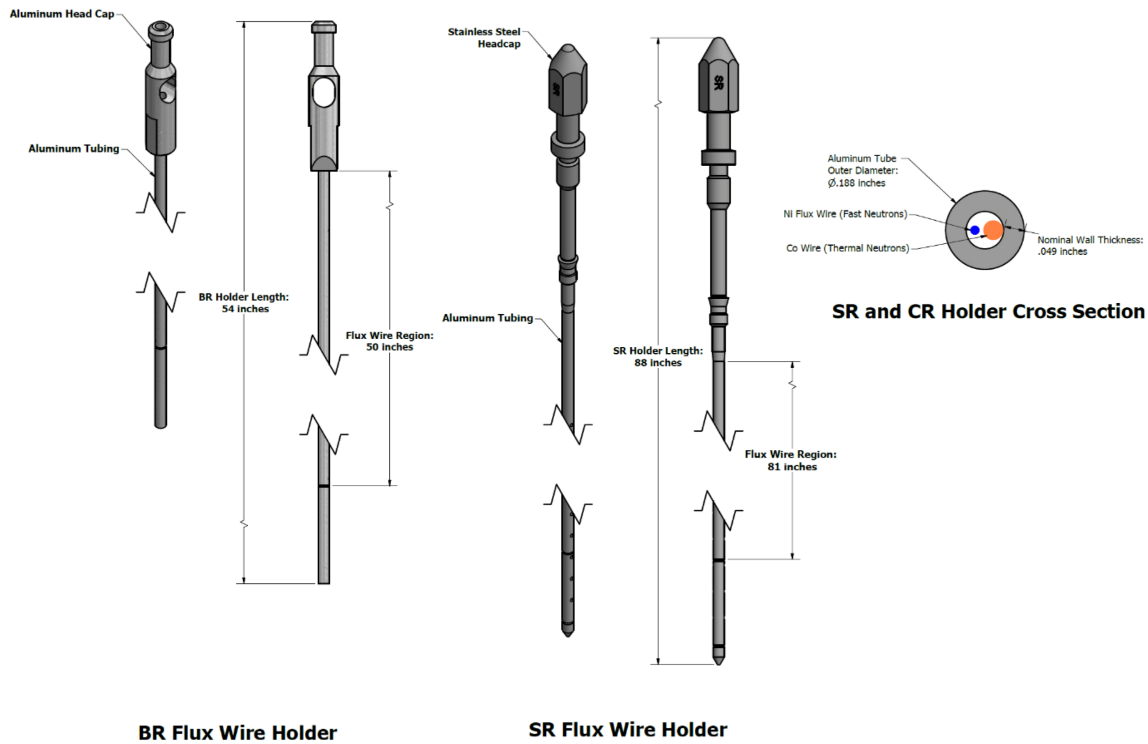

Figure 2.2: BR flux wire holder (left) and SR flux wire holder (middle); Cross-section with flux wires (right)

Each ATR cycle generates approximately 20-30 irradiated flux wire holders, but can vary significantly with reactor and experiment program needs. Following each cycle, each flux wire holder is transferred to the RML flux wire scanning station in the working canal. Each flux wire holder is dismantled by removing the bottom spacer with a tube cutter, and then each individual wire is pulled out of the holder using long-handled tools.

These specimens were chosen for the ANDES portfolio because of the continuing need to characterize reactor neutron flux and the potential benefit of using upgraded equipment with increased efficiency. Also, as described in Section 2.4, the location chosen for ANDES installment is the current flux wire measurement area.

2.2.3 Static Capsules

Static capsule specimens typically include smaller rodlets, and frequently, the goal of these experiments is to analyze specific irradiation-induced changes in the specimen. The primary disadvantages of static experiments are the inability to control specimen environment and ascertain specimen integrity in between cycles. ANDES could provide unique benefits to static capsules by giving between-cycle information. Ultimately, this could save time and resources by minimizing the need for subsequent cycles if the specimen has failed, and could provide higher quality experiment data. For conceptual design, the Advanced Fuel Cycle (AFC)-4 experiment campaign capsule was chosen as a representative static capsule (Figure 2.3).

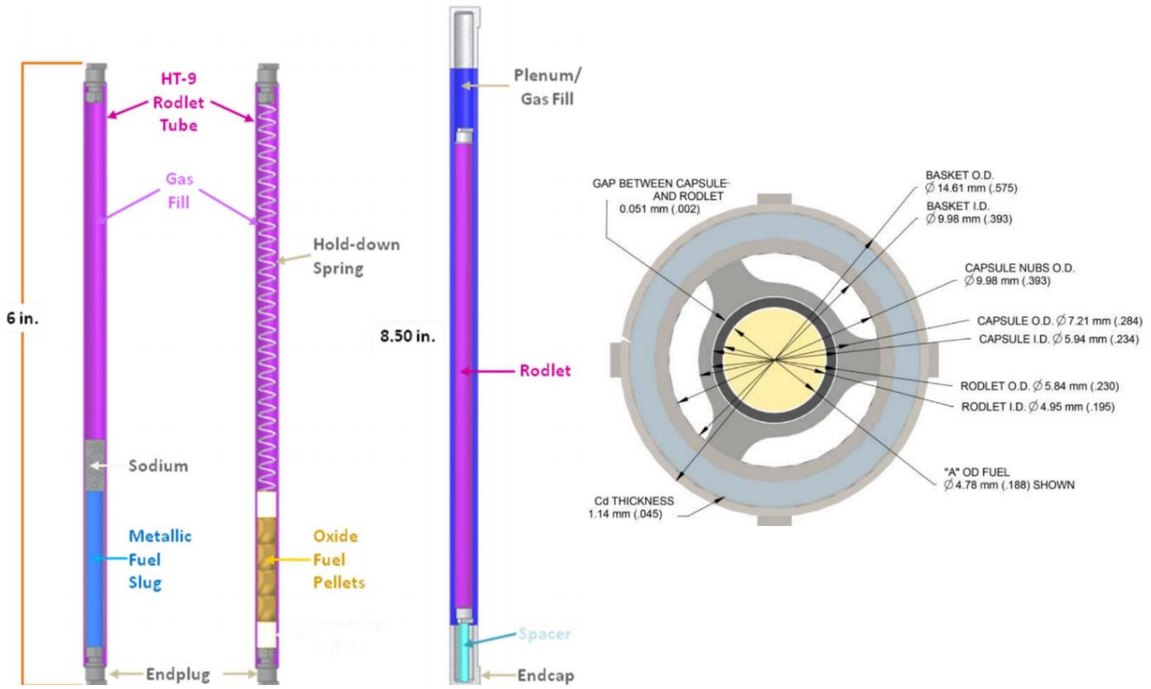

Figure 2.3: AFC-4 rodlet assembly and inner test train assembly (left); Cross-section of AFC-4 capsule contained in cadmium-lined experiment basket (right)[25]

2.2.4 Bare Rodlets

ATR experiments oftentimes require in-canal assembly prior to insertion into, or between irradiation cycles. Historically, this has involved a test train assembly, where specimens and their instrumentation are inserted into experiment containment hardware in a specified configuration. This means that bare rodlets, with their cladding directly exposed to the PCS and therefore visible, could be available for poolside NDE using ANDES. These NDE techniques could specifically include dimensional analysis (i.e., swelling, cladding elongation) and oxide thickness measurements. Like drop-in capsules, the integrity of rodlet specimens is often unknown during irradiation. Depending on assembly and disassembly processes, inspecting or analyzing rodlet specimens could be conducted to provide valuable between-cycle specimen integrity or inspection information. Bare rodlets were, therefore, chosen as a specimen to be included in the ANDES portfolio. The Accident-Tolerant Fuel Experiment, Phase 2 (ATF-2) light water reactor (LWR) reference rodlets were chosen as a representative specimen for ANDES conceptual design due to its recent use and similarity to other historical LWR rodlets (Figure 2.4). It should be noted that both LWR and metallic fuel-containing rodlets (e.g., AFC-4) could conceivably be used in ATR experiments.

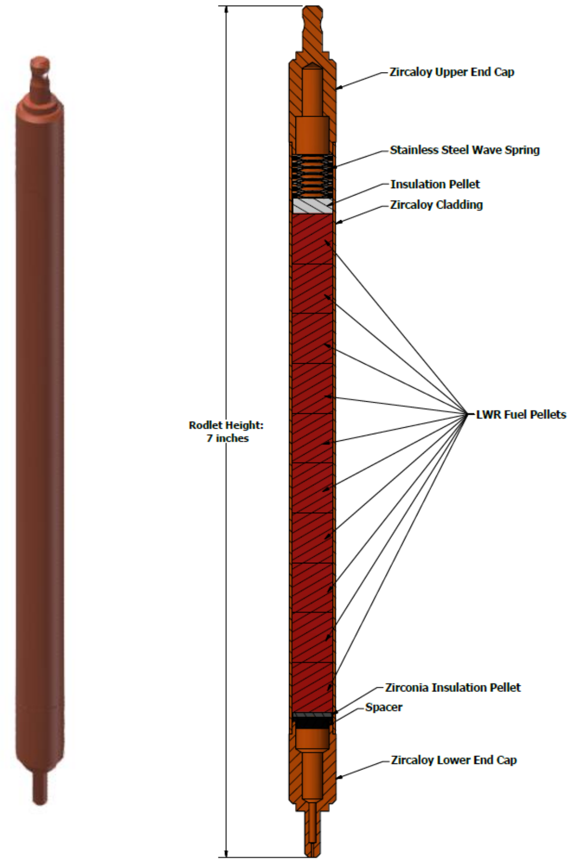

Figure 2.4: ATF-2 LWR rodlet

2.2.5 Plate-type Experiments

The opportunities of poolside NDE for plate-type experiments are similar to those of drop-in capsules and bare rodlets. However, the obvious difference in form factor, and the unique PIE of fueled plates compared to rodlets necessitated specific inclusion in the ANDES specimen portfolio. There have been many plate-type experiments within ATR (Figure 2.5). The AFIP experiment had a plate assembly that was quite large, having an active length comparable to the ATF Mark-VII fuel assembly's active length. Other experiments used smaller hardware, such as the mini-plate-1 (MP-1) capsule. The MP-1 capsule with its 3-4 plate specimens directly exposed to the PCS, has a much smaller geometric footprint, and was chosen as a basis for ANDES conceptual design (Figure 2.5).

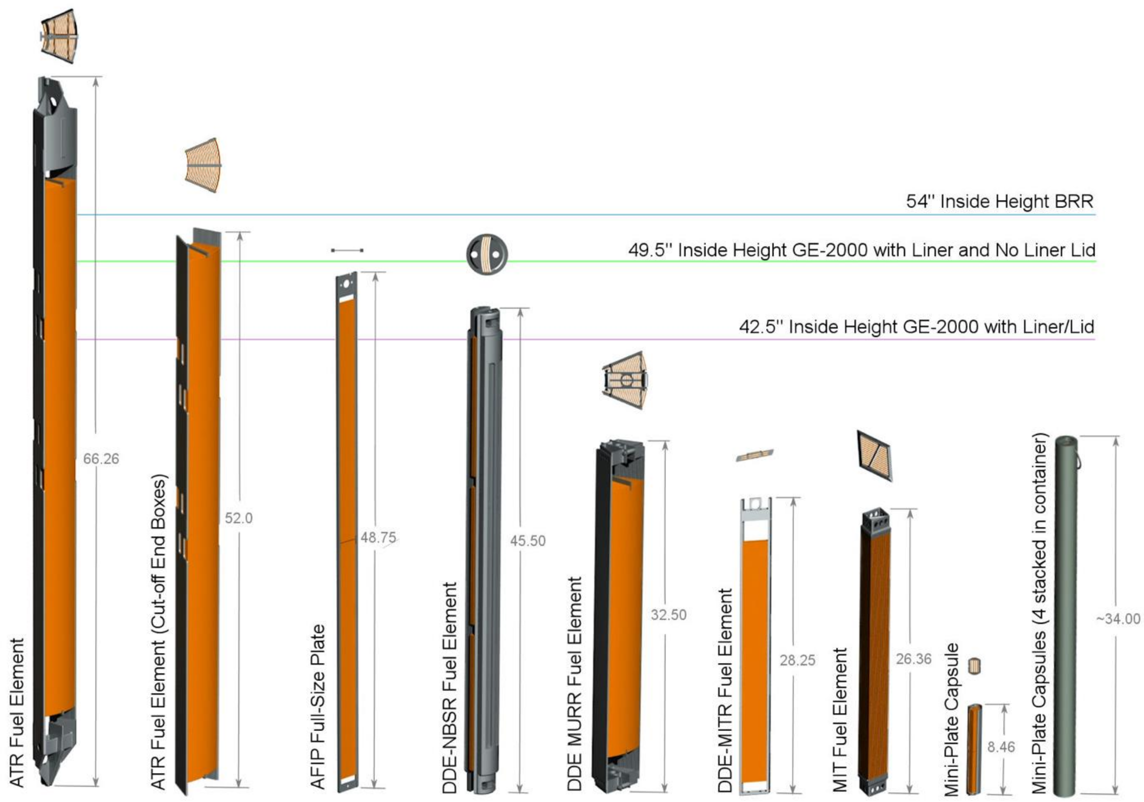

Figure 2.5: Plate-type experiment overview[26]

2.3 ANDES NDE and Support Systems

The ANDES design team held focus group discussions were also held to determine the baseline PIE capabilities that ANDES would provide for the specimens. It was established early on that the ATR canal was not a suitable location for destructive dismantling of experiment hardware or ATR fuel specimens. DE techniques (e.g., tensile testing, gas sampling) were eliminated from consideration. Given the large researcher presence in these focus group discussions, many different NDE techniques immediately proposed measured a range of properties or phenomena.

These techniques were classified into the following examination functions: (1) High-Resolution Burnup and Spatial Radioisotope Distribution, (2) Dimensional Analysis, (3) Exposed-Surface Inspection, (4) Internal Features Characterization and (5) Handling, Orientation and Manipulation. Individual techniques within each of these examination functions were compared through trade studies. A brief discussion on each of these functions and the down-selected techniques are described below. Detail regarding the functional design is described in Chapter 3.

2.3.1 High-Resolution Burnup and Spatial Radioisotope Distribution

From the focus group discussions, one of the most resounding needs for ANDES was a method for measuring the location of radionuclides within fueled experiments and intensity within flux monitors. This function was recommended as a baseline capability for ANDES due to its promise for validating as-run neutronics models for experiment programs, while improving ATR driver fuel management and reactor power control for ATR operations. In contemporary PIE, this is typically accomplished by gamma spectroscopy using a high-resolution gamma detector focused by a long collimator. Underwater gamma spectroscopy is widely practiced commercially[27], and was deemed as a viable technique for providing this function. The focus group requested the ability to change out detectors to accommodate a wider range of specimens, whose activity and geometry call for different spectral resolution or efficiency. The technique selected for this ANDES function was an interchangeable gamma detector system with a collimated gamma beam for high-resolution, underwater gamma spectroscopy.

2.3.2 Internal Features Characterization

Focus group discussions identified gamma CT as a prioritized ANDES capability. In addition to gamma spectroscopy, it was also requested that ANDES to characterize three-dimensional subsurface phenomena, including oxide thickness, fuel relocation and fuel annulus changes. The ANDES design team considered ultrasonic techniques. While ultrasonic detection can be valuable for determining traits such as oxide layer thickness, it is limited for specimens not specifically designed to accommodate this NDE technique. Infrared imaging was also proposed, albeit more of a qualitative technique. Non-contact techniques such as neutron scatter or X-ray tomography can provide exceptional spatial resolution in air, but are severely limited in a submerged environment. Gamma CT was proposed, along with gamma spectroscopy, to determine specimen density and the three-dimensional distribution of radioisotopes within the specimen.

Gamma CT is classified as two types: emission and transmission. Emission gamma CT relies on the emitting gamma energy from the specimen itself to provide information on the spatial location of radioisotopes. The specimen is then rotated on an axis in view of the detector, which measures planar images with each angular rotation of the specimen[28]. These images can then be reconstructed to form a three-dimensional image of the specimen's radionuclide composition[29].

However, emission gamma CT is not capable of discerning internal features such as cladding-fuel gaps or cracks. Transmission gamma CT uses a high-energy gamma emitting source to transmit gamma energy through the specimen and into the detector. This technique is valuable for measuring the attenuation-coefficient distribution of different materials within the specimen, which makes it possible to characterize density of specimen materials within the sample. This technique has been demonstrated previously above water on irradiated specimens[30]. If properly sized and designed, such a technique could have the resolution sufficient for reconstructing three-dimensional images showing the density of materials for a variety of nuclear fuels and cladding materials. Given the wide variety of specimens within the ANDES portfolio, the design team chose both emission and transmission gamma CT for providing internal feature characterization.

2.3.3 Dimensional Analysis

Irradiation-induced deformation is expected for experiments and other specimens. Deformation includes swelling, axial elongation and surface damage. For most experiments, the extent of this deformation is not characterized until PIE is possible. Similar to internal features characterization, linear variable differential transformer (LVDT)-based contact profilometry was considered to characterize rodlet or capsule swelling. Contact profilometry methods are currently practiced at ATR. For example, Mark-VII assemblies undergo inspection prior to insertion. This includes both profilometry visual inspection by pasting a self-curing rubber on top of plates 1 and 19, and then peeling of the cured layer and inspecting gouge depths. Channel gap probe measurements of the Mark-VII are conducted using a strain gauge that measures the distance between plates by running the strain gauge along the axial length of the assembly. However, these techniques have had questionable reliability[31] and are specifically geared to one dimensional characteristics (e.g., plate buckling, cladding swelling) and would not be applicable to the form factors of certain specimens within the ANDES specimen portfolio.

