INL/CON-24-77440-Revision-0

Pu-238 Production Progress at INL From December 2022 to December 2023

May 2024

Changing the World's Energy Future

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Overview

- Program Introduction
- Advanced Test Reactor (ATR) GEN I Target Design
- CY 2023 Production and CY 2024 Upcoming Cycles
- 20 vol-% Np and 30 vol% Np Target Qualifications
- Shipping and Storage Updates
- ATR Operation Updates
- Questions

INL Pu-238 Production Life Cycle

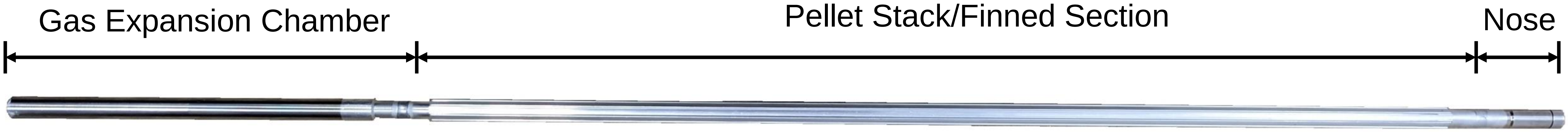
1. INL packages and transfers Np-237 to Oak Ridge National Lab (ORNL)
2. ORNL fabricates targets and inserts Np-237 pellets. Then ORNL ships a portion of the completed targets to the Idaho National Lab (INL) for irradiation and keeps some to be irradiated in the High Flux Isotope Reactor (HFIR).
3. Targets are irradiated in INL's Advanced Test Reactor (ATR) and HFIR to convert Np-237 to Pu-238. All targets are processed at ORNL.
4. ORNL processes the targets and ships the Pu-238 to Los Alamos National Lab (LANL)
5. LANL fabricates Pu-238 into iridium clad pellets and ships them to INL to fuel radioisotope thermoelectric generators (RTG).
6. INL fuels the RTG and performs acceptance testing. Then the RTG is shipped to support the identified launch window at Kennedy Space Center.

**ORNL also irradiates the same design of targets in HFIR. Targets from both facilities are processed at ORNL and sent to LANL.*

Pu-238 Production Background

- Goal is for ATR and High Flux Isotope Reactor (HFIR) to contribute to the 1.5 kg per year constant rate production goal of Pu-238 in the United States by 2026.
- Current goal is to qualify as many positions as possible so Pu-238 production will be a backup experiment in these positions
  - If other experiments are having difficulty qualifying and miss the insertion date, Plutonium Fuel Supply (PFS) will replace the experiment
  - Enables better utilization of the ATR core by ensuring that positions are fully utilized
- The HFIR GEN II is a previous target design that was specifically designed for use HFIR. The ATR GEN I target is a newer target design that was specifically designed for use in ATR as well as HFIR. Both types of targets have been qualified for use in ATR.
- The northeast flux trap (NEFT), south flux trap (SFT), east flux trap (EFT), inner-A and H positions have all been qualified for the insertion of the ATR GEN I target.

