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A Neutron Generating Target Using Recycled Uranium Discs

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Abstract

The Intense Pulsed Neutron Source utilizes a neutron production target that contains a stack of eight depleted uranium discs, each 10 cm in diameter and 2.5 cm thick. The lifetime of a typical target has averaged about four years. After each target has reached end-of-life, a new target containing fresh uranium discs has been installed. An impending lack of available fresh uranium discs, together with budget considerations (a supply of new uranium discs would cost nearly $1M), gave rise to a good idea: fabricate a target containing some viable, low burn-up discs that could be removed from targets that have reached end-of-life. Such a target was built and placed into service, resulting in considerable cost savings and enhanced facility reliability. This paper will discuss the removal of the discs from targets that reached end-of-life, fabrication steps followed to build the new target, and the rationale used for the positional placement of used discs in the new target based on a calculation of remaining disc life. A neutron flux performance comparison to the previously operated target will also be given.

1. Introduction

IPNS is a highly reliable spallation neutron scattering facility, historically operating at an availability of over 95%. Reliability is mainly governed by availability of the accelerator; however, overall facility reliability is limited by the weakest link in the chain. Any significant problem with the neutron generating target would directly affect facility reliability and therefore IPNS has a policy that requires that a spare target always be available for service. This paper describes the fabrication of a new target, herein called the "recycled" target, intended to increase the spare inventory and help to maintain the high reliability of IPNS.

The IPNS neutron generating target is a passive component, having no mechanical moving parts, that essentially consists of a stainless steel enclosure containing eight depleted uranium discs. See Figure 1. The disc material is called "adjusted uranium". The base material is ^{238}U with 0.2 wt % ^{235}U, and the following minor additions: 450 wt ppm C, 250 wt ppm Fe and 350 wt ppm Si [1]. The discs are clad in a zirconium alloy called Zircaloy II. The two cup-shaped halves of the cladding that cover each disc are circumferentially welded and the cladding is bonded by hot isostatic pressure processing to the uranium core. The cladding is then machined to the final thicknesses of .5 mm on the disc faces and 1.25 mm on the circumferences. The cladding has a twofold purpose. First, it maintains confinement of the radioactive fission and spallation products arising from the impingement of the 450 MeV, 15 μA, 30 Hz pulsed proton beam on the target. Second, the cladding prevents direct contact between the uranium discs and the cooling water circulating through the target. Such contact would cause rapid corrosion of the uranium.

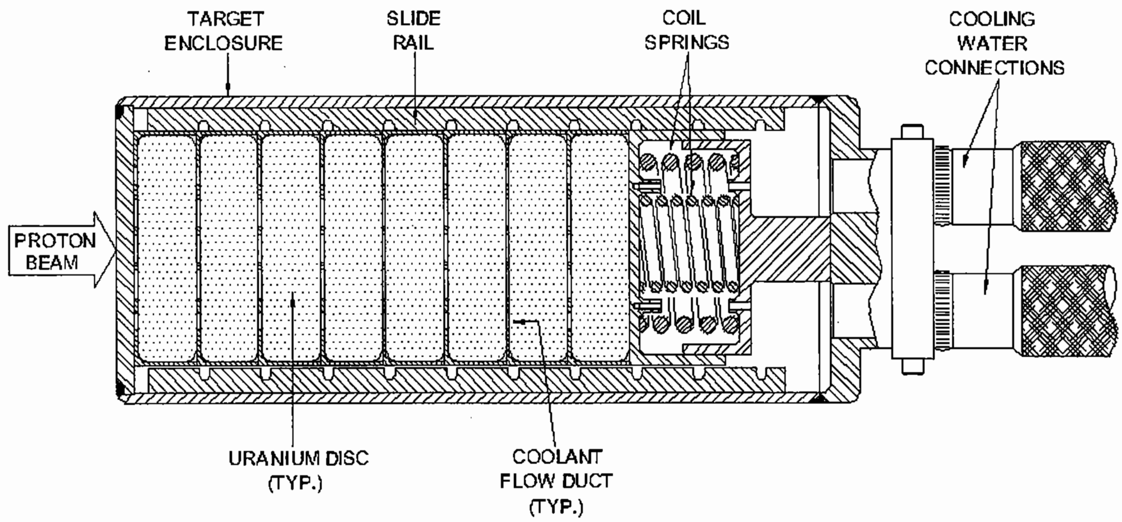


Figure 1: Cross section of IPNS neutron generating target.