The ANDES design team chose underwater laser metrology was as a flexible, non-contact, high-resolution dimensional measurement technique. This technique projects a laser onto the specimen’s surface, and any deformation of the incident beam is detected by an adjacent high-resolution camera. This deformation is recorded as a point cloud, and then exported for post-processing using computer-aided design (CAD) software. The result is a three-dimensional rendering of a specimen’s surface. This technique has been demonstrated commercially by analyzing defects of spent PWR and boiling water reactor fuel bundles with micron-scale resolution[32].

2.3.4 Exposed-Surface Inspection

As previously mentioned, ATR Mark-VII assemblies undergo visual examination prior to reactor insertion. This process consists of placing the fuel assemblies on a rotating stand in view of a radiation-hardened video camera. This same camera is used for the Mark-VII assembly channel gap probe measurements. However, the camera lacks pan/tilt capability, meaning that the camera must be manually moved into position and zoomed in and out to retrieve the desired image. Underwater infrared videography was proposed as a method of characterizing surface temperature profiles and potentially subsurface phenomenon (e.g., molten fuel pool). However, the lack of commercially-available radiation-hardened infrared cameras, combined with the limited benefit when considering the already available NDE techniques, limited ANDES to high-resolution, radiation-hardened optical videography to enable qualitative NDE. The ANDES design team determined an enhanced underwater videography capability was needed potentially support these activities and aid specimen handling.

2.3.5 Handling, Orientation and Manipulation

In the ATR canal, long-handled tools are used to manually transfer specimens and hardware to various locations throughout the canal. Specimens containing fissile material must not come within 6 ft of the canal water surface, per ATR facility requirements. All the ANDES specimens, except flux-monitoring wires, are considered fissile material due to their uranium-235 equivalent content. Flux-monitoring wires are not considered fissile material, but still are handled remotely 2-3 ft underwater during flux wire scans to comply with radiological contamination requirements. The ANDES design team determined that a handling system would need to accommodate the ANDES specimen portfolio, operate reliably underwater and provide high-resolution movement of specimens as dictated by the NDE technique being employed. In addition, the ANDES handling system should also accommodate hardware for channel gap probe measurements of Mark-VII fuel assemblies.

2.4 ANDES Siting in the ATR Canal

The ATR canal is the most opportune area for a poolside NDE system for ATR experiments. It is broken up into three main areas: storage canal, working canal and the ATR Criticality Facility (ATRC) canal (Figure 2.6).

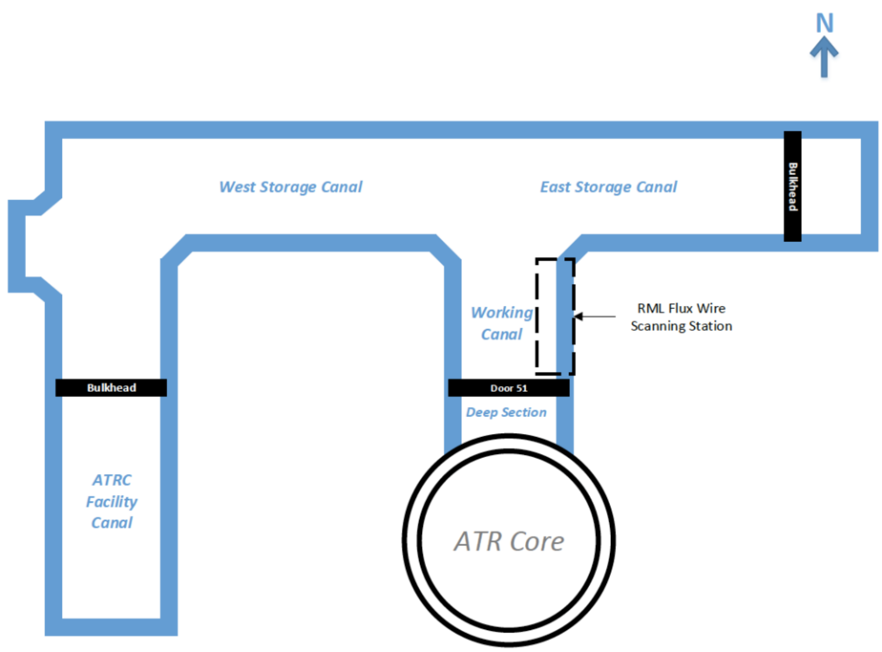

Figure 2.6: Top-view of ATR canal

The storage canal is one the most high-traffic areas of the canal facility. The west end of the storage canal is where the storage, handling, assembly and disassembly of various ATR experiments and other hardware takes place. The east end of the storage canal is primarily where ATR fuel assemblies are stored between cycles or after use and awaiting disposition. The storage canal itself is 8 ft wide x 156 ft long. The parapet permits manual handling of various types of ATR hardware (Figure 2.7). The operating depth of the storage canal is 20 ft.

Figure 2.7: ATR canal operators working from the parapet in the west storage canal [33]

The working canal comprises only a small portion of the canal, but is the pathway through which anything going to and from the ATR core must pass. It is 2 ft deeper than the storage canal, giving it a water depth of 22 ft. The working canal is also adjacent to another deep section, where a drop tube connects the canal to the ATR core. During reactor operation, this deep section is separated from the working canal by a concrete barrier called Door 51. On the east side of the working canal, ATR's Radiation Measurements Laboratory (RML) has a submerged sodium-iodide (NaI) gamma detector for scanning flux-monitoring wires.

Several locations within the ATR canal were identified as potential locations to position the ANDES system. Working with ATR Operations staff and other canal users, four different locations within the canal were considered as potential ANDES locations (Figure 2.8). The preferred location is described below. Additional information on the alternate locations can be found elsewhere[34].

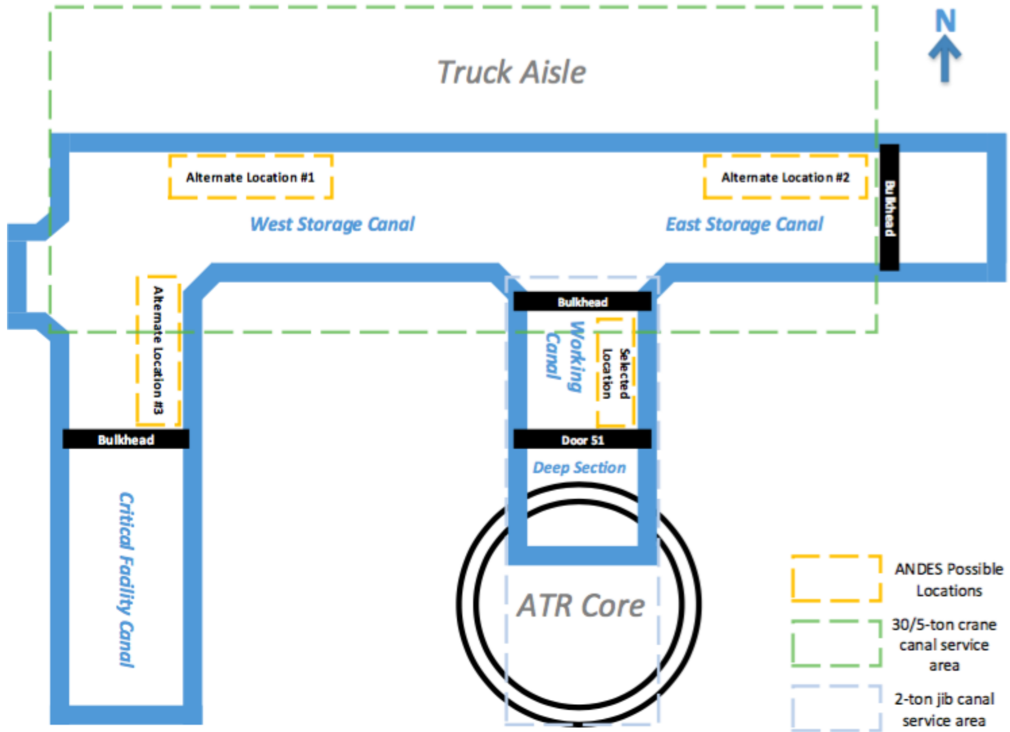

Figure 2.8: ATR canal locations for ANDES

The selected canal location identified for ANDES is in the working canal east wall in the existing RML flux wire scanning area. This location is defined by a 10 ft (L) × 3.5 ft (W) × 35 ft (H) footprint in the canal area. The length is the distance between Door 51 and the bulkhead that separates the working canal and the storage canal. This bulkhead is not usually installed, no permanent structure should impede its ability to be rapidly installed in case of a loss water level. The footprint width is less than half of the overall canal width (8 ft) to minimize interference with canal operations. The height of this footprint is the water depth in the working canal (22 ft) plus 13 ft above water to allow personnel to operate ANDES equipment and permit automated specimen handling.

Advantages of this location include minimal traffic and infrequent use; proximity to specimen storage (i.e., reactor fuel, experiment holders and experiment hooks); no interference with reactor-canal transfers; access to the 2-ton jib crane and 5-ton overhead cranes; and closeness to the low-pressure demineralized water (LDW) makeup valve for a potential approved fuel storage design.

One condition of using this area is that the ANDES system would be required to maintain the current flux wire scanning capabilities. One of the base capabilities for the ANDES system is a gamma detector capable of serving this function as described later in Chapter 4.

At this location, ANDES could include a temporary parapet extension to permit ease of specimen and material transfers across the east and west ends of the working canal. A potential disadvantage of the selected location is the adjacency to the deep section, which poses the risk of dropping equipment near high-activity specimens freshly discharged from the reactor. This is an issue already facing the RML flux wire scanning station and can be overcome either with robust handling processes or by only handling during reactor runs (i.e., when Door 51 is closed).

Finally, there are numerous pieces of equipment on the canal floor at the selected ANDES location. This hardware will need to be relocated or discarded to make room for ANDES. This challenge is not unique to the selected location. To use this space, these materials will need to be relocated and the existing wire scanner will need to be removed.

3 CHAPTER 3: ATR NON-DESTRUCTIVE EXAMINATION SYSTEM (ANDES) CONCEPTUAL DESIGN

The functions listed in Section 2.3 correspond to individual ANDES subsystems: (1) high-resolution burnup and spatial radioisotope characterization (gamma spectroscopy), (2) remote specimen handling, enhanced optical videography, (3) gamma computed tomography, (4) approved storage and (5) working tray/operations platform. The large specimen portfolio and diverse capabilities pose a risk of not having the throughput capacity to support the many ATR operational and programmatic needs. The ANDES conceptual design herein is described as a modular system, with baseline functionality of gamma spectroscopy and specimen handling. This format is intended to aid potential capability down-selection for final design and deployment.

Each subsection of this chapter contains an overview of the design rationale and hardware of its respective sub-system. While critical requirements are mentioned in each section, detailed technical and functional requirements can be found in Appendix A. A more detailed presentation of the gamma spectroscopy system design is presented in Chapter 4.

Generally, all systems will have a connection to the ANDES Data Acquisition and Control System (ADACS) for data visualization, post-processing, handling control, scanning control and other important functions. This portion of ANDES is not explicitly addressed in this document. More detail on the requirements and features of the ADACS can be found elsewhere[34].

3.1 Baseline Capability – Underwater Gamma Spectroscopy

Previous poolside NDE system designs at INL served as a starting point for the design of the ANDES gamma spectroscopy system[35]. The old systems used a stationary HPGe detector that enabled high-resolution gamma spectroscopy of irradiated specimens (fueled and unfueled). Some more recent approaches have offered the ability to use different detectors[36]. Given the high levels of background radiation in the working canal and desired spatial resolution, a long collimator was chosen to provide the necessary shielding and to focus the incident gamma energy coming from the specimen to the detector. Using a collimator of this mass, it was determined that the specimen would have to move relative to the stationary gamma detector and collimator assembly to achieve the needed spatial resolution. The novel nature and importance of this gamma spectroscopy system to ANDES is a focus of its conceptual design. Therefore, specific detail on the gamma spectroscopy system is provided in Chapter 4.

3.2 Baseline Capability – Remote Specimen Handling

The handling system was designed by another ANDES team member. However, its design and requirements are discussed here for a complete presentation of the ANDES conceptual design. More detail can be found elsewhere[34].

The position resolution of the handling system is of importance for ANDES. Comparable handling systems for in-cell gamma spectroscopy[28], along with the size of internal feature characteristics were the basis for specifying the positioning tolerance requirement. The precision gamma scanner (PGS) at the Hot Fuels Examination Facility (HFEF) specifies a linear position resolution of ±0.001 in., with repeatability of +/-0.003-0.005 in. using a three-axis lead screw handling system[37]. A comparable positional tolerance of ±0.001 in./ft was selected for the ANDES handling system. This resolution is also sufficient for providing spatial accuracy of <5% with respect specimen cross-sectional geometry, cladding thickness, fuel annulus, plate thickness and other attributes[25, 38-41]. This positioning accuracy would apply to the three linear degrees of freedom. This accuracy would not be sufficient for fuel chemical-cladding interaction (FCCI), which often requires DE and detailed microscopy for sufficient analysis. Similar processes served as the basis for the angular repeatability about the vertical axis of ±0.5 degrees.

Given the anticipated specimen radioactivity (Table 2.1), maximizing the distance between handling electronics (e.g., motors) and specimens was deemed a priority for maintaining high-precision, robust handling and ease of maintenance.

The ANDES handling system is comprised of a cantilever structure. The cantilever structure supports a horizontal, lead screw cross-slide above the water that suspends a vertical axis tube, which holds the specimen of interest. The cross-slide is controlled by two independent lead screws driven by servo motors that are guided by linear rails. These two motors provide the first two degrees of freedom (i.e., forward/backward and left/right), with four inches of total movement possible in each direction. Through the center of the cross-slide is a hole, which the vertical axis tube passes through and is partially submerged. This axis tube holds a vertical lead screw that is mounted at both ends using bearing supports. The top end of the screw is coupled to a servo motor. This servo motor, combined with an absolute encoder, provides high-accuracy vertical movement of the axis tube and the specimen supported by the axis tube. The bottom of the vertical axis tube has a platform holding a rotating bearing and gear. This gear is connected to another servo motor above water via a long shaft that provides rotational movement about the vertical axis. The specimen sits on top of this bearing and rotating gear, permitting full rotational movement. This concept avoids submerging any motor electronics Figure 3.1.

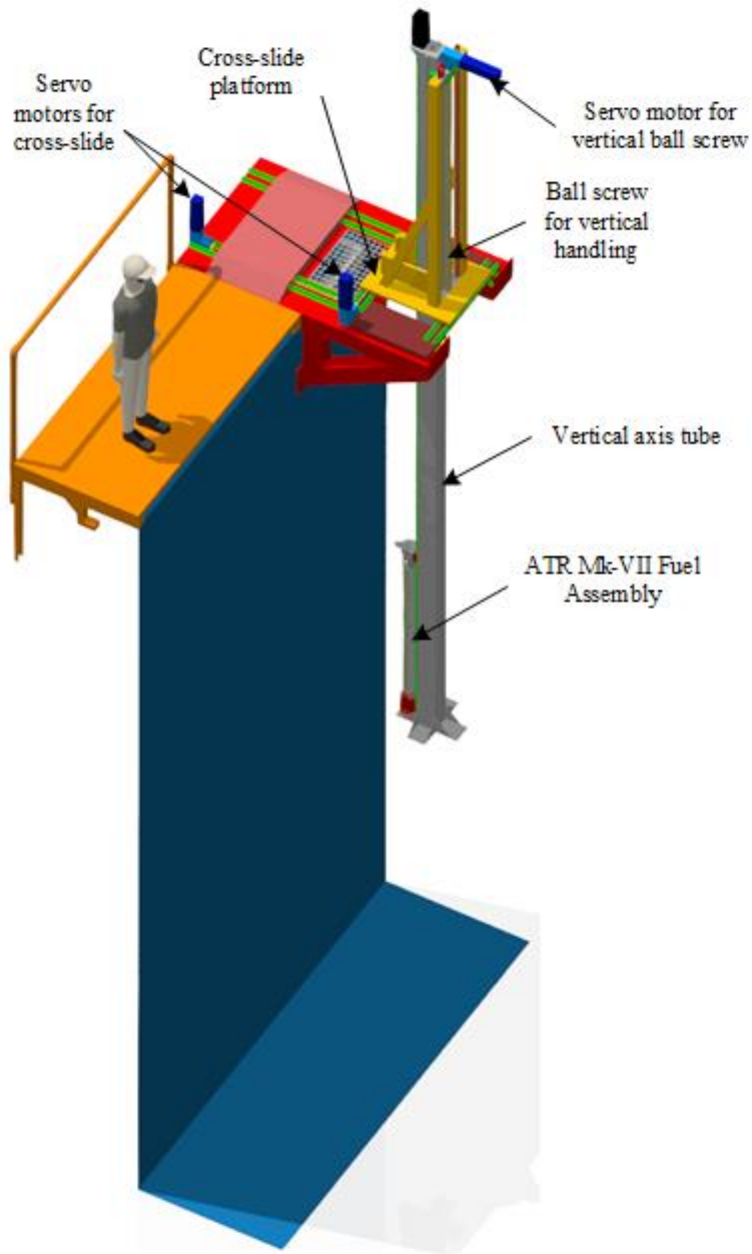

Figure 3.1: ANDES handling system concept

3.3 Enhanced Optical Videography

There are currently two modular radiation-hardened camera systems that are used at the working tray and the fuel inspection station in the ATR storage canal. Discussion with ATR Operations confirmed that the current camera systems have adequate resolution for inspection of experiment hardware and ATR fuel assemblies. The current camera unit is an S-8110 pan-tilt-zoom (PTZ) unit manufactured by R.J. Electronics (Figure 3.2), and the specifications of this camera were established as a benchmark for other radiation-hardened camera requirements. The S-8110 has a moderately rated radiation dose and dose rate of 40,000 Rad and 1,000/Rad/hr at 1 MeV, respectively. A tungsten-shielded unit is also available, which increases the rated dose up to 3.6E+06 Rad.