ATR Gen I Target



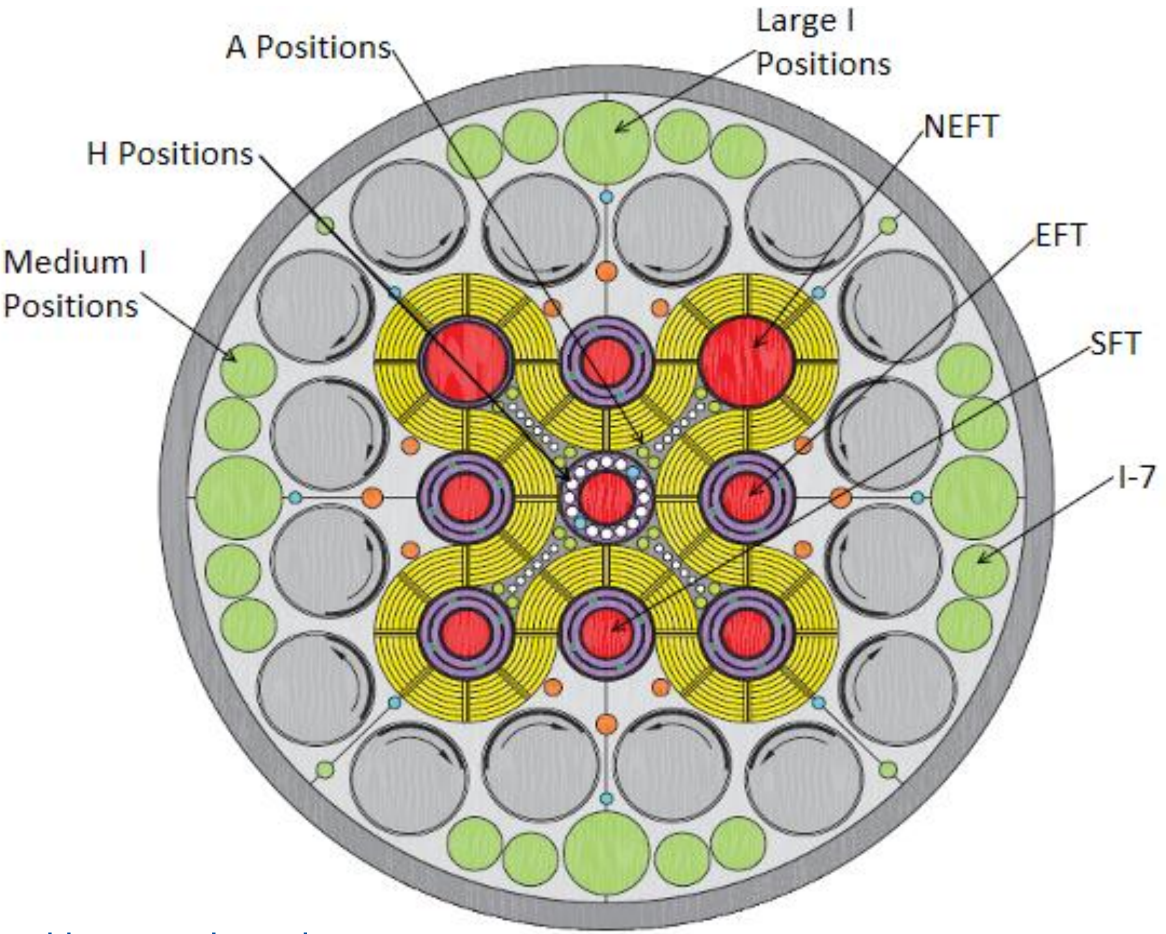
- The ATR GEN I was designed by ORNL to have a second ATR Gen I target stacked nose to nose in each basket at ATR.
- Stacking targets allows the full height of the ATR core to be utilized while the shorter target length allows the targets to be processed in ORNL's hot cells.
- The ATR Gen I is 28.69" long whereas the HFIR Gen II is 33.53" long. The difference in length and the flat nose design allows for the target to be stacked.
- ATR Gen I targets with 20 vol% Np weigh approximately 200g and contain approximately 30g Np
- Np Pellet stack is identical for ATR Gen I and the HFIR Gen II targets.
- Each ATR Gen I target contains one internal Sm spacer to reduce the flux at the center where the targets meet.

ATR Position Qualifications

Finished Qualifications
- I-7 (Medium I) Position HFIR GEN II target
- SFT HFIR GEN II Target
- NEFT ATR GEN I Target
- SFT and EFT ATR GEN I Target
- Inner A and H Positions ATR GEN I
- 30% Nominal with 35% Maximum Np for NEFT, SFT, EFT, A and H positions

Current Qualification
- Reduced Target Loading for Flux Traps
- Medium I positions

Future Qualifications
- Optimizing thermal analysis to reduce handling requirements
- Large I Positions
- ATR Increased power levels



Cross Section of the ATR Core

- Inner core positions provide high production rate with approximately 84% to 92% assay
  - One cycle to complete production
- I positions provide low production rate with approximately 90% to 96% assay
  - Typically will take 5 or 6 cycles to complete production

Production Completed in Calendar Year 2023

171 A

54 Day Cycle

- NEFT- 46 ATR GEN I Targets
- SFT – 7 HFIR GEN II Target
- Inner A Positions – 2 ATR GEN I Targets
- H Positions – 2 ATR GEN I Targets

171 B

64 Day Cycle

- NEFT- 46 ATR GEN I Targets
- SFT – 1 HFIR GEN I Target
- Inner A Positions – 0 Targets
- H positions – 2 ATR GEN I Targets

Totals

- 106 Targets were irradiated in CY 2023
- It is estimated that this will produce approximately 450g of heat source material.

