A New High-Efficiency LEU Oxide Package

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Abstract

Safe, efficient shipment of fissile uranium oxide used in the fabrication of fuel for electricity production is necessary to support the public demand for energy. Efficiency is necessary not only for economic reasons but also for enhanced safety margin. High efficiency packages result in fewer packages and fewer shipments in the public domain. This provides for increased focus and attention to detail, reduces the opportunity for accidents and reduces the overall risk. The Type A, Fissile Package, NPC (new powder container), recently introduced by Global Nuclear Fuel (GNF) addresses safety and efficiency as a design basis. The package is rectangular in geometry, which has been optimized for packing in transport devices. Detailed consideration was given to the weight of the package to maximize the amount of available payload while still meeting overall transportation weight restrictions. The package is constructed of stainless steel and polyurethane to be durable and near maintenance free. The efficiency is made possible by the unique patented nuclear design of the nine internal canisters. Currently the package is licensed in the United States and Japan for the transport of homogenous uranium oxide enriched to not more than 5%.

Introduction

Previous container designs like the original BU-7 (or the Japanese equivalent BU-J) utilized the exclusion of water from the inner container as the critical design feature to gain a moderate payload. This water exclusion feature has been in disfavor with the US Nuclear Regulatory Commission for several years to the point that they no longer approve designs based on water exclusion arguments (for fissile material transport safety demonstrations). Consequently, existing designs required re-evaluation assuming water intrusion and maximum reactivity of the contents. The result caused a 40% reduction in the payload for the BU-7 and resulted in a significantly increase in the number of packages to be maintained and in transit.

Licensing Process

In 1996, Global Nuclear Fuel – Americas, LLC (formerly GE Nuclear Energy) investigated preliminary design concepts to optimize a new package design for homogeneous uranium oxide forms. During early scoping calculations, both boron and cadmium effects on reactivity and configuration were studied. Based on the result of analysis and economic considerations, cadmium was ultimately selected for use in the NPC final design. This element is much less expensive than enriched boron, very stable and a very effective thermal neutron absorber. When properly handled and sealed poses minimal industrial health risks when handled properly and encapsulated within the package. The diameter of the inner containment geometry was adjusted to a favorable cylindrical geometry so that moderator exclusion was not a questionable issue.

Studies determined the unit remains subcritical through optimum internal H/U235 atom ratio and full water reflection. To assure safety of the NPC under these conditions, the design features a 3x3 array (9 inner containers) appropriately spaced, each surrounded by a special “neutron trap” close fitting around the inner stainless steel canister.

Following some conceptual test work in 1997, two prototype designs were constructed in 1999 and tested. These initial prototype tests resulted in modifications to structural and thermal characteristics of the package. The results of these tests aided in setting the final mechanical and neutronic design

In 2000, GNF finalized the design, built and subjected four individual Certification Test Units (CTUs) to hypothetical accident condition testing at the Southwest Research Institute (San Antonio, TX). The CTUs 1-4 were subjected to various normal conditions of transport and hypothetical accident condition test sequences as stipulated in the IAEA, US and Japanese regulations. Representatives from both the US regulatory agencies as well as the Japanese regulatory bodies were invited but none were available to witness the tests.

Four separate meetings were held in Washington, D.C. with the NRC to describe the initial design, discuss the prototype test results and to discuss the test plan for certification of the package. Further meetings were held at the time of the application and during answering the review questions. Similar activities were conducted in parallel in Japan.

Upon completion of the testing of the CTUs, the maximum measured “damage package” condition was determined, and used as a basis in the damaged (2N) package array models.
The result of these tests, careful SAR preparation, and expeditious review by the NRC resulted in approval in February of 2001. The first completed units are arriving at GNF and undergoing QC Acceptance criteria. The first international shipment in the NPC is scheduled for the fall 2001.

An Overview of the NPC

The GNF LEU oxide package, Model Number NPC, Package Identification Number USA/9294/AF-85 (Patent #6,166,391) represents an innovative design for moving large payloads of uranium oxide. The packaging efficiency has been optimized for homogeneous UO2 powder, but other fissile material payloads could also be justified. The NPC package has been extensively tested and analyzed to meet the NRC, IAEA, Japanese licensing constraints, and is now NRC and DOT approved Type A, Fissile Nuclear Package [1, 2] in the US and Japan.