Since the ANDES camera system was anticipated to be used more frequently than the S-8110, the design team considered additional units with dose limits up to 5E+08 Rad and dose rates up to 3E+06 Rad/hr. Figure 3.2 shows an example unit manufactured by Diakont. The current ANDES design permits moving the camera away from specimens to minimize dose, so an ultra-radiation hardened camera may not be required. Furthermore, R.J. Electronics are familiar with ATR operations, and so the S-8110 PTZ is the preferred camera for the ANDES videography system.

Figure 3.2: R.J. Electronics S-8110 PTZ camera (left); Diakont D40 ultra-radiation hardened camera with no pan-tilt assembly (right)

The camera unit will be handled using a wall-mounted lead screw assembly. This handling system will provide automated vertical movement of the camera unit. This lead screw will be 12 ft long to capture high-resolution video of specimens approximately 12 ft underwater. The screw will be mounted at both ends by bearing supports, and coupled to a stepper motor on the top side of the lead screw. The camera will be mounted onto a plate, which is fastened to the lead screw nut and guided by linear rails on both sides of the screw. All materials used in this vertical drive system will be comprised of corrosion resistant and radiation-tolerant materials (i.e., polyether ether ketone, or PEEK, polymer, stainless steels). Specifications for the camera and its accompanying handling system are presented in Table 3.1. Calculations showing how the lead screw and motor were sized for this application are presented in Appendix B.

Table 3.1: Videography system specifications for ANDES

	ANDES Specifications	**Identified Supplier**
Camera Rated Radiation Dose (Rad @ 1MeV)	3,600,000	R.J. Electronics
Camera Rated Radiation Dose Rate (Rad/hr @ 1MeV)	1,000	R.J. Electronics
Camera Weight (lb)	13	R.J. Electronics
Lead Screw Material	303 SST	Haydon Kerk
Lead Screw Dimensions (Length, Diameter – Lead) (in.)	144, 7/8-1.0	Haydon Kerk
Bearing Mount Configuration	Simple-Fixed	National Precision Bearing
Driving Motor Type (Size)	Stepper	Kollmorgen (NEMA 34)
Screw Rated Load (lb)	70	NA
Maximum Speed (rpm)	200	NA

The camera system position will be controlled by a simple switch at the operator control station. Feedback of camera position will be provided to the operator by a digital gauge indicating vertical position of the camera. The ANDES design team determined that the camera would need independent vertical movement to capture imagery of ANDES specimens and help with manual operations. Since the camera will have PTZ capability, forward/backward and left/right movement are not necessary to obtain specimen imagery. The lead screw will be driven by a top-side stepper motor to provide holding torque of the camera in case of power loss. Limit switches will be installed at the ends of the lead screw to prevent the operator from driving the camera system beyond the lead screw. An absolute encoder will provide camera position to the operator at ADACS. Figure 3.3 provides an overview of the camera and its handling system.

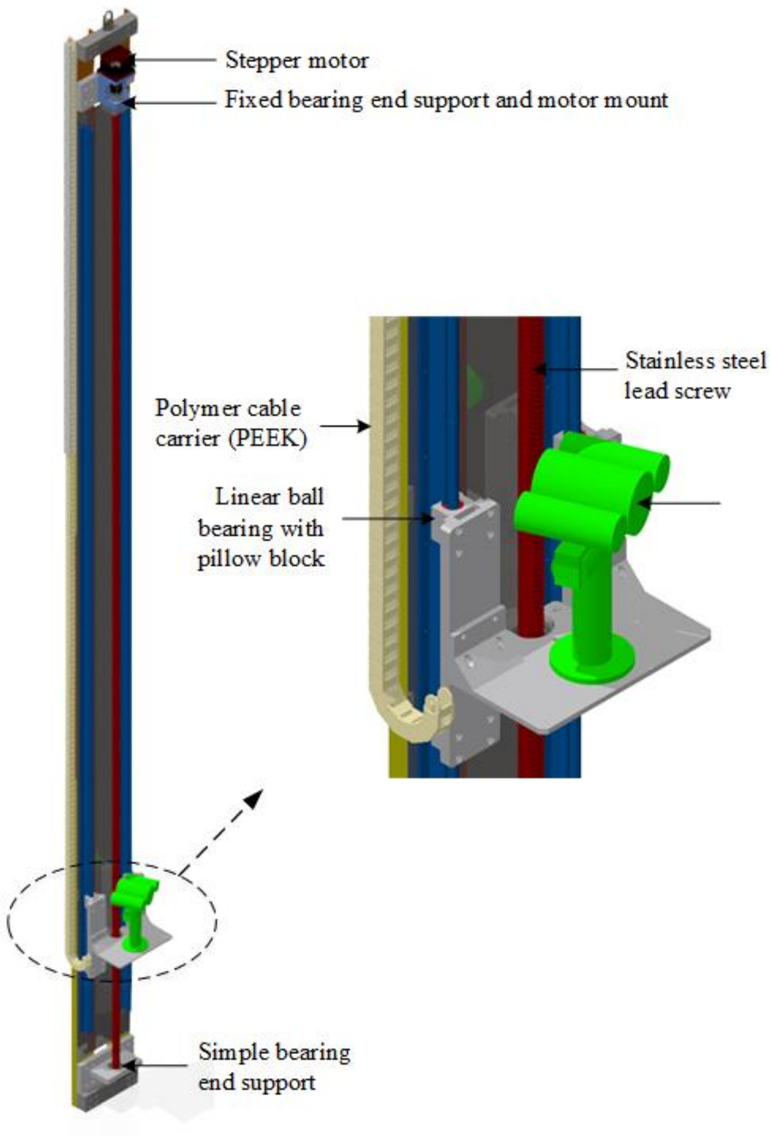

Figure 3.3: ANDES camera handling system

3.4 Gamma Computed Tomography

While gamma CT has been commercialized for characterizing liquid radioactive waste[42] and also used for PIE of nuclear fuel[30], underwater gamma CT for characterizing internal features of fueled specimens has not been demonstrated. As a prioritized capability, ANDES seeks to incorporate such a concept, using the same gamma detector and collimator described in Chapter 4 with minor hardware modifications.

First, the ANDES design team assumed that gamma CT would solely be of interest for fueled experiments, and not for flux wires or ATR driver fuel. Currently, flux wires only require gamma spectroscopy for measuring the intensity of specific gamma energies, which means gamma CT for characterizing internal features would be unnecessary. Characterization of the Mark-VII fuel assembly internal features could be of interest. However, accurately reconstructing a tomographic image of the 19 concentrically stacked plates could be difficult, meaning some geometries may be too complex for gamma CT. Therefore, only three of the five specimens were determined to use ANDES gamma CT: rodlets, capsules and plate-type experiments.

Second, the internal features of interest were determined to be irradiation growth and swelling, fission gas release fractions, and fuel product and constituent migration. These features are key performance parameters that have been specifically outlined in previous PIE reports for other fueled experiments[43]. As previously mentioned, FCCI would not be considered due to the high degree of spatial resolution required to obtain meaningful subsurface information.

Finally, the ANDES design team considered the two techniques for gamma CT, transmission and emission. Discussions with gamma spectroscopy and CT experts indicated that transmission techniques would be needed to characterize features such as density, and that a europium-152 source would be ideal due to its characteristic gamma energies. The ANDES design team determined that the gamma CT system will, therefore, include the capability for emission and transmission gamma CT. ANDES will have a source holder across from the gamma collimator and aperture that will be sized to accommodate the common Co-60 capsules in ATR (Figure 3.4). These capsules and other gamma-emitting sources will be loaded into this holder for transmission CT and for calibration purposes.

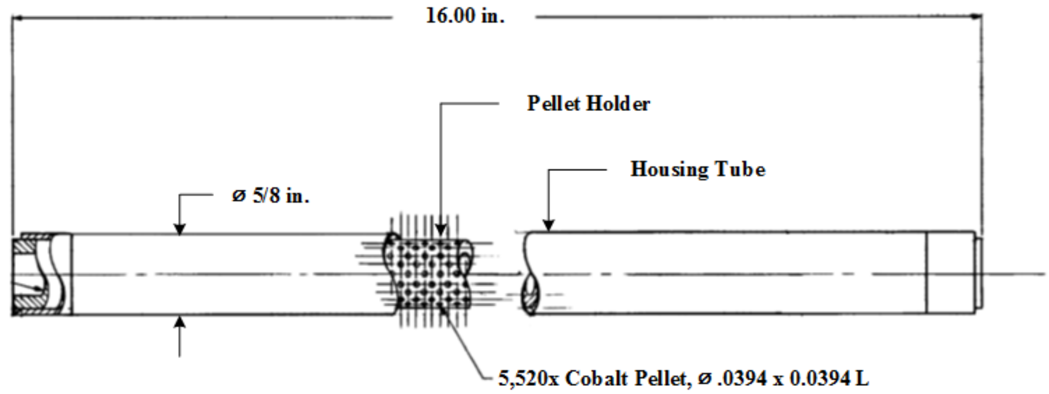

Figure 3.4: Co-60 capsule source[44]

Gamma CT scans will take an exceptionally long time to complete, even for specimens as small as rodlets. For example, gamma CT scans of metallic fuel-bearing capsules took seven days of continuous scanning using the PGS[45]. Careful consideration should be given to gamma CT and the additional hardware that would be needed to support it (e.g., approved storage containers). The accompanying gamma CT software will also be of extreme importance for data collection and visualization. Both commercially available and developing software platforms will be considered for final design[46-47].

3.5 Underwater Laser Metrology

As previously mentioned, laser metrology will be used for conducting high-resolution profilometry and generating high-quality 3D surface renderings that can be used to identify profile changes, swelling, surface damage and corrosion.

Typically, NDE dimensional analysis and profilometry are conducted using contact-measurement techniques such as LVDT. These consistently provide ±0.003 in. linear accuracy with microinch resolution, depending on the sensitivity of downstream electronic equipment[48-49]. Recognizing the ANDES operating environment, the design team selected a ±25 µm (0.001 in.) resolution as a benchmark for laser metrology.

Newton Laboratories was identified as a supplier with experience in underwater laser metrology for nuclear applications. Newton offers a laser scanner capable of providing ±50 μm (0.002 in.) raw accuracy, and down to ±10 μm (0.0003 in.) resolution with post-processing and a 6-in. field of view. Newton would need to design and provide their own handling system for the scanner to meet the required spatial resolution. The current handling system concept shows the same system that is used for the camera (i.e., lead screw with stepper motor drive).

Figure 3.5: Newton Labs underwater laser scanner selected for ANDES[50]

The laser scanner is proposed to be positioned on the ANDES handling system as shown in Figure 3.6. Although Newton may design the handling system, it is assumed that this laser scanner will be mounted to the canal wall very similarly to the radiation-hardened camera discussed previously (Section 3.3), with one hardware difference. The top-side motor will likely be a stepper motor combined with an optical encoder for ultra-high accurate control and feedback during automated scanning. This overall layout will require the previously mentioned handling system to position the specimen within 6 in. of the scanner to achieve the ±10 μm (0.0003 in.) resolution.

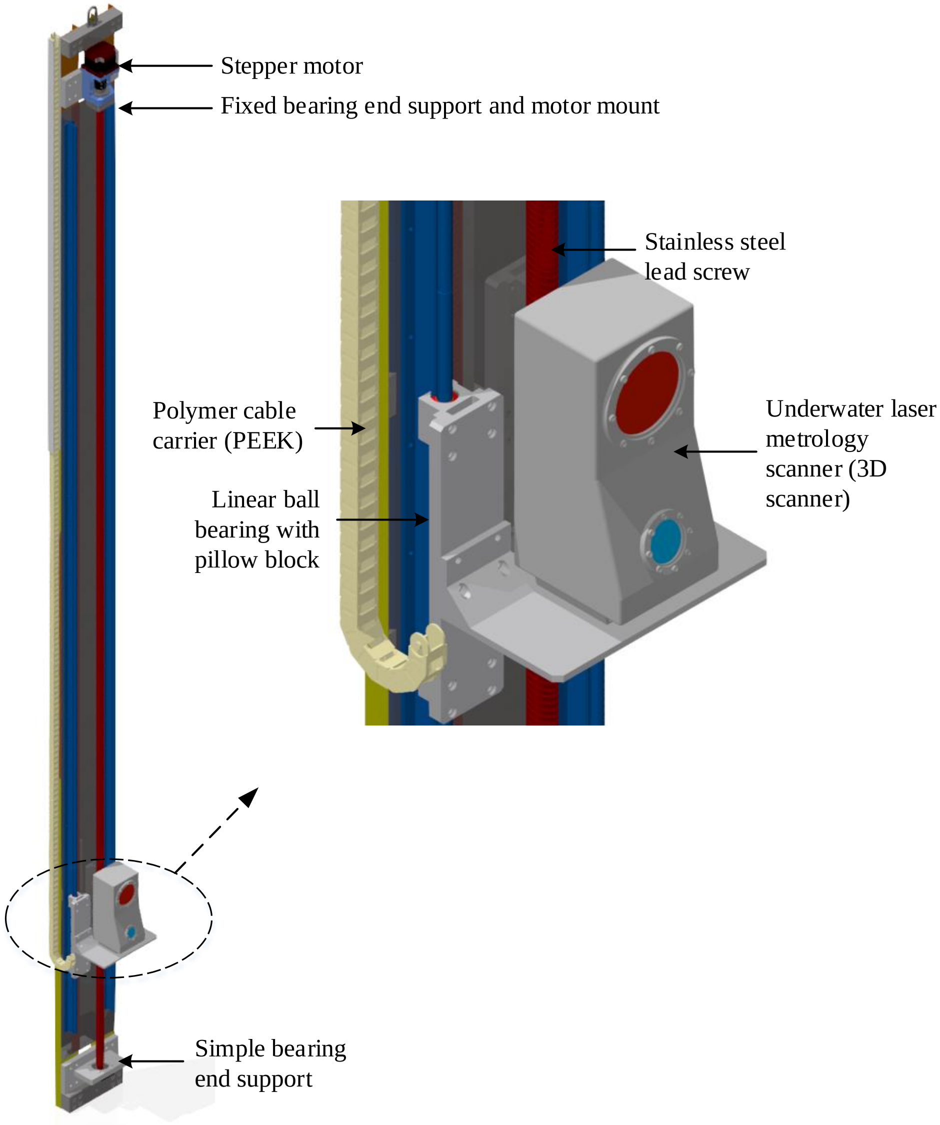

Figure 3.6: ANDES laser metrology system

It is worth noting that the laser scanner has both a laser scanner aperture and an optical camera. A high-resolution, monochrome image of specimens will be possible with the laser scanner and the optical camera mentioned in Section 3.3. Shielding will likely be required and is a common feature on these laser scanners. The addition of shielding will add up to 20 lb to the camera weight. This will be within the buckling load and torque requirements of commonly available lead screws and stepper motor drives, respectively.

3.6 Approved Storage

Generally, it is expected that for more accurate data, the scan times will be long and may continue for several hours or even days. ATR canal facility requirements state that fissile material forms, ranging from miscellaneous specimens to ATR fuel elements, must be stored in approved locations. Otherwise, fissile material in excess of established uranium-235 thresholds or outside of approved storage must be supervised by ATR personnel[51]. This supervision is necessary to mitigate an accident scenario where the fissile specimen may lose its cooling environment—such as a canal break with water loss sufficient to expose the material[52]. Therefore, the typical operating time of ANDES is particularly important.

The exact duration of the examinations is unknown. However, the following scan time estimates for specimens provide some insight on the potential workload of ANDES:

- Flux-monitoring wires: 184 hrs/yr, 130 tubes per year (gamma spectroscopy only)
- Experiments (for example, ATF-2 rodlet): 1284 hrs/yr, 11 experiments per year (3D scanning and gamma spectroscopy only)
- Experiments (e.g., ATF-2 rodlet): 320 hrs/yr, 1 experiment /yr (gamma CT only)*
- Mark-VII assemblies: 291 hrs/yr, 3 assemblies per year (gamma spectroscopy and 3D laser scanning of plate 19 only)

These scan times are based on: (i) the current throughput of ATR experiments, flux wires and fuel assemblies and (ii) gamma spectroscopy and gamma CT scan times of experiments done at MFC. Gamma CT might seem a smaller portion (one experiment per year) because scan times even above water are extremely long (up to seven days). Therefore, it is assumed that most experiments will request initial spectroscopy, and only do CT if gamma spectroscopy shows something unexpected. Additional detail on these scan time calculations can be found in Appendix C.

Operational efficiencies and cost savings can be anticipated if the specimen and ANDES equipment could operate without operational supervision. If ANDES could include an approved storage system for specimens, the examination configuration could operate independently for hours or days without oversight until measurements are complete. It should be noted that without approved storage, gamma CT will likely be unfeasible to implement because of extremely long scan times.

