WORLD NUCLEAR ASSOCIATION

Transport of Low-Enriched Uranium

Transport Working Group

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This report reflects the views of industry experts but does not necessarily represent those of any of the World Nuclear Association's individual member organizations.

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Foreword

Today 440 nuclear reactors in 30 countries provide over a quarter of the world's low-carbon electricity. The vast majority of these reactors rely on low-enriched uranium (LEU) as their fuel.

With its radioactive and fissile properties, LEU is regarded as a highly specialized cargo by ports and shipping lines. Yet its risks are well understood, and it has been shipped safely for more than 50 years. Producers are ready to work closely with all relevant stakeholders to help them understand this cargo.

As an expanded role for nuclear power as part of a low-carbon energy transition is now predicted, this report is timely. It aims to give stakeholders an overview of how LEU is transported, and how related risks are mitigated and liabilities are managed. The report focuses on maritime transport, which is a vital mode for international movement of LEU.

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1 Introduction

1.1. What is Fissile Material?

Fissile material contains one or more radioactive elements that, under the right conditions, will fission, or split, into smaller elements, and in doing so produce heat that can be used to generate electricity.

This report focuses only on unirradiated low-enriched uranium (LEU), *i.e.* on material that has not been in a reactor. This can be in the form of fuel rods, powder, pellets, or uranium hexafluoride (UF_6).

Types of fissile material that are not addressed here include:

- Plutonium.
- Highly enriched uranium.
- Spent nuclear fuel (*i.e.* fissile material that has been in a reactor).

1.2. Fission Process

Uranium is primarily composed of two isotopes, U-238 and U-235. Isotopes of an element have the same number of protons in the nucleus but a different number of neutrons. Natural uranium comprises about 99.3% U-238 and 0.7% U-235 as well as trace elements of U-234.

What makes uranium valuable as an energy source is that the fissile U-235 isotope can – in specific circumstances – split, releasing significant amounts of heat. This heat can in turn be used to create steam to generate electricity.

In LEU, a fission event can occur when a U-235 atom is hit by a low-energy ('slow', or 'thermal') neutron. The absorption of the neutron causes the atom to split into other radioactive elements and emit two or three high-energy ('fast') neutrons. A chain reaction results when the emitted fast neutrons lose energy and become thermal neutrons, which can then cause other U-235 atoms to fission. Water is used as a neutron 'moderator' because the hydrogen atom is about the same size as a neutron, allowing for an efficient transfer of energy during neutron-hydrogen collisions. After several collisions, a neutron may reach a thermal or low-energy state so that it can then cause a U-235 atom to fission.

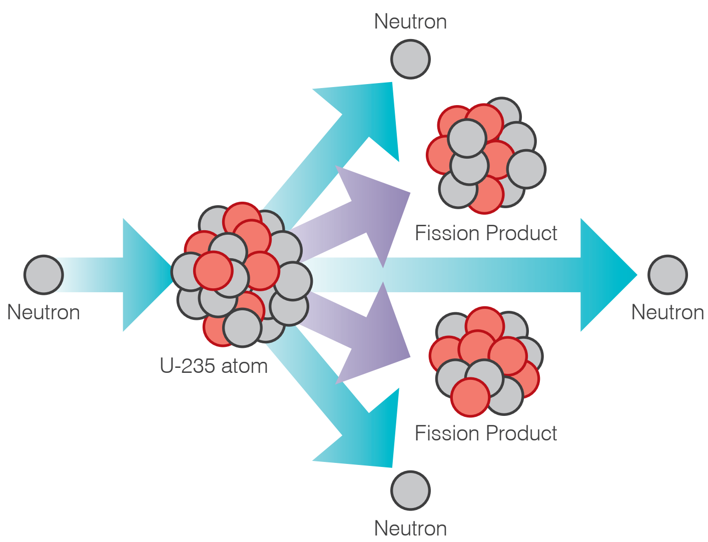

Figure 1. U-235 Fission Process

When the chain reaction becomes self-sustaining, the fission process is said to be critical. This means that the rate at which neutrons are generated matches the rate at which they are absorbed or lost (through leakage out of the reactor core).

1.3. Low-Enriched Uranium

For uranium to support a chain reaction in most nuclear reactors[1], it must have a higher proportion of U-235 atoms than found in natural uranium. Natural uranium must therefore be ‘enriched’ in the U-235 isotope so that it has a higher proportion of U-235 compared with U-238.

To be made usable as fuel in most commercial reactors, the U-235 content must be increased to between 3% and 5%[2]. This is usually accomplished by using gas centrifuges.

Once the uranium is enriched, it is classified as fissile material, and must be handled differently to natural uranium.