A disc reaches the end of its life when the cladding develops a small breach due to the anisotropic swelling of the uranium during service. See Figure 2. This swelling is characteristic of the orthorhombic crystal structure of the α-phase "adjusted" uranium. The degree of swelling correlates most closely with the number of fissions that have occurred in the material [2]. Three IPNS targets have reached end-of-life, exhibiting a mean lifetime of 260,000 μA-hrs, or about four years given the average proton beam current of 15μA. When any individual disc experiences clad breach, small amounts of fission and spallation products are released into the cooling water system. A γ radiation monitor sensitive to the 250 keV γ-ray from ^{135}Xe detects the elevated levels and the neutron generating system is shut down, taking the target out of service. Facility safety is not compromised by clad breach. A clad breach is the expected end-of-life event for the target. No more than one disc in any one target has ever been shown to have developed a breach. To date, the only confirmed breaches have occurred in either the first or second discs, at the front of the target where the proton beam enters. This fact is consistent with the expectation that the majority of the proton beam energy is deposited in the first few discs.

Figure 2: Photo of disc cladding breach.

2. Need for Discs Arises

The available inventory of uranium discs has dwindled as they have been used up in the previous five targets irradiated at IPNS since 1981. The reason for the IPNS policy that we will always have a spare target available during operation is that any target could reach end-of-life prematurely. The reduced disc inventory and need for spare targets, together with increasing budgetary austerity, provided the impetus for the development of a creative idea during the year 2000. That idea was the removal of used discs from targets that had reached end-of-life and the construction of a new target containing some of those discs. A calculation was performed to estimate remaining life in the used discs [3] using the following methodology. First, results of a previous calculation from the early years of IPNS were used as input to predict the percentage of target power produced within each disc. The results were normalized to the disc in position 2, which was the disc that was predicted to generate the most power and hence was expected to develop a breach first. Conversion to a fraction and subtraction from 1.0 then yielded the predicted percent of life remaining for each used disc in the retired targets. Table 1 summarizes the results of the calculation. The percentages refer to expected lifetime compared to the 260,000 μA-hr mean target lifetime. It is obvious that the discs near the front (proton beam end) of the target would be expended first and that the discs in the rear would have considerable life remaining. It is important to note that the term "expended" as it is used here refers to the degree of swelling caused by proton beam irradiation, and not to a lessening in the production of neutrons. Even at the end of its life, an "expended" disc of depleted uranium still produces about 14 neutrons for each proton that collides with a uranium nucleus, as does a new disc.

Table 1: Percentage of remaining disc life in target that has reached end-of-life.

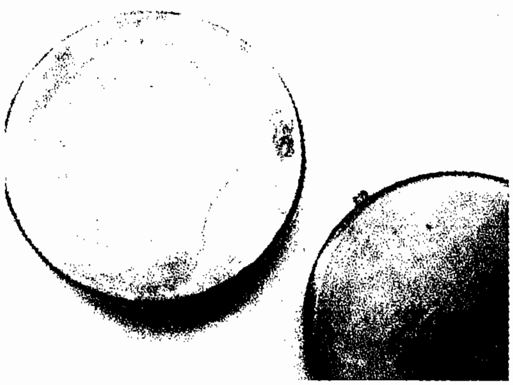
	Disc Position							
	1*	2	3	4	5	6	7	8
% Life Remaining →	1.9	0.0	10.2	21.8	34.0	61.2	90.3	94.7
* Disc closest to proton beam entry								

The estimated radioactivity levels associated with handling of the activated uranium discs, which would result in increased dosage to personnel, were an important factor in the decision of whether to proceed with the project. After an informal cost/benefit analysis was completed, the decision was made to fabricate a target containing discs recovered from retired targets. Funding was allocated and the project began early in the year 2001.