One option the ANDES design team considered is to make the entire examination area an approved storage area. Therefore, the fuel being examined would always be inside an approved storage area. The difficulty with this option is that the storage area would need to be twice the height of the longest fissile specimen (i.e., Mark-VII assembly) to be scanned by the gamma spectroscopy system because the gamma collimator/detector are both stationary. This puts the top of the storage container at approximately 10 ft above the bottom of the canal. To transfer the specimen into the storage container, it would need to go up over the top of the storage container. Nuclear safety analyses and operational procedures currently require fuel elements to be stored and handled vertically for cooling. This means the top of the element would be only 6 ft below the top of the canal. This distance is the minimum distance fissile material can be handled within the water surface, causing an increased risk of exposure to the operations staff. It is also possible that other fissile specimens (e.g., large plate experiments) may have unique requirements, further limiting their handling near the surface.

A second option is to install a storage unit tall enough to contain a Mark-VII assembly only when it is at the lowest point of the ANDES handling system. This means that if the canal water was lost, the ANDES system would need to position the fuel into the storage unit automatically. The ANDES design team determined to pursue this second option, since making the entire system an approved storage was deemed impractical. The proposed system is shown in Figure 3.7.

Figure 3.7: ANDES passive coolant container with source holder

This concept is similar to the passive coolant containment structures (PCCS) that were designed to contain Mark-VII assemblies in the storage canal[53-54]. However, unlike the PCCS, the ANDES approved storage container will be made of 316 stainless steel sheet metal due to its excellent corrosion resistance and weldability. It will be lowered onto the canal floor and held in place by either gravity or a cantilever bar that is connected to the canal parapet. (The storage container cannot be fastened to the canal floor without breaching reactor containment.)

All of the approved storage locations within the ATR canal are considered safety-related equipment[51]. The ANDES system would need to prove redundancy when locating the fuel in the storage system. Redundant water level sensors could monitor canal water levels. If the level were to drop below acceptable levels, power would be cut to the vertical drive axis using an external relay. When the power to the motor is cut, the fuel would be lowered by gravity to the lowest point in the ANDES system. The lead screw of the handling system will be designed to lower specimen of any mass and at a rate slow enough to protect the approved storage container and specimens.

Approved storage would also require two makeup water supplies to refill the container as water is boiled off. Supply would first be provided by the LDW system, and then by the fire water system for added redundancy. The nearest connections to LDW and fire water system are about 50 ft east of the ANDES location, as shown in Figure 3.8. The piping for the LDW would be installed along the canal parapet wall on the operator side. This piping for the LDW would come from the firehose rack located on the wall opposite the LDW connection point. These connection points are on the base floor and wouldn't require drilling in the concrete floor and breach of containment. A hole exists near the top of the parapet wall near where ANDES is located. This hole would convey the piping to the canal, then down the canal wall to the storage position.

This replacement water would need to provide enough in case of boil-off from a radioactive element. The maximum flow rate for this makeup was determined to be 0.013 gallon/minute for an ATR fuel element and is presented in Appendix D.

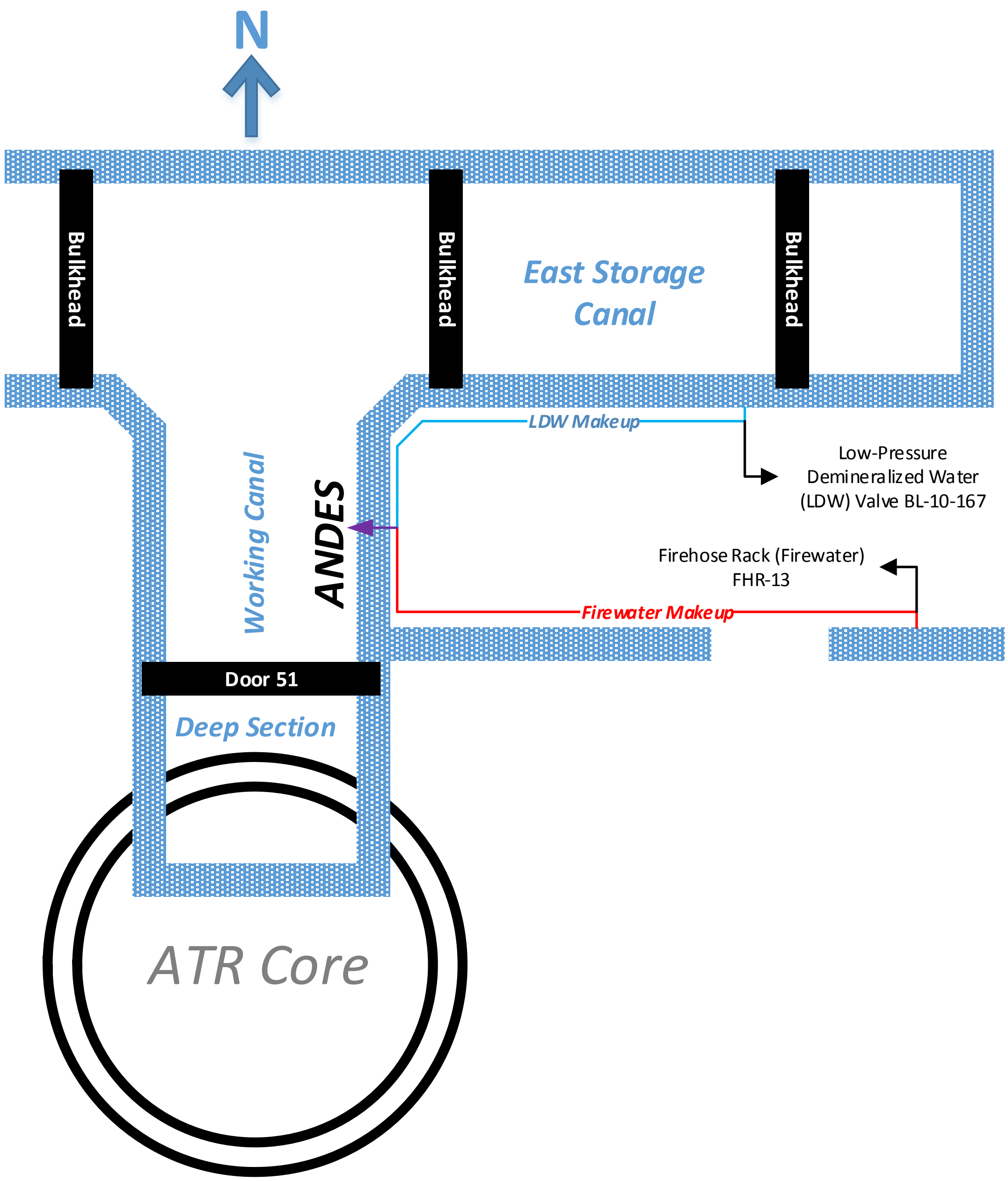

Figure 3.8: Fire water and LDW connections[55-56]

3.7 Working Tray and Operations Platform

ATR canal operations frequently include remote handling, assembly and disassembly of hardware. Working trays are key pieces of equipment that hold and/or temporarily store irradiation hardware during assembly and disassembly. There is currently a working tray in the west end of the storage canal that includes handling ports for accommodating a wide variety of hardware.

Given the potential for assembly and disassembly operations in support of ANDES examinations, the ANDES design team decided a working tray would be useful to facilitate loading and unloading of specimens into and from ANDES. The current working tray is located a significant distance away from the preferred ANDES location, and would make specimen handling operations cumbersome. It was decided that a smaller working tray similar to the current storage canal design be included as part of the ANDES design.

The ANDES working tray will consist of a 30-in. (L) × 18-in. (W) platform suspended by stainless steel cables connected to a spool operated by a hand crank and balanced by a counterweight (Figure 3.9).

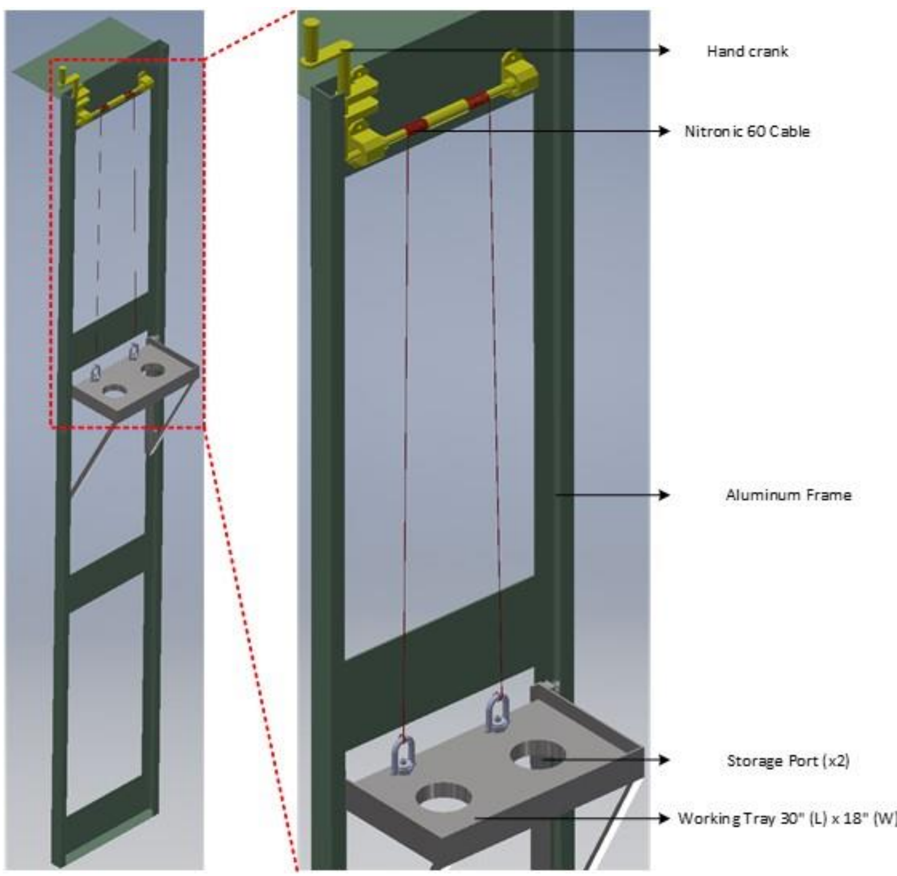

Figure 3.9. ANDES working tray

This working tray platform is shrunk relative to the current storage canal working tray (60 in. [L] × 30-in. [W]). Due to the smaller platform, the tray will also include two ports for temporary storage of hardware during loading and unloading. The tray platform was made smaller to fit within the footprint requirements of the preferred working canal location and because it will only facilitate ANDES specimen loading and unloading. On a related note, ANDES will include hooks for storing flux wire tube holders, baskets and other support hardware.

It was also noted by operations staff that handling of fuel elements adjacent to the canal is often difficult. At other areas of the canal, a removable platform has been added to allow more walking area on the parapet. The platforms also have handrails for support. Figure 3.10 contains a depiction of the existing platforms incorporated into ANDES based on existing designs[57].

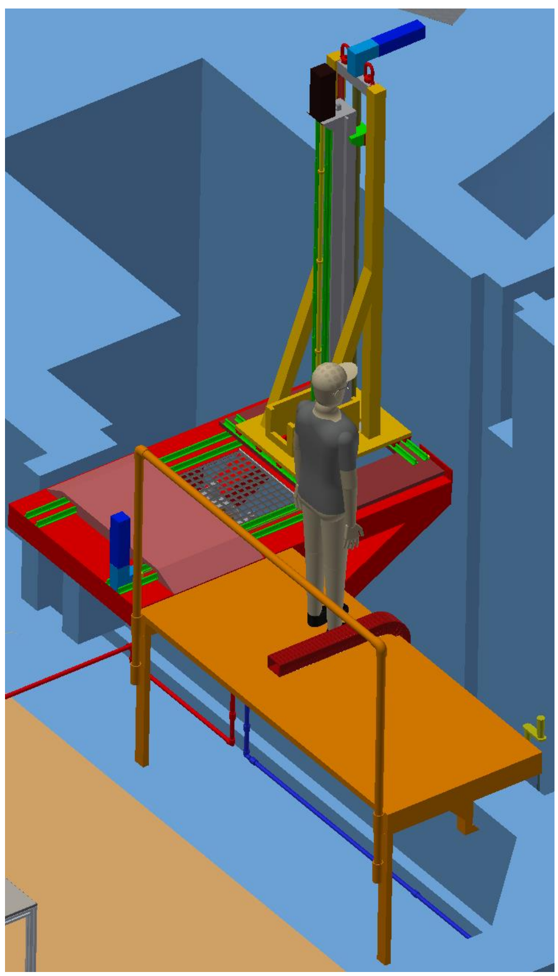

Figure 3.10. ATR canal operations and ANDES proposed platform

4 CHAPTER 4: POOLSIDE GAMMA SPECTROSCOPY OF EXPERIMENTS USING ANDES

High-resolution poolside gamma spectroscopy has not yet been demonstrated, but ANDES poses a unique opportunity for non-contact NDE of ATR specimens. With the ability to examine fissile material in between operating cycles, much more information can be obtained to inform future PIE and subsequent ATR irradiation conditions. This chapter discusses this ANDES capability in more detail. The conceptual design for the gamma spectroscopy system is generally comprised of the collimator assembly, detector and support frame. A depiction of the proposed system is shown in Figure 4.1. Note that the required handling system (Section 3.2) is not shown in this figure for clarity.

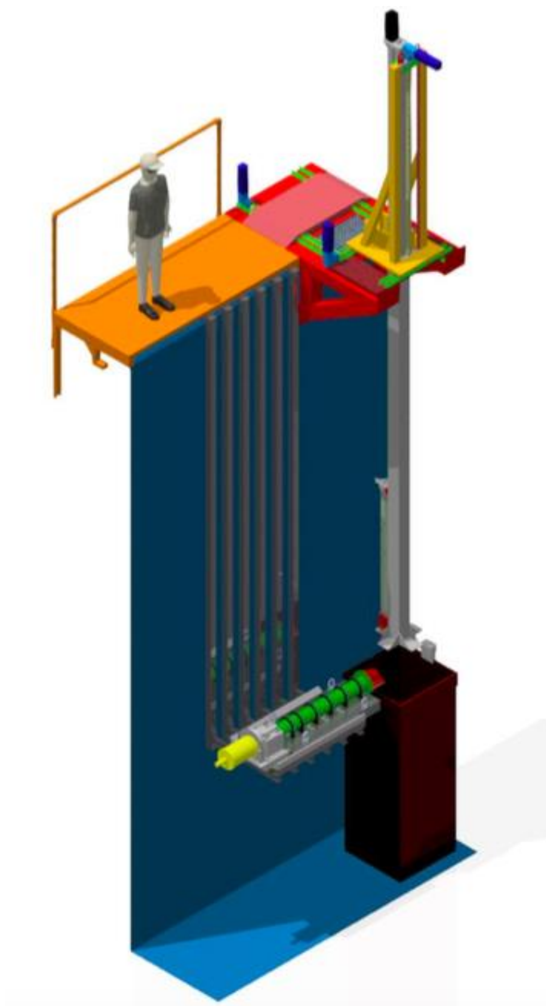

Figure 4.1: ANDES gamma spectroscopy conceptual design

4.1 ANDES Gamma Spectroscopy System Design

The ANDES design team considered two options for specimen scanning: holding the specimen in a fixed configuration and moving the gamma scanner, or holding the gamma scanner in a fixed configuration and moving the specimen. Discussions with subject matter experts (SMEs) and HFEF operators indicated that high-resolution gamma spectroscopy would require a collimated gamma energy beam in line with the detector material. The size of this prospective collimator would be determined in part by the desired count rate and spatial resolution of the gamma spectra measurements.

Given that ANDES will be gathering gamma spectra underwater and the limited footprint in the working canal, careful consideration was given to the geometry of the collimator. As a reference, HFEF's PGS collimator is made of high-density tungsten, weighing more than 2600 lb. It is 7 ft long with a 0.875-in.-wide variable aperture with an adjustable length of 0 – 0.1 in. with 0.001-in. increments by a stepper motor[58]. The PGS uses a HPGe detector crystal combined with a liquid nitrogen cryostat that maintains crystal temperature at -320°F.

The current RML collimator used in the ATR working canal for flux wire scans is approximately 3.5 ft long and made of lead. Along with the NaI detector, it is completely submerged and must be sealed off inside of a stainless steel liner to comply with PCS requirements[59]. This collimator has a tapered slit, increasing from a 3/16-in. diameter aperture to less than 2.5 in. Positioning repeatability is much coarser compared to the PGS due to the manual nature of the procedure and the 0.5-in. steps typical during most flux wire scans.

The ANDES design team used Monte Carlo N-Particle (MCNP) calculations to simulate intensity and spatial resolution. A collimator length of 4 ft with a 3-in. radius was sufficient for the desired spatial resolution and count rate. A collimator of this length and thickness for shielding would weigh more than ~2000 lb. Based on the anticipated weight and cable connections associated with the gamma scanning equipment, the team determined the specimen should be moved and positioned with the handling system (Section 3.2). This handling technique will provide scanning with optimal control and repeatability of positioning.

A water-filled collimator would significantly attenuate the incident gamma energy from specimens. This meant the count rate for low-activity specimens (e.g., flux wires) could be too low to be practical for RML measurements. Therefore, a sealed, nitrogen-filled collimator was chosen.

Interviews with SMEs suggested that high-resolution gamma spectroscopy for burnup calculations and spatial radioisotope distribution would necessitate a detector/deconvolution system that can discern the gamma energy peaks of interest. The ANDES design team identified gamma peaks from the fission and activation products typical for specimens of interest based on previous PIE reports[29, 43, 45]. These isotopes and their key gamma energies are shown in Table 4.1.