Estimated Production for CY 2024

173 A

60 Day Cycle

- NEFT – 46 ATR GEN I Targets
- Inner A Position – 0 Targets
- H Position – 0 Targets

173 B

60 Day Cycle

- NEFT – 46 ATR GEN I Targets
- Inner A Position - 0 Targets
- H Position – 0 Targets

173 C

60 Day Cycle

- NEFT – Up to 46 ATR GEN I Targets*
- Inner A Position - 0 Targets
- H Position – 0 Targets

Total

- It is planned to Irradiate up to 138 targets in CY 2024
- This will generate up to approximately 600g of Pu-238 heat source material.

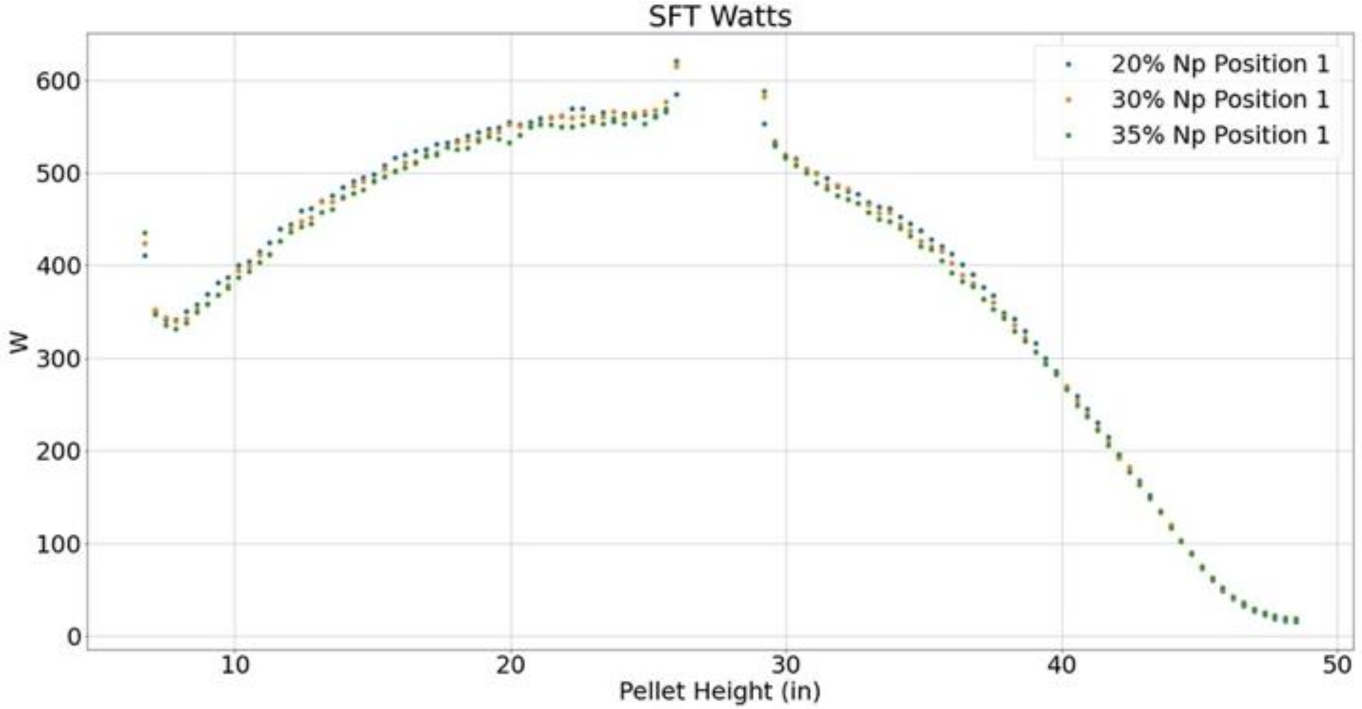
*ORNL is still determining how many targets they can provide for this additional cycle