3. Recovery of Usable Discs

The first step in the process was the removal of discs from one of the two remaining retired targets. The retired targets were held in sealed underground storage silos beneath the IPNS experimental hall. The target assembly was prepared by separating the target enclosure from the connected cooling hoses and linkage, a task that was performed in the IPNS experimental hall. Next, the target was transported to one of Argonne National Laboratory's hot cell facilities. The activated state of the retired target necessitated that the work be done in the hot cell facility, which is used for work involving highly radioactive materials such as spent nuclear reactor fuel. The target was measured and photographed for reference prior to cutting operations. A series of documentation photographs was also made of the cutting, disc removal, inspection and target assembly processes. The rear end (the end away from proton beam entry) of the target was cut to remove the cooling hose linkage extension using a band-type cutoff saw. Next, a suitable cut location toward the rear end was selected based on minimizing material cross sectional area. The target enclosure was secured with a hold down clamp and the ends were held in place to prevent spring out as the cuts were made. This was necessary because targets are designed to be under an internal spring compressive force of 670 N (150 lbs.) to prevent vibration of the discs in the cooling water flow of 190 liter/min (50 gal/min) passing through the target. Six cuts to predetermined depths were carefully made sequentially around the circumference of the enclosure, with the body of the enclosure being reclamped for each cut. After full separation, the end restraints were slowly released against the internal spring tension. Internal mechanical components and five of the discs were then removed. Figure 3 shows a photo of two removed discs. The three front discs resisted removal and were left in place in the enclosure for disposal, an acceptable situation since there was no plan to use them in the recycled target in any case. Measurements showed the average radiation dose rate from a typical removed disc to be 1.7 mSv/hr (170 mR/hr) at 1 m. The removed discs were visually inspected and identified. The other internal components were also visually inspected for future design reference. The discs that would be used in the recycled target were selected based on the remaining life calculation [3]. The selected discs were segregated in a clean area and a careful cleaning step was performed. The cleaning consisted of immersion in an ultrasonic water bath, rinsing with deionized water and air drying. This step was a precaution against "tramp" contamination that might have been deposited on the discs after removal from the target. Because the hot cell is used for a variety of projects involving cutting and grinding of very radioactive materials, contamination of the discs from non-target sources was possible. Such contamination could result in the unintentional shutdown of the facility after the target was placed in service, as the sensitive radiation detection system could mistake the activity from the contamination for that arising due to a clad breach during operation.

A careful leach test of each selected disc was then performed. This consisted of immersion of the disc in deionized water for a minimum of one hour, followed by analysis of the water for fission or spallation products. This process was repeated a minimum of four times for each disc, with a deionized water rinse occurring between each cycle. Decreasing concentration of a particular activation product with each iteration, or no detection of activation products, confirmed that there were no breaches in the cladding of the discs.



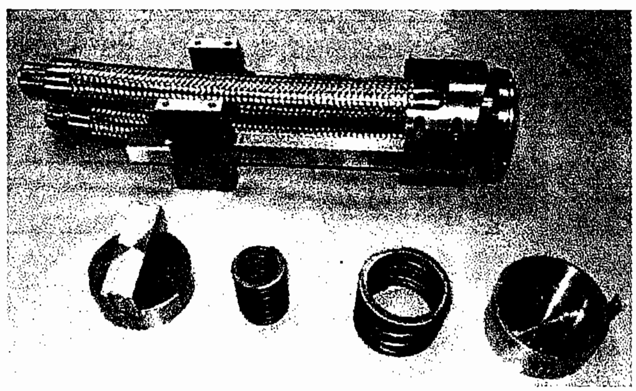


Figure 3: Left: Removed target discs. Right: New target components.

4. New Target Fabrication

Next, new target components were procured and fabricated. The recycled target fabrication process was similar to that used for the previous five IPNS targets, with the exception that the work occurred in the hot cell and consequently required somewhat more preparation and deliberation. All the components in the recycled target were new with the exception of the used discs, since the cost of working with the activated components from the retired targets outweighed the cost of producing new components. Figure 3 shows some of these components. The new parts were assembled and delivered to the hot cell facility.

Both recycled and new discs were stacked inside the target enclosure. The target was filled with six used uranium discs, one new uranium disc, and one tantalum disc, which was located in the rear most position. (Only five used discs were removed from the retired target as part of this project; an earlier retired target opened in 1993 in order to study radiation effects provided several more usable discs for the recycled target.) The life expectancy of a used disc will be less than that of a new disc, because fission and spallation have occurred in the used disc, and it has been expended (anisotropically swelled) to some extent. The order of disc placement in the recycled target was based on the percentage of life remaining in the disc and the rate at which the disc would be expended in the new location in the recycled target. In general, the placements were arranged to maximize target life by locating the least expended discs in the forward most locations. A refined calculation [4] using MCNPX Monte Carlo simulation predicts that the recycled target will last 90% as long as a target containing all fresh discs.

The target enclosure was welded, inspected and pressure tested. The recycled target was transported to the IPNS experimental hall where the new cooling water hoses and linkages were installed and inspected. It was decided to place the target in operation to confirm that it would perform as expected; the operating target that it replaced would then serve as the spare. If the recycled target performed up to expectations, it would be left in place as the operating target.