Table 4.1: Radioisotopes of interest for ANDES gamma spectroscopy

Activation Products	**Characteristic Gamma Energy (keV)**
Cobalt (Co)-58	810.8
Co-60	1173.2, 1332.5
Fission Products	
Cesium (Cs)-134	795.8
Cs-137	661.7
Cerium (Ce)-144	133.5
Zirconium (Zr)-95	724.2, 756.7
Niobium (Nb)-95	765.8

4.1.1 Gamma Detector

In addition to the NaI currently in use by the RML flux wire scanning station, underwater gamma spectroscopy systems have previously been investigated[36] and implemented[60] in the ATR canal. A cadmium-zinc Telluride detector-based system, was implemented and installed in the ATR canal and named The Underwater Gamma System (TUGS)[60]. The purpose of TUGS was to determine the presence of fissile material in radiologically active objects by the presence of ^{137}Cs.

A more recent effort used a lanthanum bromide (LaBr) detector system for non-destructively acquiring experimental burnup and cooling time data from Mark-VII fuel assemblies[36] in the ATR canal. This effort considered several detector types during design, including HPGe, NaI and LaBr. While all gamma detectors, these materials differ significantly in terms of their resolution and efficiency[61].

Gamma detector materials can be sensitive to background radiation[36]. Figure 4.2 shows background radiation levels obtained by ATR Operations along the length and depth of the working canal. The large concentration of radiation at the bottom of the working canal is likely from activated hardware. This material will need to be moved for ANDES installation and once removed, this will likely reduce background radiation levels currently present at the bottom of the ATR working canal (Figure 4.2).

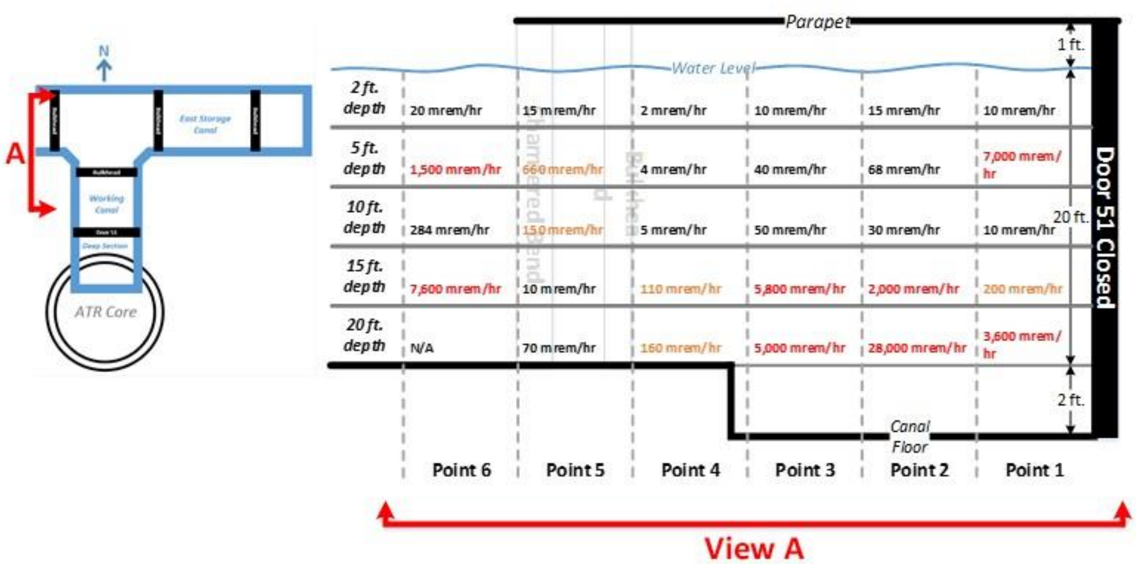

Figure 4.2: ATR working canal underwater survey (Survey-M-20180315-15)

After considering the previous trade studies and consulting vendor literature, the ANDES design team chose an HPGe detector combined with an electromechanical cooling system for conducting burnup characterization, radioisotope distribution and gamma CT (Section 3.3). The team determined that adequate shielding combined with the moderate radioactivity levels in the working canal makes HPGe an ideal choice. This would provide the highest-resolution gamma spectroscopy possible for discerning a wide variety of activation and fission product. However, to accommodate different measurement techniques and experiments, ANDES will incorporate a modular detector system to allow manual removal of detectors from the canal for change-out and maintenance.

4.1.2 Detector and Collimator Orientation and Support

The orientation of the gamma detector/collimator has significant ramifications for the overall ANDES design. The current NaI detector being used at the RML flux wire scanning station is held in a vertical orientation. This configuration requires the flux wires to be held horizontal and pulled across the top of the collimator. The PGS detector and collimator are orientated horizontally so that specimens are held in a vertical orientation, directly in front of the collimator. The ANDES configuration resembles that of the PGS.

The ANDES design team considered a vertically oriented detector/collimator attached directly to the canal wall with the detector and cooling equipment out of water. This concept provided the best detector maintenance and spatial resolution. However, this concept would require a longer collimator because irradiated specimens, which are scanned at the bottom end of the collimator, must be kept 6 ft below the water surface. In turn, using a longer collimator (with less gamma energy intensity) to reach below 6 ft would require much more time to collect the gamma spectra scans. In addition, the weight of such a long detector would likely exceed nearby crane lifting capacities. Finally, this concept would require fuel specimens to be measured horizontally in a less favorable heat transfer configuration for decay heat dissipation. Discussions were held with ATR Operations, radiological contamination, and nuclear and criticality safety personnel about the concern of holding specimens horizontally for scanning. While holding Mark-VII specimens horizontally is not explicitly forbidden by ATR safety documents, certain experiments (e.g., ATF-2) are required to be handled in a vertical orientation. Furthermore, some of the longer specimens (that is, flux wires and Mark-VII assemblies) are too long for horizontal orientation within the ANDES footprint. The ANDES design team eliminated the vertical detector/collimator orientation from consideration because it exceeded the physical footprint of the ANDES working canal location and would potentially conflict with experiment program and laboratory operating procedures.

The ANDES design team ultimately chose a horizontal orientation for the gamma detector/collimator assembly supported by a cantilever. Both the collimator and detector would be completely submerged and rest on a cantilever structure (Figure 4.1). The cantilever is comprised of six 316 stainless steel I-beams, connected to the parapet by 3 in. square tubing with a combination of bolted and welded joints. Detailed structural analysis is provided in Appendix E, which shows maximum shear and bending stress in the cantilever structure. This provides the best compatibility with scanning specimens within the defined physical footprint and providing shorter specimen gamma scan times. This concept’s primary limitation was needing to lift the collimator/detector out of the canal for maintenance. However, discussions with ATR Operations and lifting staff indicated that the nearby working canal C-3 jib crane would be sufficient for lifting loads up to 4,000 lb. To permit ease-of-access to the gamma detector for maintenance and detector material change-out, ANDES permits manual removal of the detector housing assembly by ANDES operating personnel.

4.1.3 Collimator and Aperture Design

The accuracy and resolution of gamma spectroscopy and computed tomography measurements is directly proportional to the geometry and overall design of the collimator (e.g., materials, aperture removal). High-resolution gamma detection systems, such as PGS, have long (7 ft) collimators to reduce spatial error. Given the priority of gamma spectroscopy and CT capability in ANDES, careful consideration was made to maximize the length of the collimator, while staying within the physical envelope. Furthermore, the collimator length was kept short enough to maximize gamma energy intensity, which translates to shorter scan times. MCNP simulations were completed for different collimator lengths, aperture (i.e., slit) sizes and distances to specimens with a Co-60 source. It was determined that a 4-ft-long collimator was sufficient to reduce spatial error while maximizing intensity. This length is comparable to the 2.5-ft-long collimator in a gamma CT system previously demonstrated at the Halden Reactor Project[30].

Aperture sizes, while not a part of the collimator itself, were also specifically considered in MCNP simulations, and their design will be discussed here. The wide variation of specimen geometry and radioactivity indicated that interchangeable apertures would be needed to collect spectroscopy and CT measurements. The ANDES design team selected a rectangular aperture geometry to permit precise lateral and axial scans of specimens. Three aperture sizes were selected based on PIE reports from previous PGS measurements[43, 45]:

- 0.875 in. (W) × 0.025 in. (H)
- 0.875 in. (W) × 0.05 in. (H)
- 0.875 in. (W) × 0.1 in. (H)

MCNP simulations indicated that these apertures 4-5 in. away from the specimen had minimal (<1%) error when gathering spectroscopy and CT data. Additional aperture sizes will be considered as part of the ANDES final design. The collimator is made of tungsten, and while not explicitly restricted from use in the canal[59], recent calculations by ATR Operations have indicated that tungsten is likely unacceptable for direct exposure to the primary coolant system. The corrosive nature of tungsten will need to be quantified in the final design, but this concept has the tungsten sealed off from direct contact with the demineralized water by an aluminum liner. The collimator assembly will include a Swagelok ball valve threaded into the aluminum lining via a thread sealant and suitable polymer (e.g., Rulon) for pressurization with an inert gas (e.g., nitrogen) (Figure 4.4). As previously mentioned, a sealed collimator also has the advantage of reduced attenuation from water.

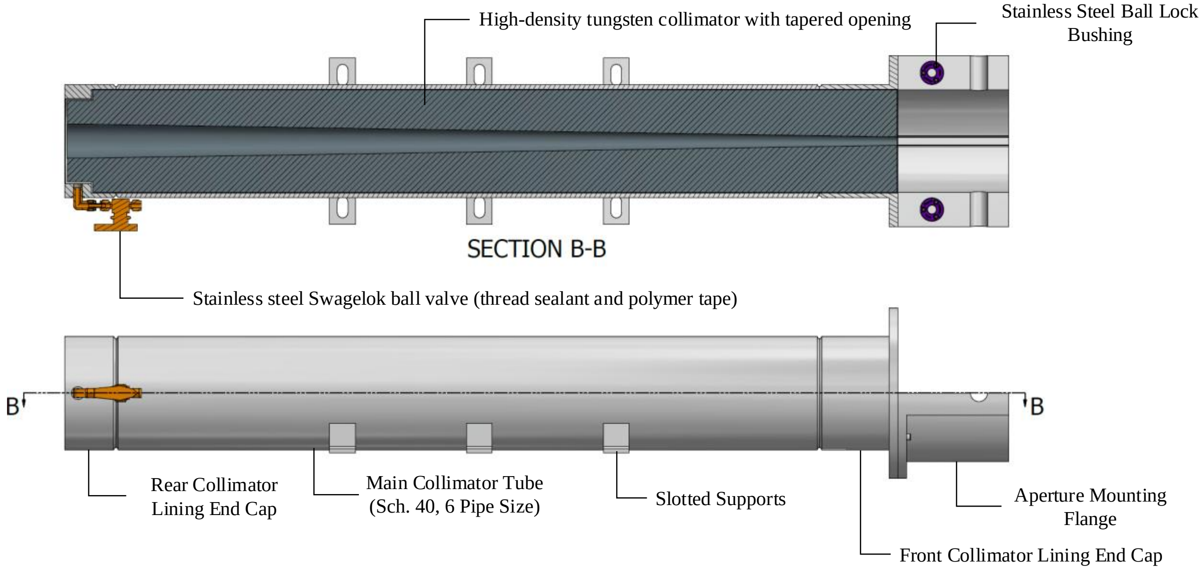

Figure 4.3: Collimator weldment

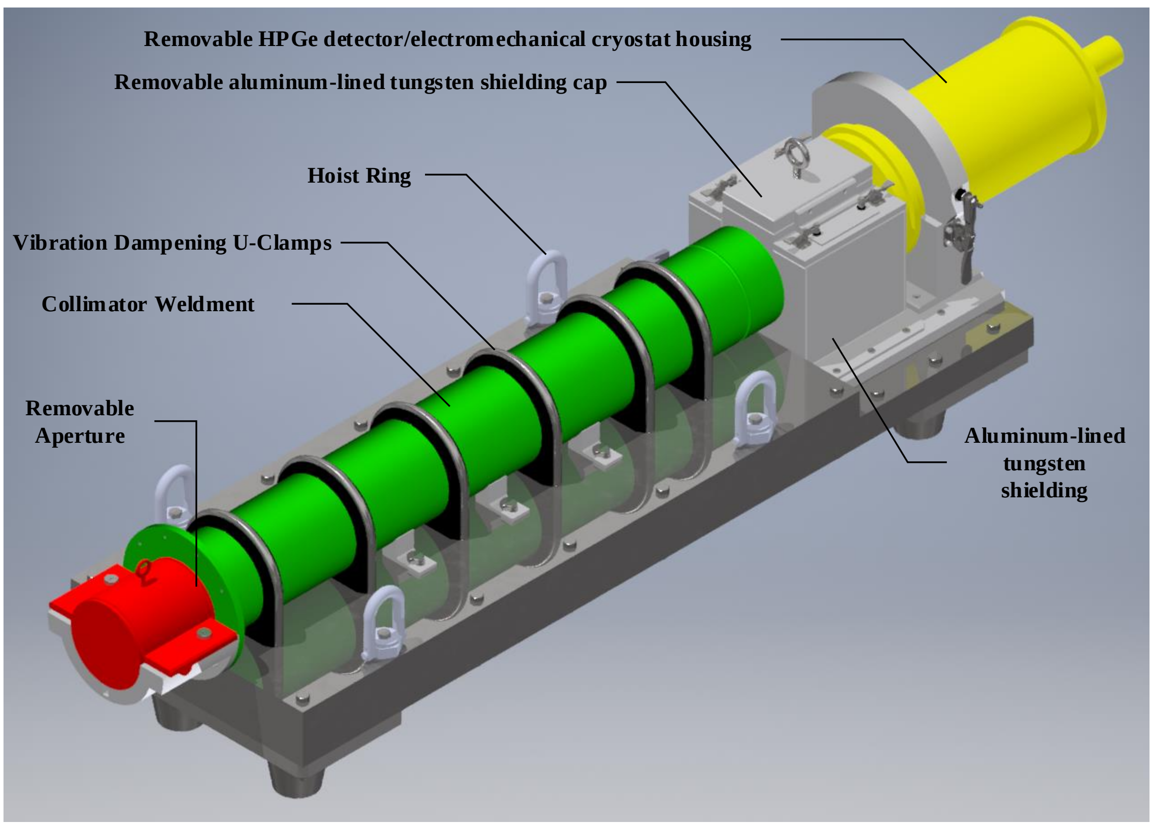

Figure 4.4: Sealed collimator (green), removable aperture (red) and removable detector/cryostat housing (yellow) mounted onto support frame tray

4.1.4 Flux Wire Scanning

The RML uses a Ni wire (99.997 wt% Ni) and Co wire (0.1-0.5 wt% Co) to measure axial profiles of fast and thermal neutron flux, respectively. The actual dimensions of the wires range from 0.02-0.04 in. in diameter. The flux wire tube holders encapsulate both wires. The most common ATR flux wire holders, the safety rod (SR) and beryllium rod (BR) holders, consist of a 3/16-in. diameter aluminum tube, crimped at each end by a bottom spacer and head (Figure 2.2). Currently, RML staff use a NaI gamma detector, which has a very low gamma energy resolution. This requires RML staff to use long tools to cut open and individually remove both flux wires from the holders. Once removed, each flux wire is scanned individually by the NaI detector for its characteristic gamma energy peak (Table 4.1). Given the long length of these flux wires (4-7 ft), this is a relatively time consuming process. Alternatively, the gamma detector chosen for ANDES will be a HPGe detector, which has a much higher resolution. This means that the flux wires would not need to be removed from the holder, and could instead remain in their holders for gamma spectroscopy. However, HPGe is less efficient at collecting gamma spectra than NaI, meaning that it takes a longer amount of time for an HPGe detector to pick up gamma peaks that a NaI detector could pick up relatively quickly. Therefore, a flux wire holder magazine capable of simultaneously clamping multiple holders was needed to offset the longer count times.

4.1.5 Flux Wire Holder Magazine

A flux wire holder magazine was designed by the design team that can hold up to five flux wire tubes (ten total flux wires) simultaneously (Figure 4.5). It weighs 25 lb dry to permit personnel handling. The flux wire holder magazine is essentially a rack of 5 individual ¼-in. 6061 aluminum tubes arranged in series. Flux wire holders are inserted into these tubes, which are spaced 1 in. apart. A hoist ring permits easy handling with existing ATR canal long-handle tools for lowering into the ANDES handling system. The bottom of the magazine will have a male connector that fits into a specially designed handling mold.