The major components comprising the NPC are presented in Figures 1-3. These figures present an exploded view of the NPC packaging assembly, details of the outer closure region, and a detailed view of the inner containment canister and its closure seal region, respectively. A detailed description of the major packaging and payload components is discussed below.

The packaging consists of a stainless steel sheet metal Outer Confinement Assembly (OCA) body and lid that encases ceramic fiber insulation and rigid polyurethane foam, and nine equally spaced, individually sealed stainless steel Inner Containment Canister Assemblies (ICCA's). A closure lid with a silicone rubber gasket provides the closure of each canister along with a standard stainless steel bolted band clamp assembly.

The NPC is authorized to ship 1,190 pounds (540 kg) of enriched uranium oxide powder (per package including powder plus powder packaging) as a Type A (F)-85, fissile material package per the definitions delineated in 10 CFR §71. The transport index (TI) for the package, determined in accordance with the definitions of 10 CFR §71.4, is determined for each shipment. The TI is based on the number of packages (2N=150) for criticality control purposes.

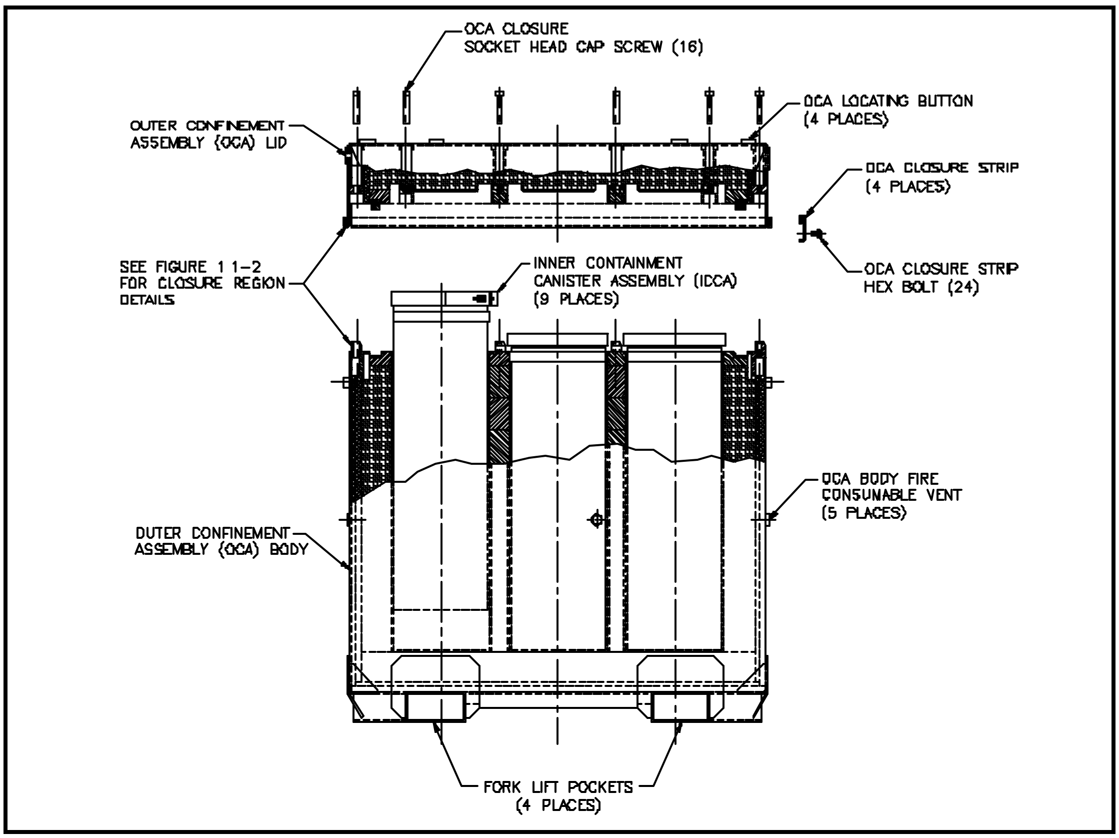

Figure 1. - GNF NPC Package Assembly

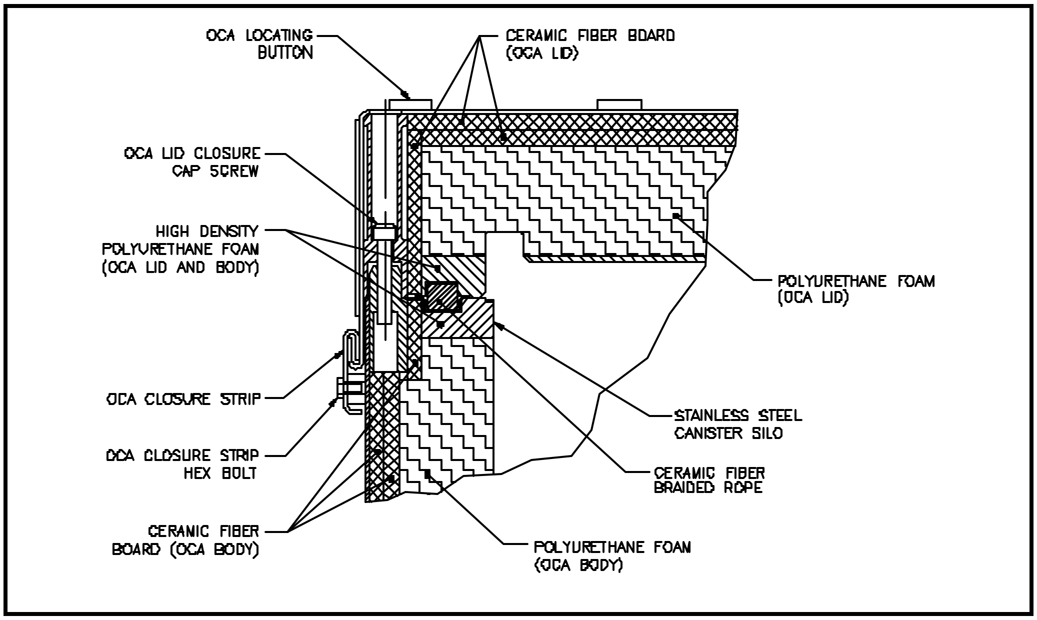

Figure 2. GNF NPC Package Closure Region

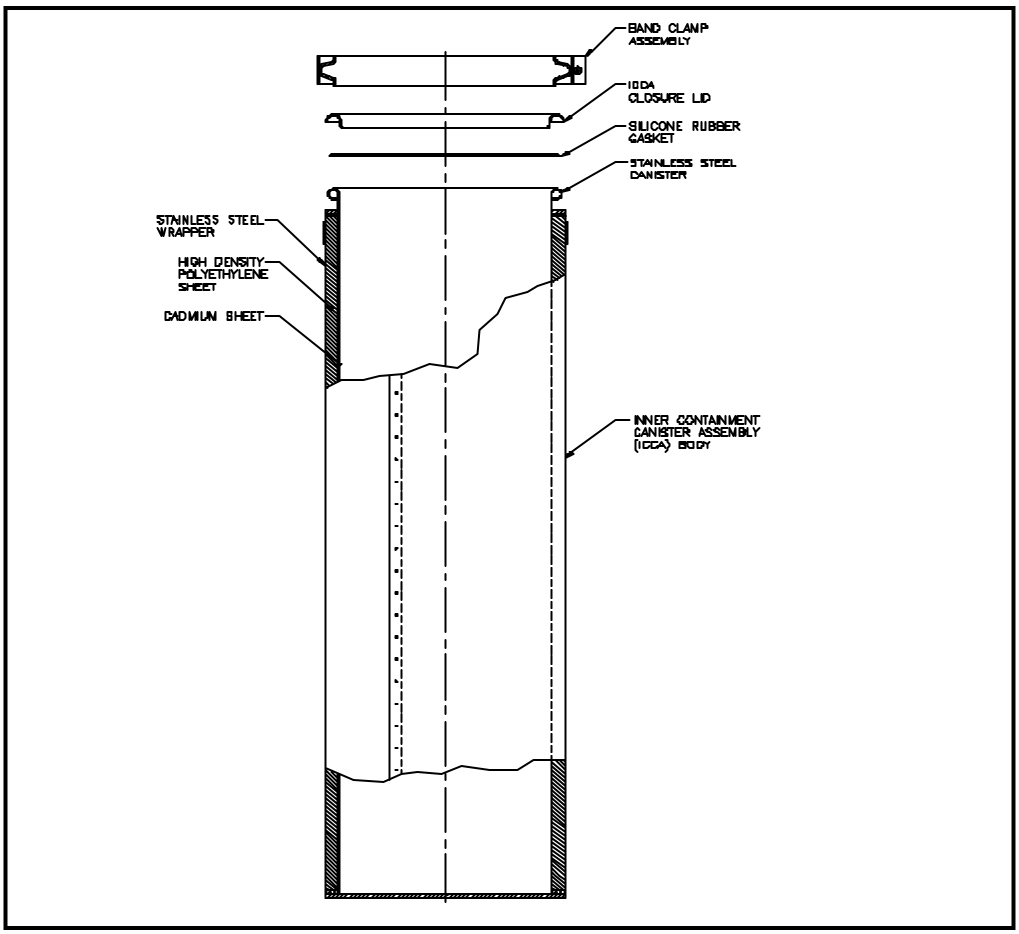

Figure 3. GNF NPC Packaging Inner Containment Canister

Payload Considerations

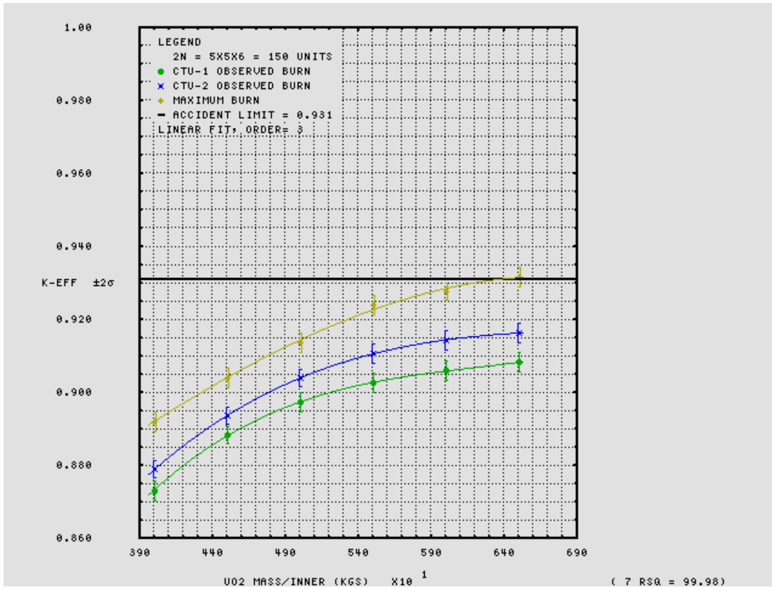

Figure 4. NPC damaged package array k_{eff} vs. UO_2 mass per canister

Figure 4 demonstrates the damaged NPC 2N package array for variable UO2 mass per ICCA. A payload of 60 kgs of UO2 compound per ICCA enriched to a maximum of 5.00 wt.% U235 is demonstrated to remain subcritical (e.g., Keff +2σ-bias < 0.95) post HAC testing.

The maximum payload for a single NPC package is demonstrated to be 540 kgs UO2. In comparison, the GNF single BU-J package payload for UO2 at 5.00% enrichment is 20 kgs/drum (current de-rated condition). Thus the NPC payload represents an increase by a factor of ~15 on a "per package" basis. Consequently, the overall number of containers required shipping a given mass of UO2 product decrease significantly.

Table 1 provides a comparison of the NPC package to other approved LEU oxide packages. For comparison purposes, UO2 powder enriched to 5% U-235 fissile material is used (in the case of the ESP package, a realistic UO2 compound bulk tap density is imposed for the comparison). On a weight basis, the ratio of the payload mass to the packaging mass demonstrates that the GNF (NPC) exhibits the highest packaging efficiency. On a volume basis (kgs/m^3) these same conclusions can be drawn.