1.4. Criticality Safety

For LEU to go critical, three things must be present. If just one is missing, criticality is not possible:

- Mass: there must be enough uranium present (*i.e.* a ‘critical mass’).
- Moderator: there must be something present to slow the neutrons down (*e.g.* water).
- Geometry: the uranium-water combination must be in a shape that will sustain a chain reaction.

It follows then that, during the transport of LEU, methods are in place to ensure that at least one of the three factors is not present.

[1] Some reactors can run on unenriched uranium by using ‘heavy water’ (deuterium) as a moderator

[2] Low-enriched uranium is defined as uranium enriched to less than 20% U-235. See IAEA Safeguards Glossary

2 How is Low-Enriched Uranium Transported?

2.1. Regulation

Since 1961, the International Atomic Energy Agency (IAEA) has published transport safety regulations[3]. These regulations cover the movement of fissile material and have been adopted by all countries.

The SSR-6 regulations are incorporated into the ‘Orange Book’, which governs all hazardous material transport and is published by a United Nations panel of experts[4]. These regulations are then incorporated into the specific regulations for each mode of transport, such as the *International Maritime Dangerous Goods Code*, which is applicable for all cargo-carrying ships around the world.

2.2. Packaging

The key to the safe transport of LEU is the packaging. Fissile material shipping packages are designed for the modes of transport that will be used and the types of accident that might occur. Most LEU packages carry greater than a critical mass of uranium, in the form of powder, pellets, fuel assemblies, or UF_6. Therefore, they are designed so that during normal transport and in accident conditions, they prevent the ingress of water into the package, or the formation of a geometry that supports criticality, or both.

All package designs are analyzed using advanced computer modelling and are subjected to rigorous testing to demonstrate that they meet the internationally approved requirements for fissile packages. Specifically, the packages must be able to withstand cumulative tests representative of accident situations, such as a nine-metre drop onto an unyielding surface, a one-metre drop onto a steel punch, a 30-minute fully-engulfing hydrocarbon fire with average temperature of at least 800 °C, and immersion under a head of at least 15 metres of water for not less than eight hours[5].

Some facts about fissile package design that pertain to sea transport are:

- All fissile material packages are designed so that the space that holds the material (*i.e.* the containment) will not be breached or deformed in an accident. This means that the containment will not assume a shape that would support criticality. It also means that water will not get in. Nevertheless, fissile material packages are typically analyzed assuming that the containment becomes fully flooded to verify that even this configuration remains subcritical.

International regulations pertaining to the transport of radioactive materials

[3] Latest version: IAEA Safety Standards Series No. SSR-6 (Rev.1), Regulations for the Safe Transport of Radioactive Material, 2018 Edition, International Atomic Energy Agency (June 2018)

[4] United Nations Committee of Experts on the Transport of Dangerous Goods and on the Globally Harmonized System of Classification and Labelling of Chemicals

[5] Packages that weigh less than 500 kg are subjected to a crush test instead of a drop test. A 500 kg mass is dropped onto the package from a height of nine metres.

- Shipping packages that transport fuel assemblies carry either one or two assemblies. While each fuel assembly contains greater than a critical mass, the geometry is strictly controlled to protect against criticality. Also, the number of packages allowed in one consignment is limited to a number that ensures that the entire consignment remains subcritical in an accident.
- As stated above, fuel assemblies in a shipping package will remain subcritical even if the package becomes fully submerged. This means that if the packages should fall overboard, or if the ship carrying them should sink, the fuel will not go critical.
- Packages that carry powder or pellets also hold more than a critical mass. However, the material is separated into subcritical compartments within the package. These packages are analyzed and tested to ensure that in an accident the compartments would not rupture, allowing material to intermingle.
- Finally, packages that carry UF_6 are pressurized vessels, designed specifically to keep water out. This is for two reasons: first, the addition of water could result in a criticality event; but of more concern is that the fluorine in UF_6 reacts chemically with water to produce heat as well as corrosive and toxic hydrofluoric acid (HF).

2.3. Safety Record

Radioactive material transport has an outstanding safety record. During more than half a century of transport according to the IAEA regulations, there has never been a criticality incident nor a case of death, injury, or significant damage to the environment due to radioactivity. More than half a billion packages of radioactive material have been shipped during that period.

Overpacks containing enriched UF_6 cylinders (Image courtesy Urenco)

LEU in oxide form (as powder or pellets), is a very low-risk hazardous material. It is not volatile, nor highly radioactive and cannot explode. It is not too dangerous to touch, nor is it unsafe to work around.

Enriched UF_6, on the other hand, though also neither highly radioactive nor an explosive hazard, is dangerous to touch as it forms HF when in contact with water.

In 2014, a handling accident occurred at the Port of Halifax, Nova Scotia, Canada involving a shipment of UF_6 cylinders. A container crane malfunction resulted in a flatrack containing four model 30B UF_6 cylinders in UX-30 overpacks being dropped approximately seven metres back into the ship's cargo hold. All four packages remained intact. There was no release of radioactive material, and no ingress of water into a package. The very low radiation levels emitted from the package remained as expected for a normal transport. This was not so much a hazardous material incident as it was a transport incident that happened to involve hazardous material.