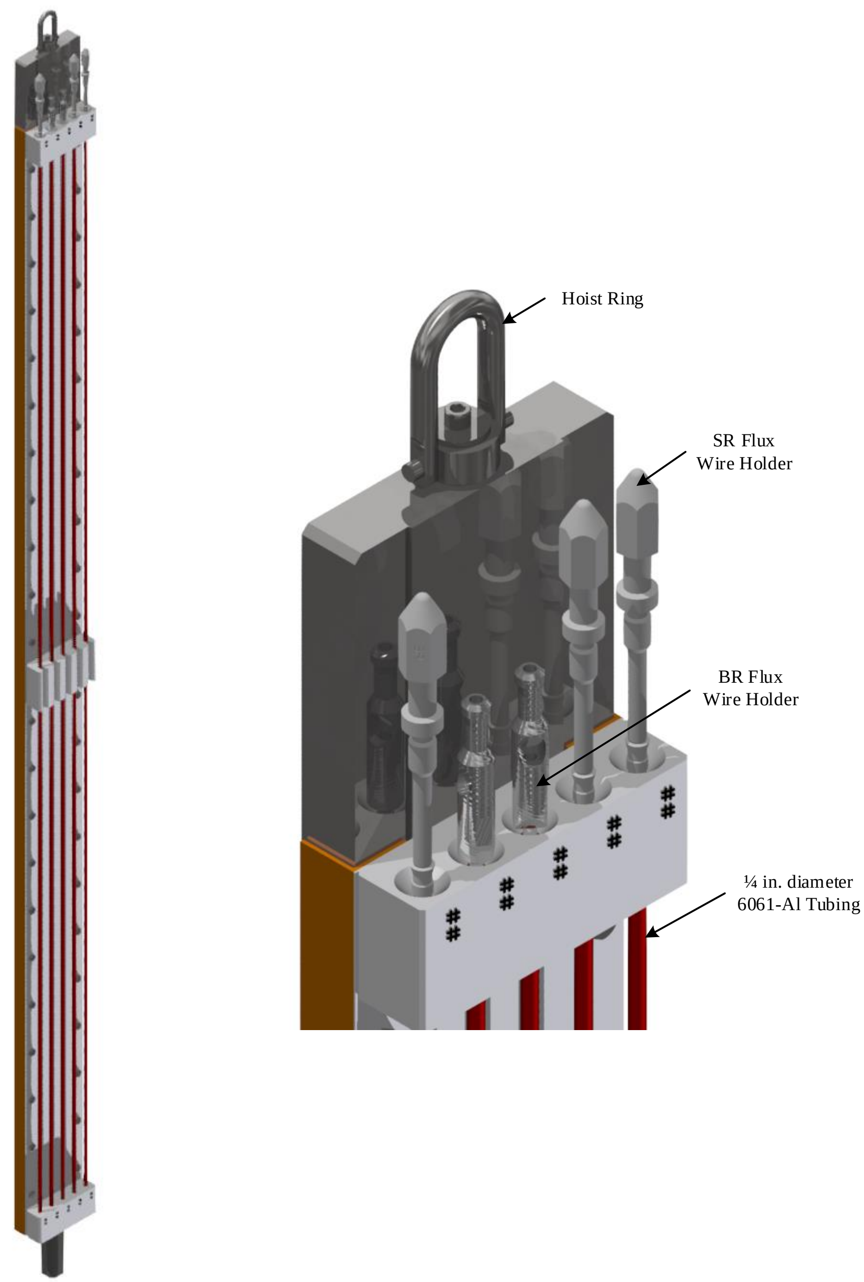

Figure 4.5: Flux wire holder magazine

Once loaded into the handling system, the flux wire holder magazine is positioned in front of the gamma detector. This means that there is potential for the gamma detector to pick up trace energy from the adjacent flux wires. This is of great concern to RML operations, who require <1% error when conducting their flux wire scan measurements. However, the flux wire holder magazine combined with the long ANDES collimator provides a significant amount of shielding (57 in.) to the detector from adjacent flux wire holders (Figure 4.6). Detailed calculations for both attenuation and required shielding for achieving <1% error are presented in Appendix F. In short, the straight-line distance of gamma energy to the detector from adjacent flux wires is much less than the 1% RML target, and drastically reduces the overall time spent disassembling and scanning flux wires with a NaI detector.

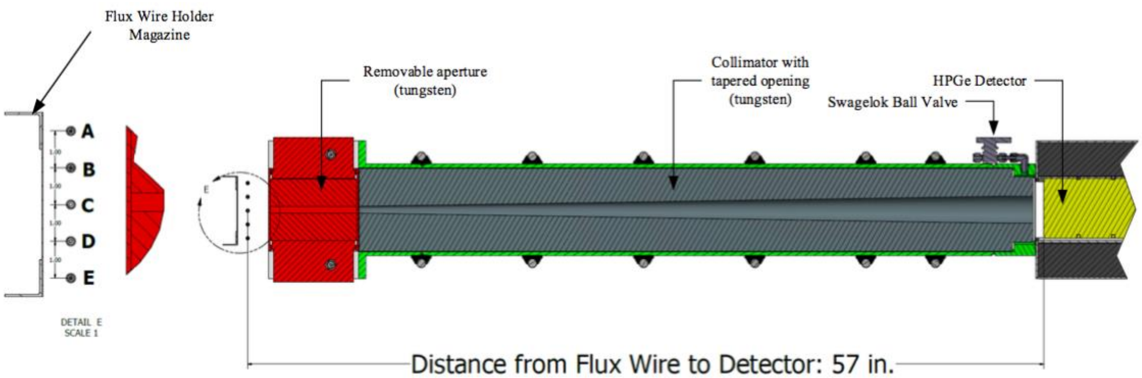

Figure 4.6: Gamma detector and flux wire holder magazine scanning configuration

5 CHAPTER 5: CHALLENGES AND OPPORTUNITIES FOR ANDES DESIGN AND DEPLOYMENT

There are several unanswered questions and notable challenges that need to be addressed for ANDES to be successfully deployed. Some challenges were discovered early in the design process, while some were discovered through review of the design with stakeholders.

It was understood that underwater gamma CT would require complex software programs, and perhaps more robust hardware to achieve the resolution requested by experiment programs. The ANDES design team will continue to investigate this function and its ability to combine with gamma spectroscopy system hardware.

Equipment installation in ATR is generally an expensive undertaking due to the facility safety requirements and work control. The overall cost of ANDES will be extraordinary, given the diverse amount of equipment involved and the location of installation. Prior to fabrication, revisions to ATR safety documents and procedures will be required and is expected to be an extensive effort (e.g., defining ANDES as an approved storage area). However, these technical and safety analyses are critical to the overall reliability of ANDES. Regarding cost, several ANDES components are long-lead items that require quality testing and inspection prior to installation. Given the conceptual nature of this design, detailed costs are not mentioned here for equipment, development and deployment activities. Rough order-of-magnitude estimates for ANDES may be found elsewhere[34].

To help address these challenges and validate the ANDES conceptual design, the ANDES design team held two conceptual design reviews with ATR Operations personnel and ATR experiment program representatives. To specifically address specific concerns with the gamma spectroscopy design, the design team met with RML Operations.

5.1 ANDES Conceptual Design Review

The ANDES discussion with ATR personnel primarily centered around minimizing impact to current ATR handling and transport operations. The footprint of ANDES (10 ft [L] x 3.5 ft

[W]) was cited by ATR Operations as a concern because of the current traffic through the working canal for transporting hardware, including ATR fuel assemblies. The proximity of ANDES to the jib crane, which is frequently used, was also brought up as a hindrance to operations.

Most ANDES system capabilities are geared to benefiting fuels and materials experiment programs, including AFC, Reduced Enrichment for Research and Test Reactors (RERTR) and others. Individuals representing these programs attended a second design review, where discussion focused on throughput and flexibility of ANDES. One concern was that one system capable of providing both operations and programmatic support could be stretched thin to the point of being a bottleneck. It was recommended that the ANDES design team come up with an estimated operational schedule for ANDES based on the current specimen portfolio and recent history of specimen throughput in ATR. The ANDES design team conducted a baseline operating schedule for ANDES. While still unclear, the annual operating estimates listed in Section 3.6 and Appendix C show that gamma CT will likely be a rare process used due to its exceptionally long scan times. Furthermore, much of ANDES operations time will be spent doing gamma spectroscopy of experiments because of the large amount of fueled experiments and its value for providing between-cycle PIE.

5.2 Gamma Spectroscopy Design Review

Maintaining RML flux wire scanning operations was arguably the most imperative topic covered. It was agreed that a clear development and demonstration plan needed to be established to show improvement to RML operations and give ANDES the best chance of approval from an operations stand-point.

Discussions with RML Operations yielded the following potential deployment plan for installing gamma spectroscopy capability:

1. Install a rack-and-pinion handling system on the parapet of the working canal adjacent to the current flux wire scanning station. This handling system will solely hold an HPGe detector above the water pointing downward at the flux wire tube holders that

are held in an angle iron. This demonstration will not require any alteration of current RML flux wire scanning operations, and will demonstrate the ability for an HPGe detector to collect data from two flux wires within the same holder in the presence of working canal background radiation.

2. Install a mockup of the gamma spectroscopy system (Chapter 4) elsewhere in the canal. This could simply include a totally submerged collimator and detector system, or it could also have the handling system mentioned in Section 3.1.2. In either case, this mockup will need to be capable of scanning the same flux wire tubes that RML has access to in order to compare results between NaI and HPGe spectra. The flux wire holder magazine (Section 4.1.5) could be fabricated for this mockup to determine its suitability.

3. Remove current RML scanning equipment and complete a full install of ANDES gamma spectroscopy equipment and handling system.

This deployment plan is very important for validating ANDES data quality for ATR customers, such as the U.S. Navy. Without a thorough and comprehensive deployment plan, ANDES will be too much of a risk to halt current RML operations.

Each of these aspects will specific aspects will be investigated thoroughly in final design by continuing to engage stakeholders and pursue the most feasible and effective design solutions.

REFERENCES

1. D. Fischer *History of the International Atomic Energy Agency: the first forty years*; ISBN 92-0-102397-9; International Atomic Energy Agency: Vienna, 1997.

2. International Atomic Energy Agency *Research Reactors: Purpose and Future*; International Atomic Energy Agency: Vienna, Austria, 2016.

3. Institute of Medicine, *Isotopes for Medicine and the Life Sciences*. The National Academies Press: Washington, DC, 1995; p 144.

4. IAEA *Neutron Transmutation Doping of Silicon at Research Reactors*; IAEA-TECDOC-1681; International Atomic Energy Agency: Vienna, 2012.

5. International Atomic Energy Agency Research Reactor Database. https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx (accessed March 6 2019).

6. N. E. A. Committee *Assessment of Missions and Requirements for a New U.S. Test Reactor*; Department of Energy - Office of Nuclear Energy: 2017; p 51.

7. C. d. É. d. l. é. Nucléaire Belgian Reactor 2 - Research Facilities. http://science.sckcen.be/en/Facilities/BR2 (accessed March 6).

8. C. Jensen; D. Wachs; N. Woolstenhulme; S. Hayes; G. Povirk; K. Richardson *Post-Halden Reactor Irradiation Testing for ATF: Preliminary Assessment and Recommendations*; INL/EXT-18-46101; Idaho National Laboratory: Idaho Falls, 2018.

9. S. M. Stacy, *Proving the principle : a history of the Idaho National Engineering and Environmental Laboratory, 1949-1999 / by Susan M. Stacy*. Idaho Operations Office of the Dept. of Energy ; For sale by the Supt. of Docs: Idaho Falls, Idaho : Washington, D.C, 2000.

10. Idaho National Laboratory *ATR Core Cross Section Diagrams*; Drawing 606000; Idaho National Laboratory: Idaho Falls, ID, 2013.

11. S. L. Hayes; D. Utterbeck *Advanced Fuel Cycle Initiative*; INL/EXT-07-12388; Idaho National Laboratory: Idaho Falls, ID, 2007.

12. Idaho National Laboratory Materials and Fuels Complex - Facilities and Instruments. https://mfc.inl.gov/SitePages/Facilities%20and%20Instruments.aspx (accessed March 6).

13. V. G. Dvoretzkij In *Poolside Inspection of Fuel Rods from Experiments in Research Reactors*, IAEA Technical Committee Meeting, Vienna, Switzerland, 21-23 October 1991; IAEA: Vienna, Switzerland, 1991.

14. IAEA *Guidebook on Destructive Examination of Water Reactor Fuel*; STI/DOC/10/322, ISBN 92-0-155091-X , ISSN 0074-1914; IAEA: Vienna, 1991; p 94.

15. J. W. Rogers; O. D. Simpson; R. A. Coates; E. W. Killian; D. A. Lopez *Conceptual Design of an ATR High Resolution Flux Wire Monitor and Fuel Rod Gamma Scanner*; EG&G Idaho, Inc.: Idaho Falls, ID, 1978; p 22.

16. N. E. Woolstenhulme; S. C. Taylor; G. A. Moore; D. M. Sterbentz *Nondestructive examination of fuel plates for the RERTR fuel development experiments*; INL/EXT--12-27225; United States, 2012; p 16.

17. D. M. Wachs; J. M. Wight; D. T. Clark; J. M. Williams; S. C. Taylor; D. J. Utterbeck; G. L. Hawkes; G. S. Chang; R. G. Ambrosek; N. C. Craft *Advanced Test Reactor In-Canal Ultrasonic Scanner: Experiment Design and Initial Results on Irradiated Plates*; INL/CON--08-14803; United States, 2008; p v.

18. K. T. Ulrich; S. D. Eppinger, *Product Design and Development*. 4 ed.; McGraw-Hill Higher Education: New York, New York, 2008.

19. J. M. Beeston; R. K. Malik *Burnup Extension Analysis of Two 7F Fuel Elements*; RE-M-77-011; Idaho National Laboratory: Idaho Falls, ID.

20. H. J. Reilly *ATR Fuel Burnup Extension*; GNF-4-76; Idaho National Laboratory: Idaho Falls, ID, 1976.

21. J. L. Durney *ATR Burnup Extension*; PR-T-77-003; Idaho National Laboratory: Idaho Falls, ID, 1977.

22. J. M. Beeston; R. R. Hobbins; G. W. Gibson, Development and Irradiation Performance of Uranium Aluminide Fuels in Test Reactors. *Nuclear Technology* **1979,** *49*, 136-149.
23. M. D. DeHart; Z. Karriem; M. A. Pope; M. P. Johnson, Fuel element design and analysis for potential LEU conversion of the Advanced Test Reactor. *Progress in Nuclear Energy* **2018,** *104*, 117-135.
24. J. O. Brower, Advanced Test Reactor (ATR) Conversion to Low Enriched Uranium Fuel. National Organization of Test, Research & Training Reactors (TRTR): San Diego, CA, 2017.
25. H. J. M. Chichester; S. L. Hayes; D. Dempsey; J. M. Harp *Advanced Reactor Fuels Irradiation Experiment Design Objectives*; United States, 2016-09-01, 2016.
26. Idaho National Laboratory *Technical Evaluation - Evaluation of Cask Characteristics for GTRI Experiment Shipping*; TEV-1737; Idaho National Laboratory: Idaho Falls, ID, 2013.
27. Mirion Technologies (Canberra), Remotely Operated Systems for Underwater Measurements. Solutions, C. D. D. C. a., Ed. 2016; p 6.
28. P. Andersson; S. Holcombe; T. Tverberg, Inspection of a LOCA Test Rod at the Halden Reactor Project using Gamma Emission Tomography. In *Top Fuel (Light Water Reactor Fuel Performance Meeting) September 11-16, 2016 BOISE, IDAHO, USA*, American Nuclear Society: 2016.
29. J. M. Harp; P. A. Demkowicz In *Investigation of the Feasibility of Utilizing Gamma Emission Computed Tomography in Evaluating Fission Product Migration in Irradiated TRISO Fuel Experiments*, HTR 2014: 7 International Topical Meeting on High Temperature Reactor Technology, United States, United States, 2014.
30. S. Holcombe; S. Jacobsson Svärd; L. Hallstadius, A Novel gamma emission tomography instrument for enhanced fuel characterization capabilities within the OECD Halden Reactor Project. *Annals of Nuclear Energy* **2015,** *85*, 837-845.
31. Idaho National Laboratory *Technical Evaluation - AFIP-7 Ultrasonic Channel Gap Test Results*; TEV-1169; Idaho National Laboratory: Idaho Falls, ID, 2012.
32. EPRI *Noncontacting Laser Scanner for Fuel Assembly Distortion Measurement*; 1025177; Electric Power Research Institute: 2012; p 150.
33. Idaho National Laboratory Capabilities. https://inl.gov/about-inl/capabilities/ (accessed March 6).
34. Idaho National Laboratory *Conceptual Design Report for the ATR Non-Destructive Examination System (ANDES)*; CDR-172; Idaho National Laboratory: Idaho Falls, ID, 2019; p 98.
35. Idaho National Laboratory *Innovative Technology Summary Report* DOE/EM-0588; Idaho National Laboratory: 2001.
36. J. Navarro *A Feasibility and Optimization Study to Determine Cooling Time and Burnup of Advanced Test REactor Fuels Using a Nondestructive Technique*; INL/EXT -13-29997; Idaho National Laboratory: Idaho Falls, ID, 2013.
37. Idaho National Laboratory *Technical and Functional Requirements*; TFR-621; Idaho National Laboratory: Idaho Falls, ID, 2009.
38. J. Tonks, ATF-2 (ACCIDENT TOLERANT FUEL) REFERENCE 6 INCH FUEL PIN ASSEMBLY AND DETAILS. 2 ed.; 605616, D. N., Ed. Idaho National Laboratory: Idaho Falls, ID, 2017.
39. I. N. Laboratory *Fuel Specification for MP-1, MP-2, and FSP-1*; SPC-1691; Idaho National Laboratory: Idaho Falls, ID, 2017.
40. N. Oldham, ATR RERTR US HIGH POWER RESEARCH REACTORS MINI-PLATE FUEL DETAIL. 6 ed.; 604607, D. N., Ed. Idaho National Laboratory: Idaho Falls, ID, 2014.
41. T. Hyde; M. Teague *Project No. 28203 Specification*; SPC-1372; Idaho National Laboratory: Idaho Falls, ID, 2012; p 39.
42. Mirion Technologies (Canberra), WM2900 TGS Tomographic Gamma Scanner. (Canberra), M. T., Ed. 2017.