Table 1. Type A, Fissile Package Comparison

Description	Owner/LEU Oxide Container			
	GNF/NPC USA/9294/AF-85 (rev. 0)	**BNFL/3516 GB/3516A/AF-85 (rev. 3)**	**ESP/Eco-Pak USA/9288/AF-85 (rev. 3)**	**GNF/BU-J USA/0220/AF-85 (rev. 11)**
Container Configuration	Cubic	Cubic	Cubic	Drum
Neutron Absorber	Cadmium	Boronated Foam	N/A	N/A
Transport Index	0.7	1.04	2.0	0.4
Dimension of Outer Container (cm)	L= 114.3 W= 114.3 H= 111.76	L= 105.92 W= 105.92 H= 69.09	L= 114.3 W= 114.3 H= 154.94	D= 60.96 H= 88.90
Package Volume (m^3)	1.46	0.78	2.02	0.26
Dimension of Inner Canister, Inches (cm)	D= 21.63 H= 80.01	D= 22.09 H= 49.02	D= 17.78 H= 98.04	D= 30.0 H= 22.0
Inner Canister Volume (m^3)	0.0294	0.0188	0.0243	0.0156
Number of Inner Canisters per Container[1]	9 pcs	9 pcs	4 pcs	3 pcs
Payload per Inner Canister (kgs UO2)	60	27	48.7[2]	6.67
Total Package Payload (kgs UO2)	540	243	194.8	20
Maximum Package Gross Wt. (kgs)	1302	693	1704	204
Package Efficiency: Weight Basis (payload mass / packaging mass)	71%	54%	13%	11%
Package Efficiency: Volume Basis (payload mass, kgs / package volume, m^3)	370	233	96	77

[1] Excludes “inner packaging” material confined to the inner canister.
[2] Assumes nominal UO2 compound density = 2.0 gUO2/cc.

NPC Nuclear Physics

To better appreciate the increased packaging efficiency for this fissile package, a discussion of important nuclear physics parameters is warranted. Each cadmium lined canister is surrounded by ~½” polyethylene to ensure thermalization and subsequent neutron absorption by cadmium. The 3x3 canister array is then encased in a polyurethane insulation called LAST-A-FOAM®. The foam density distribution within the package was evaluated to minimize overall container tare weight, provide structural strength, act as a thermal barrier, and protect the ICCA seal post immersion testing. Another benefit of the polyurethane foam is that it provides additional neutronic isolation between inner sleeves due to hydrogen capture and spectrum softening.

The fissile material (with moderator) is contained within nine 30” tall cylinders, each wrapped with cadmium around its circumference. Therefore, the cadmium can be used to reduce neutron reflection back into a cylinder and neutron exchange among cylinders (or packages in the case of close packed array configurations). Cadmium has a low energy resonance which results in a microscopic capture cross-section that is relatively flat (between 2500 and 8000 barns) up to about 0.2 ev, then drops quickly to 20.0 barns at 1.0 ev, and continues to drop.

Since most fission neutrons start out above 100,000 ev ("fast" neutrons), they must be moderated down to thermal velocities before the cadmium becomes highly effective. Since most neutrons that leak from the fissile regions are fast, they would pass through the cadmium and into another fissile region unless they are moderated sufficiently for them to be captured when they pass through the cadmium. Therefore, each cylinder is wrapped with ½" of polyethylene outside of the cadmium. This results in 1" of polyethylene between any two cadmium regions. Additional thermalization of the neutrons is provided by the low-density polyurethane foam between the cylinders.

Neutron Probe of ICCA

The design of the neutron flux trap is such that it is very easily assured to be present and properly configured during the manufacturing process. However, because of the importance of this feature (~ 17% of the total neutron absorption takes place in this neutron flux trap), a non-destructive neutronics verification is performed on the completed canisters.

Neutron interrogation is used to verify the initial presence in all ICCA's and a sampling of ICCA's over their lifetime. Specifically, the Safety Analysis Report[1] commits to the following:

- *Prior to first use, each ICCA shall be evaluated utilizing neutron reflectometry techniques to confirm that the neutronic configuration is correct.*
- *Five (5) years after the initial service date and every 5 years thereafter, a 1% random sample of the ICCAs will be re-evaluated using neutron reflectometry (or equivalent) techniques to confirm the neutronic configuration remains correct. If any ICCA is rejected, the entire population representative of the suspect production batch shall be 100% re-evaluated and all non-conforming items eliminated from use.*

It is important to understand the response function of the neutron detector. The neutron cross section as a function of the energy spectrum must be well understood. The detectors use He3, which has a "one-over-vee" (1/v) absorption cross-section. Figure 5 shows the microscopic absorption cross-sections for He-3, boron, and cadmium.