Neutronics Analysis SFT and EFT

- SFT is one of the most challenging positions in ATR to qualify due to typical power levels creating challenging thermal and neutronic conditions.
- Nominal values of ATR operating conditions were used to model the ATR GEN I targets in MCNP and the results were scaled to the projected peak power splits. To properly capture the axially dependent behavior of the neptunium pellet material in each target, each pellet stack was divided into forty axial segments.
- MCNP5, a general-purpose Monte Carlo N-Particle transport code, was used to calculate the following:
    - Pertinent neutron and photon heat generation rates within all experiment materials.
    - Neutron fluxes and reaction rates for pertinent reactions on the neptunium pellet material.
    - The reactivity worth of the unirradiated experiment and the end of cycle experiment were calculated using the 19-plate MCNP model of ATR.
- After 60 days of irradiation, the Pu-238 average assay was calculated for each target located in the SFT. The peak average Pu-238 assay is 87.49%. It is estimated that approximately 56 grams of Pu-238 will be produced in the SFT of ATR during a 60-day cycle which is approximately 75 grams of heat source material.

Neutronics Analysis 30% Np Qualification

- Analyses were done to qualify an ATR GEN I target with both a 30 vol-% Np target and a 35 vol-% Np target using the common Monte Carlo design tool (CMCDT). CMCDT consists of the Physics Unified Modeling and Analysis (PUMA) API, version 9.1.1, and the Monte Carlo code, MC21, version 9.00.02. ORIGEN, as part of the SCALE6 package, was used for the decay heating and source term calculations.
- Nominally, the desired target concentration will contain 30 vol-% Np with analyses also completed at 35 vol-% Np to account for variances in the pellet manufacturing process.
- Due to self-shielding in the targets, the overall wattage produced is largely the same regardless of Np loading, with the notable exception being at the center where the two ATR GEN I targets meet.



Neutronics Analysis 30% Np Qualification

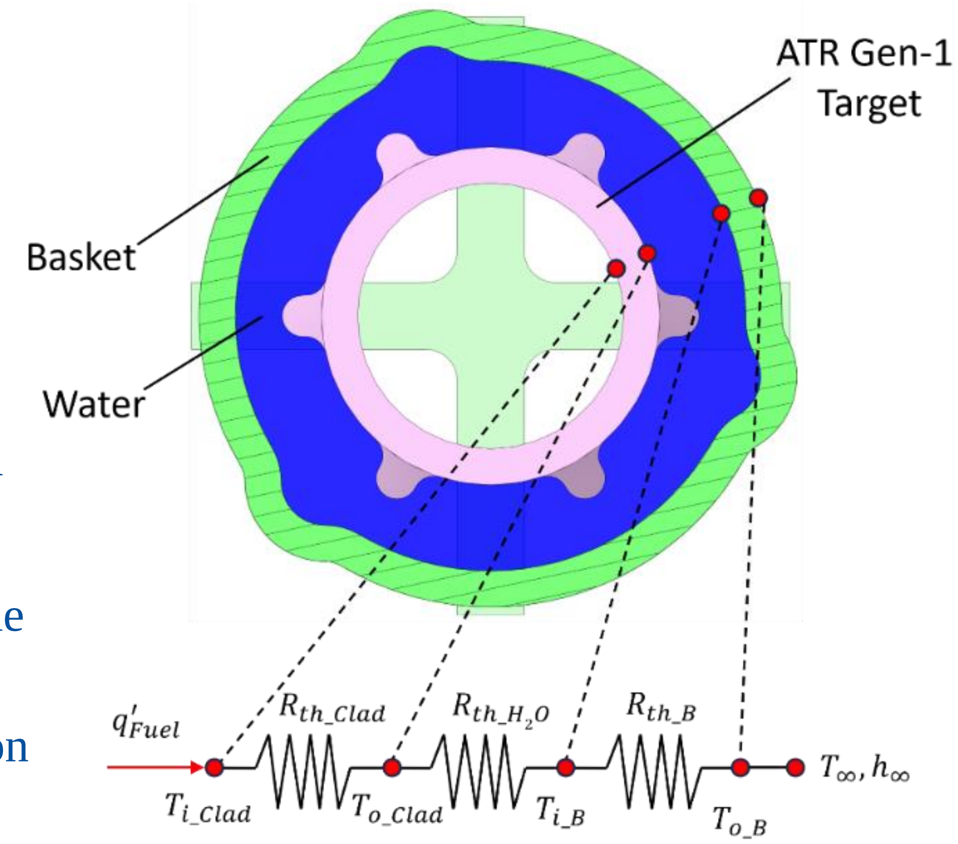
- The table below gives averages for production values at 60-days for a single target with 30 vol-% Np.
- The production rates and Np conversion parameters are for each of the individual positions. Each position is scaled to its respective bounding lobe power – 22 MW in the NE, 25 MW for the inner-A and H positions, 25.7 MW in the S, and 23.7 in the E.
- Over a 60-day cycle, the NEFT has a maximum total production of 202 g Pu-238, the SFT has a maximum total production of 71.6 g Pu-238, and the EFT has a maximum total production of 67.4 g Pu-238.