3 Insurance and Liability

3.1. Liability

While organizing a shipment of fissile material, as with any nuclear transport, the question arises of who bears the nuclear liability. Liability for nuclear incidents is covered by international conventions: the *Convention on Third Party Liability in the Field of Nuclear Energy*, usually known as the 'Paris Convention', signed in 1960, as amended in 2004, the *Vienna Convention on Civil Liability for Nuclear Damage*, signed in 1963, as amended in 2007, and the *Convention on Supplementary Compensation for Nuclear Damage*, entered into force in 2015.

Nuclear countries which are not party to one of these international conventions, such as China, have passed national laws on nuclear incidents. A common principle existing in most of those laws is the strict liability of the nuclear operator, which means that the nuclear operator is responsible for nuclear damage irrespective of fault.

Where those conventions or national laws apply, they prevail on regular civil liability or transport liability. Their principles are the strict and exclusive liability of nuclear operators for damages caused by nuclear incidents, meaning that victims do not need to prove any fault or negligence of the nuclear operator, and its liability excludes the liability of any other party. The carrier will never be liable for a nuclear incident, as the nuclear operator will be exclusively liable.

However, a shipment can cross countries which are not party to the international conventions and have no nuclear legislation. If a nuclear incident were to occur within such a country or in its territorial waters, the regular tort law may apply. Such a case has never happened, but this is why contracts between nuclear operators and freight forwarders should always provide a clause according to which the nuclear operator is the sole and exclusive liable party in case of a nuclear incident wherever the incident happens (within or without the scope of an international convention). It is the role of the freight forwarder to include such a clause within its contract with the nuclear operator, so that neither the freight forwarder itself nor the carrier can be liable for a nuclear incident.

It should be noted that not all fissile material consignments require nuclear liability insurance, for example shipments of material with less than 1% U-235, as well as some shipments in small quantities of fissile material.

3.2. Insurance

According to the Paris and Vienna Conventions, the nuclear operator liable for a transport of nuclear material shall provide the carrier with a certificate issued by its insurer evidencing the existence of the insurance policy.

The certificate contains the following details:

- Name and address of the nuclear operator.
- Duration, nature and amount of insurance.
- Details of the type of nuclear substance being transported.

It is signed by the insurer and countersigned by a public authority confirming that the operator stated on the certificate is a nuclear operator within the meaning of the Convention.

3.3. Physical Protection

The *Convention on the Physical Protection of Nuclear Material and Nuclear Facilities* (CPPNM) sets levels of physical protection to be applied in international transport of nuclear materials. It outlines security requirements for the protection of nuclear materials against malevolent acts relating to the transboundary carriage of nuclear materials and provides for the prosecution and punishment of such offences. An amendment to the convention came into force in May 2016. It strengthens arrangements by, for example, covering domestic transport, introducing new offences such as smuggling and sabotage, and providing new arrangements for international cooperation, assistance and coordination among state parties and the International Atomic Energy Agency and other relevant international governmental organizations.

According to the CPPNM, nuclear material is divided into Categories I, II and III. LEU is classified as Category III, the lowest risk category with the lowest security provisions. Any consignor of Category III nuclear material is obliged to only use a shipping line that has a flag whose state is party to the CPPNM.

The responsibility for implementing physical protection systems rests with the states which are shipping and receiving the nuclear material. Prior to each shipment, a transport plan is prepared documenting the specific arrangements to be implemented for the shipment to assure, among other things, adequate physical protection of the material to be transported. The plan is established through coordination among the industry parties concerned and the respective governments of the countries involved. The whole transport system thereby ensures the appropriate measures are in place to counter the threat of theft, sabotage or other unlawful removal of the nuclear material.

World Nuclear Association
Tower House
10 Southampton Street
London WC2E 7HA
United Kingdom

+44 (0)20 7451 1520
www.world-nuclear.org
info@world-nuclear.org

With its radioactive and fissile properties, low-enriched uranium (LEU) – used in the majority of the world's nuclear reactors – is regarded as a highly specialized cargo by transport supply chain. Yet its risks are well understood, and it has been shipped safely for more than 50 years.

This report prepared by the World Nuclear Association's Transport Working Group aims to give stakeholders in the transport supply chain an overview of how LEU is transported, and how risks are mitigated and liabilities managed. The report focuses on maritime transport, which is a vital mode for international movement of LEU.

This Transport Working Groups acts as a forum for exchanging leading practice and for identifying and resolving issues relating to the shipment of nuclear material. Its primary focus is on topics relating to the transport of front-end nuclear materials.