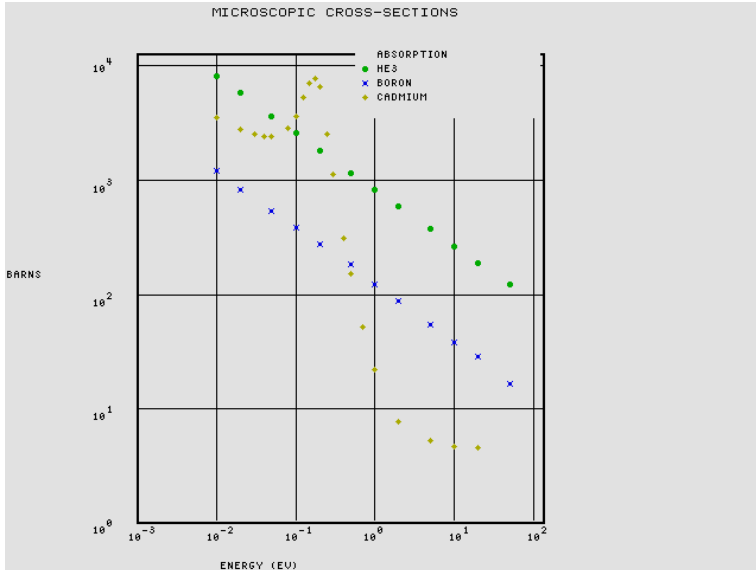

Figure 5. Microscopic Absorption Cross-Sections For He-3, Boron, And Cadmium.

As shown in Figure 5, the He-3 can be represented by any 1/v absorber in relative comparisons. Of special note is the difference between cadmium and the 1/v absorbers as a function of energy. All have high cross-sections at thermal energies (ie- below 0.625 ev). However, while the 1/v absorber cross-sections decrease gradually with increasing energy, the cadmium cross-section drops quickly to a negligible value. This means that the He3 detectors will receive a large contribution from neutrons at energies that are not affected by the cadmium.

The probe consists of a pair of parallel connected He3 detectors and an Americium-Lithium neutron source (~10E6 n/s). The detectors are 0.5" diameter and 6" active length. The probe is contained within a fixture designed to center the probe radially within the ICCA (see Figures 8a-8c). The mechanical equipment is designed to lower the probe into an ICCA and center the probe in each 1/3 height of the ICCA for a 5-second count. Qualification tests of the measurement system provided the following results, clearly indicating the capability of the system to detect no cadmium or no poly:

CONDITION	COUNT RATE
Correct ICCA	16000 cts/min
No cadmium	>66000 cts/min
No poly	2000 cts/min

Figures 8a-8c show production units undergoing ICCA neutron probe reflectrometry measurements upon receipt at GNF.

Figure 8a. NPC with lid, one ICCA removed

Figure 8b. ICCA removal using overhead crane

Figure 8c. ICCA centrally position in neutron probe

Facility Modifications

To release the package to operations for production use, facility modifications were required. These are summarized as follows:

- The neutron probe verification station was installed using automated and shielded design using parallel He3 neutron probes and an Americium-Lithium neutron source (~10e6 n/s). The device positions the source to be radially centered within the ICCA via hardware and software control equipment.
- To pack the powder into the NPC, facilitation of use of a new inner package (poly bottle) was required, new roller conveyors, bottle skid conveyors, 3-separate Package Vacuum Lift Systems (PVLS), and engineered control changes to control net UO2 weight in bottle.
- To store loaded (and empty) NPCs, the shipping warehouse analysis was revised to include the NPC stacked 3-high, with required structural floor loading spacing between each stack.
- To ship the loaded NPCs, custom seavans and were manufactured, and low weight trailer was required to accommodate the maximum payload for US interstate transport (maximum NPCs per seavan = 13). Maximum certificate allowable NPCs per "conveyance" = 71.

Summary

The Global Nuclear Fuel – America's new powder container (NPC) represents an innovative approach to efficiently ship UO2 product domestically and internationally. The packaging efficiency compares favorably relative to other similar LEU oxide packages.

Aspects of design, licensing, acceptance testing, and deployment measures are described to better understand the challenges associated Type A radioactive fissile material shipments in the U.S and abroad. GNF-A is confident the package will enable economic shipment of UO2 product.

Although the NPC fissile package has been designed for homogeneous UO2 powder enriched to 5% U-235, other future fissile material content provisions could be justified (e.g., LEU at higher enrichments, or MOX applications).

References

1. Safety Analysis Report, GNF NPC, Docket Number 71-9294, Revision 02, 01/29/01.
2. Model Number NPC, *NRC Certificate of Compliance for Radioactive Materials Package*, Package Identification Number USA/9294/AF-85, Revision 0, 02/22/01.