Position	Avg. Pu-238 (g)	Avg. Assay (%)	Avg. Pu-236 content (ppm)*	Lobe Power (MW)	Number of Positions
EFT	4.82	89.5	4.54	23.7	7
SFT	5.11	88.9	4.67	25.7	7
NEFT	4.39	90.9	5.60	22	23
H	4.15	93.3	6.77	25	14
Inner-A	3.90	93.7	8.04	25	8

*Note that Pu-236 limit is 2 ppm and the half life is 2.86 years

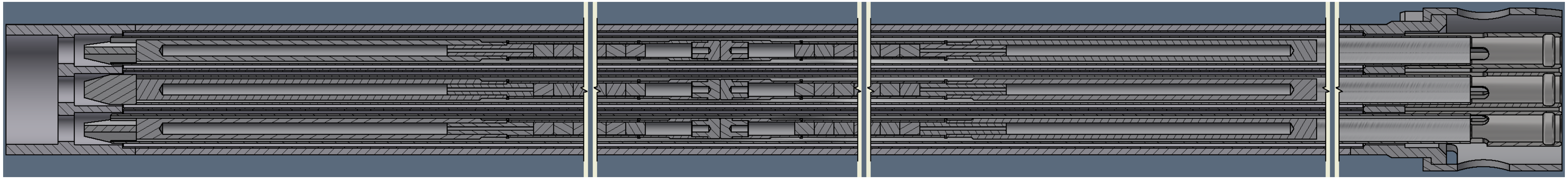
Thermal Analysis

- The thermal qualification of the 30-35% Np loaded ATR GEN I targets was accomplished by leveraging previous analyses and utilizing a combination of finite element analysis (FEA) using ANSYS and ABAQUS and thermal/hydraulic system codes (RELAP5).
- The general safety analysis for the ATR GEN I target performed in the qualification of the 20% Np targets was used to facilitate the qualification of the 30-35% Np loaded targets. The heat rates for the A and H positions were well within the applicable bounds of the generalized analysis.
- The required cooling time for the experiment via natural convection in air and water must be assessed for handling times or in the case that the experiment is dropped to the canal floor and/or a canal draining event. In the horizontal-in-air and water scenarios, the experiment assembly was modeled within the basket and immersed in the desired medium (water or air) using a 1-D thermal resistance network. A schematic of the resistance network, overlayed on the ATR GEN I geometry, is shown on the right.



Thermal Analysis

- The high heating rates experienced in the SFT and the reduced flow rates in the NEFT required further analysis to demonstrate compliance with requisite safety requirements for irradiation in ATR.
- Due to the increase in thermal load of the 30% Np, there needed to be an increase in flow through the SFT housing. The orifice under each basket was increased from 0.25-in. to 0.5-in. diameter
- The thermal qualification of the 20% Np targets in the SFT/ EFT was sufficiently bounded by the analysis performed for the 30-35% Np loading in the same position. The total heat rate, peak heat rate, and decay heat rates were all below the 30-35% cases at the same hydraulic conditions. Therefore, the results of the 30-35% qualification, as well as the experiment handling times, were directly applicable to the 20% Np loading.