43. J. Harp; H. Chichester *Baseline Postirradiation Examination of the AFC-2D, AFC-2E, AFC-3A and AFC-3B Experiments*; INL/LTD-15-36358; Idaho National Laboratory: Idaho Falls, ID, 2015.
44. B. Hendricks, ATR High Specific Activity Cobalt Irradiation Capsule Assembly B-Hole. 427647, D. N., Ed. Idaho National Laboratory: Idaho Falls, ID, 1988.
45. J. M. Harp; S. L. Hayes; P. G. Medvedev; D. L. Poter; L. Capriotti *Testing Fast Reactor Fuels in a Thermal Reactor: A Comparison Report*; INL/EXT-17-41677; Idaho National Laboratory: Idaho Falls, ID, 2017.
46. Mirion Technologies (Canberra), Genie 2000 Gamma Analysis Software. (Canberra), M. T., Ed. 2015.
47. J. Graham, T.; H.-K. Lee; M. Abir *NEUP Project 17-13011: Gamma-ray Computed and Emission Tomography for Pool-Side Fuel Characterization*; U.S. Department of Energy: 2017.
48. S. H. Ahn; J. Hong; C. Y. Joung; T. H. Yang; S. H. Heo; S. Y. Jang, Online Measurement of Fuel Stack Elongation. *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* **2016,** *10*, 1097-1101.
49. D. L. Knudson; J. L. Rempe, Linear variable differential transformer (LVDT)-based elongation measurements in Advanced Test Reactor high temperature irradiation testing. *Measurement Science and Technology* **2012,** *23* (2), 025604.
50. Newton Labs, Underwater Laser Scanner M210UW. Labs, N., Ed. Renton, Washington.
51. Idaho National Laboratory *SAR-153 - INL Safety Basis List for Advanced Test Reactor, Revision 25*; Idaho Falls, ID, 2017.
52. Idaho National Laboratory *Technical Safety Requirements for the Advanced Test Reactor*; TSR-186; Idaho National Laboratory: Idaho Falls, ID, July 19, 2017; p 26.
53. C. E. Stuart *Criticality Safety Evaluation for the Passive Coolant Containment Structures for the ATR Fuel Storage Grids at the ATR Complex*; INL/INT-09-15680; Idaho National Laboratory: Idaho Falls, ID, April 2009, 2009; p 17.
54. I. N. Laboratory *Fabrication of ATR Canal Irradiated Fuel Passive Coolant Containment Structures (PCCS)*; SPC-1870; Idaho National Laboratory: Idaho Falls, ID, 2015.
55. D. Robinson, First Basement and Above Raw and Fire Water Piping Sections. A ed.; 448713, D. N., Ed. Idaho National Laboratory: Idaho Falls, ID, 1995.
56. S. W. Dieiro, ATR Raw and Fire Water Piping Plan - 1st Basement and Above. 31 ed.; ATR-1075-MTR-670-P-56, D. N., Ed. Idaho National Laboratory: Idaho Falls, ID, 2007.
57. K. Peterson, North Canal Parapet Work Platform. 7 ed.; 437596, D. N., Ed. Idaho National Laboratory: Idaho Falls, ID, 1991.
58. Idaho National Laboratory *Operating Instructions - Precision Gamma Scanner*; HFEF-OI-4352; Idaho National Laboratory: Idaho Falls, ID, October 10, 2018; p 28.
59. Idaho National Laboratory *Material PRactices and Restrictions for ATR PCS and Experiment Loops*; SP-10.3.1.13; 83404: Idaho Falls, ID, March 16, 2010.
60. Idaho National Laboratory *Measurement of a Pneumatic Terminal and Two Compact Ignition Tokamak Plugs at the Advanced Test Reactor Canal Using The Underwater Gamma System*; EDF-5332; Idaho National Laboratory: Idaho Falls, ID, January 30, 2003; p 20.
61. G. F. Knoll, *Radiation detection and measurement*. 4 ed.; John Wiley & Sons, Inc.: USA, 2010.
62. Haydon Kerk Motion Solutions, Linear MOtion Catalog and Design Guide. Solutions, A. A. M., Ed. Waterbury, CT, 2018; pp 17-20, 26.
63. R.J. Electronics, Underwater Viewing System: S-8300. Kennewick, WA, 2019.
64. Thomson, Linear Motion Catalog and Design Guide. Solutions, A. A. M., Ed. Radford, VA, 2018; pp 189-202.
65. A. L. Balsmeier *ATR Canal Passive Coolant Containment System (PCCS) Boil-off Analysis*; ECAR-358; Idaho National Laboratory: Idaho Falls, ID, January 15 2009, 2009; p A1.
66. Y. A. Çengel; R. R. Turner; J. M. Cimbala, *Fundamentals of Thermal-Fluid Sciences*. 3 ed.; McGraw Hill: 2008.

67. H. H. Nielsen *Heat Transfer Analysis of ATR Fuel Element Lying Horizontal in Canal with Plates Vertical*; RE-A-78-032; Idaho National Laboratory,: Idaho Falls, ID, February 23 1978, 1978.

APPENDIX A – FUNCTIONAL AND TECHNICAL REQUIREMENTS OF ANDES SUBSYSTEMS

Requirements—Burnup and Radioisotope Distribution Analysis

- The gamma scanner shall have both emission and transmission capabilities, and shall include a mechanism for deploying and shielding an active source.
- The gamma scanner shall include a gamma detector that complies with resolution and efficiency requirements based on the specimens (Table 2.1) and characteristic gamma energies of interest (Table 4.1).
- The ANDES support frame shall support a collimator without deflection exceeding that allowed by the manufacturer.
- The gamma scanner shall facilitate interchangeable detector materials and cryostat assemblies.
- The collimator/detector assembly shall be housed in a water-tight housing to prevent equipment from coming in contact with the canal water, with the controls outside of the canal water.

Requirements—Handling

- The ANDES handling sub-system shall not conduct any cutting or similar destructive operation that results in the release of fission products or ignitable material.
- The ANDES handling sub-system shall be adaptable for mounting the specimens of interest (Table 2.1).
- The ANDES handling sub-system shall not move any portion of a specimen above the established 6 foot radiation buffer zone below the canal water surface.
- The ANDES handling sub-system shall permit manual removal of assemblies using existing experiment handling methods.
- ANDES handling sub-system shall not lift heavy loads (e.g., gamma scanner collimator) over fissile material during specimen attachment, detachment or examination activities. If heavy loads are unavoidable, an analysis is required to demonstrate a drop scenario will not result in fuel damage sufficient to create a risk for inadvertent criticality.
- Cladding (when present) shall not be damaged during ANDES handling of ATR Fuel Assemblies, or other specimens with exposed cladding to coolant.
- ANDES shall permit top access to ATR Fuel Assemblies for channel gap probe measurements.

- ANDES handling of dimensional evaluation equipment (e.g., laser metrology scanner) shall adhere to strict tolerances/specifications outlined by instrumentation vendor technology.
- Requirement: The positioning stages for the fuel specimen shall be designed to provide at least the same positioning accuracy as the PGS system:
  - X and Y axis = +/- .003 in
  - Z axis = +/- .005 in
  - Q rotation axis = +/- 0.5º

Requirements—Enhanced Videography

- Videography system shall move up and down the axis of the specimen
- Videography system shall pan and tilt 180 degrees on their respective axes
- Videography system shall provide zoom no less than 18x magnification
- Videography system shall function underwater to a depth of 45 ft
- Videography system shall function in a radiation environment with 1,000 Rad/Hr dose rate and 4E+04 Rad cumulative dose
- Videography system shall provide 470 TV Lines resolution
- Videography system shall connect to the ADACS
- Videography system shall provide real-time, true color video of captured images to a display at the ADACS
- Videography system shall have the ability to record video stream

Requirements—Laser Metrology

- The scanner shall collect high-resolution dimensional data consisting of specimen physical dimensions and quantification of surface features (rust, wear, fissures, and corrosion).
- The scanner shall consistently collect high-resolution dimensional data at a minimum of 25 µm (0.00098 in.) resolution.
- The scanner shall where practical consistently collect dimensional data at a minimum of 10 µm (0.00039 in.) resolution.

- The scanner shall collect high-resolution (for example 25 µm) dimensional data across a stationary 210 in^2 area in less than four (4) hours for precision scans.
- The scanner shall collect moderate resolution (>100 µm) dimensional data across a stationary 210 in^2 area in less than two (2) hours for accelerated scans.
- The scanner shall collect high resolution (for example 25 µm) dimensional data from a stationary cylinder in the axial direction with the following dimensions: 0.327 in. (diameter) × 4.0 in. (length).
- The scanner shall maintain normal data collection, operability, and resistance to radiation environments with a maximum 500 rad/hr gamma dose rate.
- The scanner shall maintain normal data collection, functionality and resistance to a cumulative lifetime gamma dose of 500,000 rad.
- Scanner equipment or scanner housing (if a dry box is needed) shall have a water depth rating of ≥ 50 ft
- Data obtained from laser scanner shall be transmitted from the submerged location to a top-side data acquisition unit no further than 30 ft from the scanner when the scanner is placed at the bottom of the canal.
- Gathered data shall be presentable in the form of a computer 3D model demonstrating the high resolution required.
- Laser scanner software shall be coordinated with the ANDES system to provide a central ANDES computer which serves data acquisition, modeling, and controls functions for both the laser scanner, the ANDES system, and other examination equipment.
- Scanner components shall be capable of ascent above water to a location reachable by ATR personnel for any necessary maintenance activities.
- Scanner components, once topside, shall be capable of manual disassembly for any necessary maintenance activities.
- Scanner technology shall collect high-resolution dimensional data from submerged specimens through demineralized water having the following nominal parameters and properties listed in SDD-7.4.6.1, "ATR Canal Recycle":
    - Conductivity: < 3.0 µmho/cm
    - pH: 5.0-7.0
    - Total suspended solids: < 5 ppm
    - Total organic solids: 2.8 ppm

  - Total dissolved solids: < 2 ppm
  - Total activity: $< 4.03 \times 10^{-5}$ μCi/mL.
- No wireless technology is allowed for functionality of the scanner, data collection or associated equipment.

APPENDIX B –ANDES CAMERA SYSTEM SUPPORTING CALCULATIONS

$L = 144\ in.$	Lead screw length[62]
$d_s = 0.875\ in.$	Lead screw nominal diameter[62]
$d_r = 0.742\ in$	Lead screw root diameter[62]
$l_s = 1.000\ in.$	Lead screw lead (pitch × no. of starts)[62]
$m_{camera} = 13\ lb.$	Mass of shielded S-8300 camera unit[63]
$F_{\omega,C} = 1.47$	End fixity constant for simple-fixed support configuration (critical speed calculations)[62, 64]
$F_{b,C} = 2.0$	End fixity constant for simple-fixed support configuration (buckling load calculations)[64]
$\eta_s = 0.8$	Screw efficiency

Critical Speed:

The critical rotational speed (speed at which resonance of the screw occurs) is given from manufacturer literature by[64]:

$$\omega_{critical} = \frac{(4{,}760{,}000 \cdot d_r \cdot F_{\omega,C})}{L} = \frac{(4{,}760{,}000 \cdot 0.742\ in \cdot 1.47)}{144\ in.} = 250\ \frac{rev}{min}$$

Manufacturers recommend that at most, 80% of this value be used for selecting a lead screw.

$$\omega_{allowable} = \omega_{critical} \cdot 0.80 = 200\ \frac{rev}{min}$$

The desired linear rate of travel of the camera is to travel the full length of the lead screw in no more than 2 minutes. Therefore,

$$v_{design} = \frac{L}{t} = \frac{144\ in.}{2\ min.} = 72\ \frac{in.}{min.}$$

$$\omega_{design} = \frac{v_{nominal}}{l_s} = \frac{72\ \frac{in.}{min.}}{1.000\ in.} = 72\ \frac{rev}{min}$$

The margin of safety with respect to the nominal and critical rotational speeds is:

$$MOS = \frac{\omega_{allowable} - \omega_{design}}{\omega_{design}} = \frac{200\ \frac{rev}{min} - 72\ \frac{rev}{min}}{72\ \frac{rev}{min}} = 1.8$$

Referencing manufacturer's charts for screw speed vs distance between supports, a 144 in. screw with a fixed-simple support configuration will not reach resonance with the design or de-rated rotational velocities[62, 64].

Buckling Load

The buckling load for a given screw is given by manufacturing literature as[64]:

$$P_{buckle} = \frac{F_{b,C} \cdot (1.405 \times 10^7) \cdot {d_r}^4}{L^2} = \frac{2.0 \cdot (1.405 \times 10^7) \cdot 0.742\ in.^4}{(144\ in.)^2} = 411\ lb.$$

The margin of safety with respect to the camera weight, m_{camera}, and the buckling load is given by:

$$MOS_{camera} = \frac{P_{buckle} - m_{camera}}{m_{camera}} = \frac{411\ lb. - 13\ lb.}{13\ lb.} = 30.62$$

The dynamic load rating for this screw is 500 lb, which exceeds the buckling load. Therefore, the buckling load is the limiting factor for determining maximum working loads on this lead screw assembly. In reality, the weight of the cable carriers, camera support platform and friction of the linear rails will induce additional load on the lead screw larger than the camera weight. These components will be designed not induce a load greater than 70 lb. With a load rating of 70 lb, the margin of safety is:

$$MOS_{assembly} = \frac{411\ lb. - 70\ lb.}{70\ lb.} = 4.48$$

$$P_{max} = 70\ lb.$$

Torque Calculations

The torque required to drive the maximum working load of 125 lb is given in manufacturer literature by[64]:

$$T_{drive} = \frac{P_{max} \cdot l_s}{2\pi \cdot \eta_s} = \frac{70\ lb. \cdot 1.000\ in. \cdot (\frac{1\ ft.}{12\ in.})}{2\pi \cdot 0.80} = 1.16\ ft \cdot lb_f$$

The backdrive torque (i.e., axial load on screw that would cause rotation of the screw) is given by[64]:

$$T_{back} = \frac{P_{max} \cdot l_s \cdot \eta_s}{2\pi} = \frac{70\ lb. \cdot 1.000\ in. \cdot 0.80 \cdot (\frac{1\ ft.}{12\ in.})}{2\pi} = 8.91\ ft \cdot lb_f$$

Kollmorgen provides a NEMA 34 size stepper motor (PMX Series Part no. 3440-B10), which has a holding torque of 9.06 ft-lb_f and torque-speed performance that suits the above-mentioned torque and speed requirements. Therefore, the holding torque, combined with additional torque in the system (i.e., from linear rails, bearings) will prevent backdriving for loads of 70 lb and below.

APPENDIX C – DETAILED CALCULATIONS OF ANDES SCAN TIMES FOR SPECIMEN PORTFOLIO

Specimen Dimensions			
Specimen	Active Length (in.)	Effective Width (in.)	
Mark-VII Fuel Assembly	*49.5*	*4.27*	
ATF-2 Rodlet	*6*	*NA*	
AFC Capsule	*1.5*	*NA*	
Flux Wire	*83*		
3D Scanning Specifications[50]			
Quick 3D Scan Speed	*15 seconds/scan*	Fine 3D Scan Speed	*3 minutes/scan*
Field of View - Height	*5.9 in.*	Field of View - Width	*7.5 in.*
Overlap between scans	*10%*		
ATF-2 Fine 3D Scan Time	*24 minutes*	Mark-VII Fine 3D Scan Time	*199 minutes*
Gamma Spectroscopy and Computed Tomography (CT) Scanning			
Quick Scan[43]	*5 min/scan*	Long Scan[29]	*30 min/scan*
Step Size	*0.025 in.*		
Aperture Width	*0.875 in.*		
Number of Gamma CT Angles[45]	*16*		
Specimen Throughput Information			
Flux Wires Per Cycle	*20 tubes/cycle*	Flux Wire Scan Time	*0.5 minutes/in.*
ATR Operating Days	*255 days/year*	ATR Outage Days	*111 days/year*
Average Fueled Experiments/Cycle	*10*	Percent of experiments requiring ANDES PIE	*20%*

First, calculations of the baseline specimen scan times were first based on current RML counting times of the Co and Ni flux wires. Next, experiment scanning times were determined assuming that only a fraction (20%) of all ATR experiments in a given year will request ANDES PIE. Experiments were assumed the primarily require 3D scanning and gamma spectroscopy. It was further assumed that gamma CT would only be used if unusual spectra was observed during gamma spectroscopy. It should be noted that gamma CT completed in MFC HFEF indicate that gamma CT takes an extremely long time to complete. Therefore, only a select few experiments will be able to use this feature, unless other functionality is sacrificed *or* if approved storage is granted, which will allow for automated scanning after-hours. Finally, Mark-VII fuel assembly scanning times were calculated as the remaining time left over. This time would likely include 3D scanning, gap channel probe measurement and other fuel assembly inspection deemed necessary by operations.