5. Performance

The recycled target was lowered into the operating position in the moderator/reflector assembly and entered service in January of 2004. The target operated as expected, with no abnormal indications from the cooling water or radiation detection systems. Initial reactions from the instrument staff and users were encouraging, with no apparent deficiency in flux being noticed. A quantitative comparison was necessary to confirm target performance; therefore, neutron flux data from seven of the thirteen IPNS scattering instruments were collected and analyzed. The data were retrieved from the period of August 2003 to December 2003 for the previous target having all original uranium discs, and from the period of February 2004 to June 2004 for the recycled target containing the used discs. Five data points, spaced about thirty days apart, were selected for each target to perform the comparison. Two of three IPNS moderators contain solid methane, and undergo a complete inventory exchange once per week. To minimize effects of moderator variation, all data were collected on days after methane exchanges, a time when methane condition could be expected to be most consistent across all instruments. On each selected day, a multi-hour run was chosen. For each run, the total number of neutron counts recorded by the instrument beam monitor was divided by the total number of proton beam arrival pulses sent by the accelerator monitoring circuitry. The results of the comparison are presented in Figure 4. The data are compared as ratios of flux from the recycled target to flux from the previous target. It can be seen that the values of the ratios are near unity. The fact that the ratio is not exactly equal to one could be due to a small change in positional placement of the target in the moderator/reflector assembly, or to variations in neutron production caused by differences in disc location from the previous targets to the recycled target. For practical purposes, the neutronic performance of the recycled target, as measured by this method, is identical to that of the previous target.

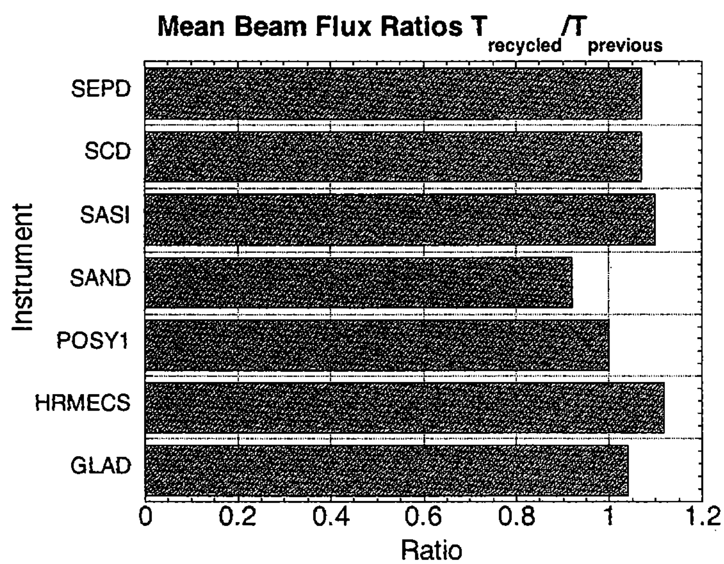


Figure 4: Ratios of mean beam flux from recycled target to mean beam flux from previous target measured at seven IPNS scattering instruments.

6. Results and Plans

This project was successful from a performance standpoint and also successful economically. A considerable amount of direct cost, over $100K, was saved through use of the recycled discs. More important, however, was the deferment for four years of the spending of nearly $1M for a supply of new uranium discs. This is especially relevant during times of tight budgets. The fabrication of another recycled target would defer the spending at least another two years. An additional soft benefit was the presentation of an Argonne National Laboratory award for recycling materials to the two individuals principally responsible for this project.

Because of the successful outcome of this project, IPNS is in the process of repeating the exercise at the time of this writing. There are a sufficient number of usable spent discs in the one remaining intact retired target, together with those already removed or available, to allow the fabrication of one more recycled target. The final recycled target will also probably contain one or two tantalum discs. Although tantalum produces about half the number of neutrons per proton as depleted uranium, the flux penalty will not be great because the tantalum discs would be located in the less critical rear positions. The fabrication of the next recycled target will allow IPNS to operate with a spare target on hand for an anticipated six years from present, taking into account the minor penalty in target lifetime. For operation beyond six years, new uranium discs will need to be procured sometime in the years 2007 or 2008. The new disc cores will likely consist of a γ-phase uranium-molybdenum alloy of cubic crystal structure that is not expected to exhibit anisotropic swelling. For this reason, it is likely that target lifetime will be extended significantly.

7. Conclusions

A neutron generating target utilizing partially expended uranium discs has been constructed and placed into service. The neutronic performance of the target is effectively identical to that of a target containing all fresh uranium discs; however, there is roughly a 10% penalty in expected target lifetime. This project was successful operationally and financially, and it resulted in enhanced facility reliability. Another such target is being fabricated and will allow IPNS to operate with a backup target for six more years from present. Subsequent targets will require purchase of new uranium discs that are expected to have longer lifetimes because of improved metallurgy.

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References

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