Structural Analysis

- The loadings considered in this evaluation included the following:
  - Internal pressure within the target due to the release of fission gas,
  - External pressure and external pressure differential acting on the length of the assembly,
  - Pressure and skin friction drag forces due to coolant flow velocities, flow induced vibrations, thermal loads, and cyclical loads.
  - Accidental drop through water from a height of 45 ft, which is the deepest portion of the ATR canal.
- ASME Boiler and Pressure Vessel Code were used as a guide although other acceptance criteria could have been used.
  - Provides a nationally accepted design/analysis approach which INL has used and adapted to various nuclear experiments.
- Utilized a bounding case approach
  - Calculated maximum limits for temperature, pressure and coolant velocities.
  - Compared the maximum limits to the those calculated from the thermal analysis and from the design specification of the ATR. The Comparison showed that the SFT and 30% qualifications were within the calculated limits and each structural component was considered to meet the safety requirements; thus, the targets are allowed into the ATR

Single Target in The SFT and Power Increase in the NEFT

- Single Target in the SFT
  - To support complete utilization of all Pu-238 targets located at INL, an analysis was completed to qualify the irradiation of a single HFIR GEN II target in the SFT.
  - MCNP5, a general-purpose Monte Carlo N-Particle transport code, was used to ensure that the original analysis of 7 HFIR GEN II targets in the SFT sufficiently bounded a single target. The analysis concluded that a single target is bounded.
- Power Increase in the NEFT.
  - Due to an increase in the projected ATR power splits, a full neutronic analysis was completed for the NEFT. This analysis demonstrated compliance to the safety requirements for continued irradiation in ATR.
- Both the thermal hydraulic and structural analysis were checked to verify that they still bounded the revise Neutronic Analysis.

Shipping and Storage Updates

- Two shipments of ATR Gen I targets were received in 2023. The first shipment contained 25 targets and shipped in February. The second shipment contained 24 targets and shipped in March. These targets were irradiated in cycle 171B.
- Storing the targets for 1 year rather than 6 months allows for a greater than 40% reduction in isotopic gamma activity.
- New source term for BRR cask Safety Analysis Report (SAR) update
  - Original SAR source term was based upon HFIR Gen II targets being irradiated in the A positions.
  - Targets are now being irradiated in the Flux traps and it is planned to go from 20 vol-% Np to 30 vol-% Np target.
  - A new neutron and gamma source term was developed based upon a maximum target isotopic inventory from both the 20 vol-% Np and 30 vol-% Np Targets. These values will be used to update the BRR Cask SAR.

ATR Operations Updates

- Irradiated Targets Stored in ATR Canal

Position	169A-1	171A-1	171B-1	Target Type
SFT	7 Targets	7 Targets	1 Target	HFIR GEN II
NEFT		46 Targets	46 Targets	ATR GEN I
H		2 Targets	2 Targets	ATR GEN I
Inner-A		2 Targets		ATR GEN I
I-7	7 Targets			HFIR GEN II
			Total	120 Targets

- Safety Analysis experienced several process improvements this past year
  - The most notable is a cask list for ATR. The purpose of it is to organize and implement the requirements for the different casks used at ATR. This list includes the BRR Cask that will be used to ship targets to ORNL.
  - The cask list hands off to a shipping compliance (cask-specific) which utilizes an experiment configuration checklist (cask-specific) to verify compliance to the safety requirements prior to the shipment leaving ATR

Conclusion

- INL has successfully completed qualification for the ATR GEN I targets for both 20 vol-% Np and 30 vol-% Np in the NEFT, SFT, EFT, inner A, and H positions.
- Irradiated a total of 120 targets in ATR with plans to irradiated up to 138 more targets in CY 2024
- During the past year, the INL team has made great advancements in the progress of contributing to the overall program goal and is on track to meet production goals by 2026.

Acknowledgments

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