Specimen Scan Time (Based on 2,080 hour work year)	
Flux Wires	*184 hrs/year*
Experiment Gamma Spectroscopy	*1284 hr/yr*
Experiment Gamma CT	*320 hr/yr*
Remainder: Mark-VII and other Scanning Time	*291 hr/yr*

APPENDIX D – DETAILED CALCULATIONS FOR WATER MAKEUP OF ANDES APPROVED STORAGE

$T_{canal} = 20\ °C$	*Nominal water temperature in the ATR canal*
$T_{in} = 40\ °C$	*Nominal water temperature of emergency canal fill water*[65]
$P_{amb} = 84.8\ kPa$	*Ambient pressure in the ATR canal operating area*
$T_{sat} = 94.84\ °C$	*Saturation temperature (boiling temperature) of water at* P_{amb} *by linear interpolation*[66]
$C_p = 4.18\ \frac{J}{g \cdot °C}$	*Specific heat of water*[66]
$h_{fg} = 2256.4\ \frac{J}{g}$	*Latent heat of vaporization of water*[66]
$v_f = 0.001008\ \frac{m^3}{kg}$	*Specific volume of water*[66]
$\dot{Q}_{Mk7} = 1944.24\ \frac{W}{element}$	*Decay heat from ATR Mark-VII assemblies with 9 MW operating power, 4 hours of cooling time*[67]*. TSR-186 requires 11 hour cooling time for 9 MW assemblies, so this is a conservative estimates. Mark-VII assemblies will have the highest energy density after reactor removal compared to any other ANDES specimen.*

The energy required to boil off one gram of emergency canal fill water is given by:

$$Q_{water} = C_p \Delta T + h_{fg} = 4.18\ \frac{J}{g \cdot °C} \cdot (94.84\ °C - 40\ °C) + 2256.4\ \frac{J}{g} = 2485.63\ \frac{J}{g}$$

Mass flow rate of emergency canal fill water required to replace boil-off from one single Mark-VII assembly is given by:

$$\dot{m}_{water} = \frac{Q_{water}}{\dot{Q}_{Mk7}} = \frac{1944.24\ \frac{W}{element}}{2485.63\ \frac{J}{g}} = 0.78\ \frac{g}{second} \cdot \frac{1}{element}$$

Volumetric flow rate of emergency canal fill water required to replace boil-off from one single Mark-VII assembly:

$$\dot{V}_{water} = \dot{m}_{water} \cdot v_{fg} = 0.78\ \frac{g}{second} \cdot 0.001008\ \frac{m^3}{kg} \cdot \frac{1\ kg}{1000\ g} = 7.86\ \times 10^{-7}\ \frac{m^3}{second}$$

$$\boldsymbol{\dot{V}_{water} = 0.0126\,\frac{gallon}{minute}}$$

For comparison, an entire core irradiated for an infinite amount of time at 250 MW will require 5.34 gallons/min[65]. Therefore, a single element irradiated at the permitted maximum power will require more than 400 times less emergency fill water to compensate for boil-off.

APPENDIX E – STRUCTURAL CALCULATIONS FOR GAMMA COLLIMATOR CANTILEVER

The dominating loading stresses will be in the cantilever beams that support the collimator. This stress analysis considers each individual I-beam loaded with its share of the collimator assembly total load.

I. Analytical

The collimator cantilever is comprised of six 316 stainless steel 3 x 5.7 I-beams, each 36 in. long. The center moment of inertia about the loading axis is given by:

$$I_{c,x} = \left(\frac{t_w {h_w}^3}{12}\right) + \left(\frac{b}{12}\right)\left({h_w}^3 - H^3\right) = 2.49\ in^4$$

t_w: Web thickness

h_w: Interior cross-section I-beam height

b: Beam width

H: Total I-beam cross-section height

The estimated weight of the collimator assembly is approximately 2,000 lbf. Maximum load that the nearby jib crane is rated for is 4,000 lbf. The maximum crane load is considered in this analysis. The point load considered herein for each beam is 666.67 lbf.

Maximum bending stress from the point load in each of the individual loaded I-beams is given by:

$$\sigma_{b,max} = \frac{Mc}{I_{c,x}} = \frac{(\frac{4000lbf}{6\ beams})(36\ in.)(1.5\ in.)}{2.49\ in^4} = 14{,}418\ psi$$

M: Applied moment

c: Maximum distance to extreme fiber (i.e., half of total I-beam cross-section height)

I: Beam area moment of inertia

Maximum shear stress in each of the individual loaded I-beams is given by:

$$\tau_s = \frac{V}{8I_{c,x}t_w}\left(bH^2 - bh_w{}^2 + t_w h_w{}^2\right) = 1{,}509\ psi$$

V: Maximum shear load (i.e. point load)

The principal shear stress is given by:

$$\tau_{max} = \frac{1}{2}\sqrt{(\sigma_{b,max})^2 + (2\tau_s)^2} = 7365\ psi$$

The principal normal stresses are given by:

$$\sigma_1 = \frac{1}{2}\left(\sigma_{b,max}\right) + \tau_{max} = 7365\ psi$$

$$\sigma_2 = \frac{1}{2}\left(\sigma_{b,max}\right) - \tau_{max} = -156\ psi$$

From failure theories for static loading of ductile materials, the maximum von Mises stress is given by:

$$\sigma' = \sqrt{\sigma_1{}^2 + \sigma_2{}^2 - \sigma_1\sigma_2} = 14{,}652\ psi$$

Assuming a tensile yield stress of 42,100 psi for 316 stainless steel, the factor of safety for the strain energy theory for this configuration is given by:

$$FOS = \frac{S_{y,t}}{\sigma'} = 2.9$$

Assuming 316 stainless steel with a Young's Modulus, *E*, of 29E+06 psi, maximum displacement of the I-beam due to the point load is given by:

$$y_{max,point} = \frac{PL^3}{3EI} = 0.14\ in.$$

Maximum displacement of the I-beam due to the weight of the beam is:

$$y_{max,dist} = \frac{wL^4}{8EI} = 0.0014\ in.$$

Total displacement of the beam due is dominated by the point load.

I. Finite Element Analysis

A solid model of the I-beam was developed using Autodesk Inventor Professional 2017 to validate analytical results. One end was fixed while the end was free. Both a distributed load from the beam's own weight and the point load were applied. The point load had to be applied at the two top corners of the I-beam, which resulted in high localized stresses, which are not considered in the bending stress analysis above. Results are shown in the figures below.

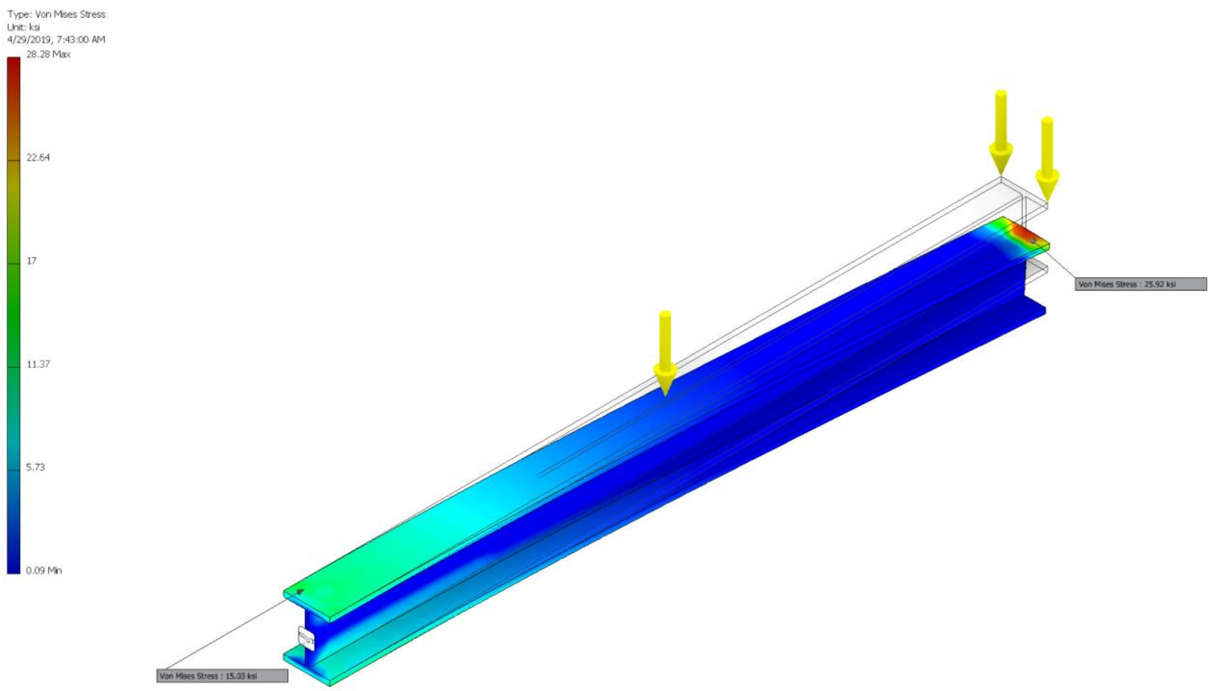

Figure E1: FEA Results - von Mises stress of cantilever I-beam with total range of observed stresses.

The largest von Mises stress observed from FEA was approximately 15 ksi (Figure E1, E2), which was within 5% of the analytical result. Again, the local stresses at the location of the point load were not considered in the analytical approach. The total displacement of the beam due to the point and distributed loads was 0.159 in. (Figure E3). This was within 10% of the analytical result.

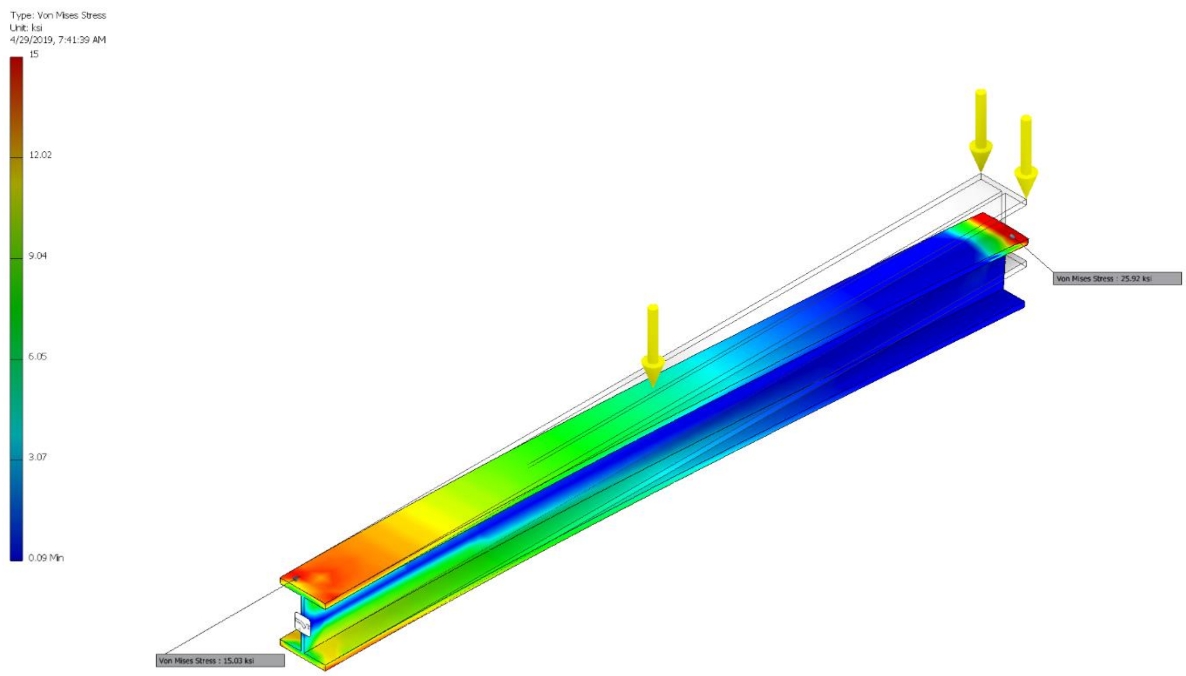

Figure E2: FEA Results - von Mises stress of cantilever I-beam with narrowed range of stresses.

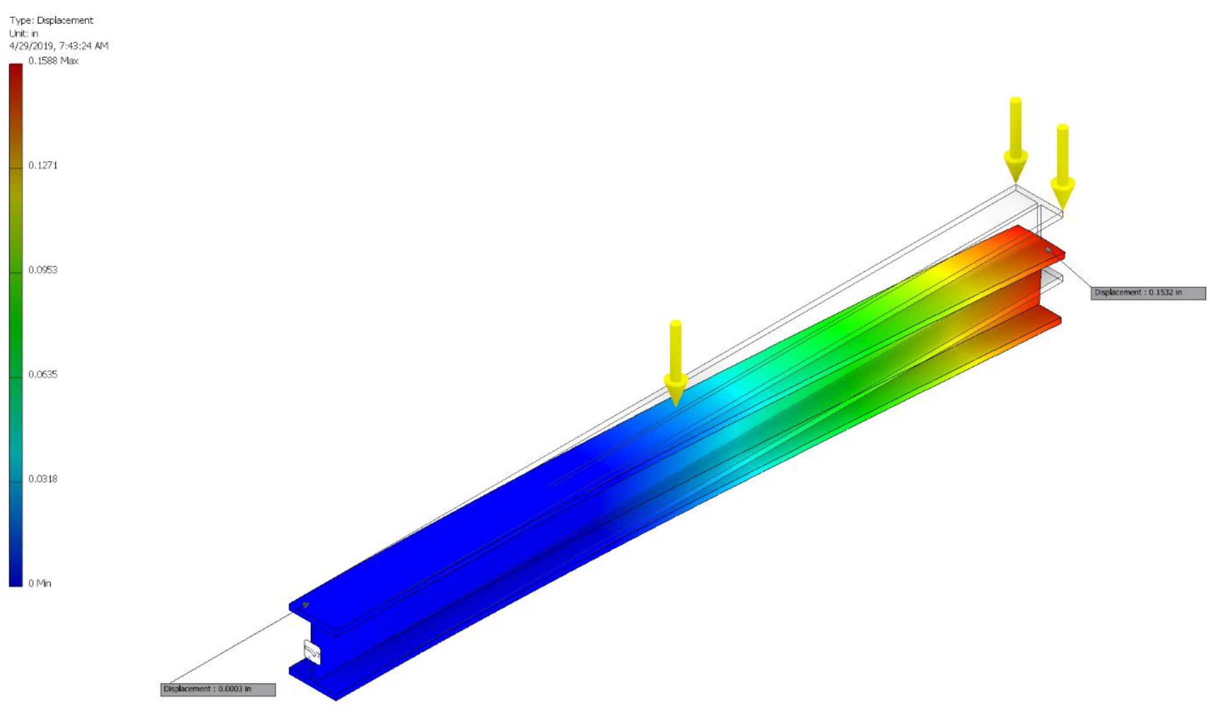

Figure E3: FEA Results – Displacement of cantilever beam due to distributed and point loads.

APPENDIX F – ATTENUATION AND SHIELDING CALCULATIONS FOR ANDES FLUX WIRE GAMMA SPECTROSCOPY

There are two characteristic gamma energy peaks that are analyzed during flux wire scans:

$I_{Co-60,1} = 1.17\ MeV$	The lowest-energy characteristic Co-60 energy
$I_{Co-60,2} = 1.33\ MeV$	The highest-energy characteristic Co-60 energy
$I_{Co-58} = 0.811\ MeV$	The characteristic Co-58 energy

These distances correspond to the configuration described in Figure 4.6.

$d_{total,A} = 57\ in.$	Straight-line distance from flux wire holder to detector
$x_{Al} = 0.33\ in.$	Thickness of aluminum between holder C and detector
$x_{water} = 2.1\ in.$	Thickness of water between holder C and detector
$x_N = 54.75\ in.$	Thickness of nitrogen between holder C and detector
$(\frac{\mu}{\rho})_{water} = 5.754 \times 10^{-2}\ \frac{cm^2}{g}$	Mass-energy absorption coefficient of water at 1.5 MeV
$(\frac{\mu}{\rho})_{Al} = 5.485 \times 10^{-2}\ \frac{cm^2}{g}$	Mass-energy absorption coefficient of 6061-aluminum at 1.5 MeV
$(\frac{\mu}{\rho})_{N} = 5.180 \times 10^{-2}\ \frac{cm^2}{g}$	Mass-energy absorption coefficient of nitrogen at 1.5 MeV
$(\frac{\mu}{\rho})_{W} = 5.000 \times 10^{-2}\ \frac{cm^2}{g}$	Mass-energy absorption coefficient of high-density of tungsten at 1.5 MeV
$\rho_{water} = 1 \frac{g}{cm^3}$	Density of water
$\rho_{Al} = 2.6 \frac{g}{cm^3}$	Density of 6061 aluminum
$\rho_N = 1.251 \frac{g}{cm^3}$	Density of nitrogen
$\rho_W = 18.5 \frac{g}{cm^3}$	Density of high-density tungsten (Kennertium)

The exponential attenuation law is given by:

$$\frac{I}{I_0} = e^{(\frac{-\mu}{\rho})\rho x}$$

I_0*: Incident gamma energy. 1.33 MeV for Co-60 (highest energy gamma energy from flux wires)*

$\frac{-\mu}{\rho}$*: mass-energy absorption coefficient*

ρ*: shielding material density*

x*: material thickness*

$$I_{water} = I_0 e^{(-\left(\frac{\mu}{\rho}\right)_{water}\rho_{water}x_{water}} = 0.978\ MeV$$

Resultant energy from water between holder and detector

$$I_{Al} = I_0 e^{(-(\frac{\mu}{\rho})_{Al}\rho_{Al}x_{Al}} = 1.18\ MeV$$

Resultant energy from 6061-aluminum between holder and detector

$$I_N = I_0 e^{(-(\frac{\mu}{\rho})_N\rho_N x_N} = 1.318\ MeV$$

Resultant energy from nitrogen between holder and detector

$$\Delta I_{total} = \sum(I - I_i) = 0.513\ MeV$$

Total attenuation from all materials (*i*) between holder C and detector

$$\frac{\boldsymbol{\Delta I_{total}}}{\boldsymbol{I}} = \mathbf{38.6\%}$$

Percent attenuation relative to incident Co-60 energy

$$I_{target} = I * 0.005 = 0.0065\ MeV$$

Target resultant energy for RML requirement of <1% detection of adjacent flux wires

$$\boldsymbol{x_W} = \frac{\ln(\frac{I_{target}}{I})}{(\frac{\mu}{\rho})_W \cdot \rho_W} = \mathbf{0.06\ m = 2.23\ in.}$$

Tungsten shielding thickness required for reducing adjacent flux wire holder energy to less than one percent of incident Co-60 energy.