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The Role of Nuclear Criticality Safety in Enabling the Transport of Highly Enriched Uranium (HEU) (and Other Fissile Materials) to Support Global Strategic Removal Projects

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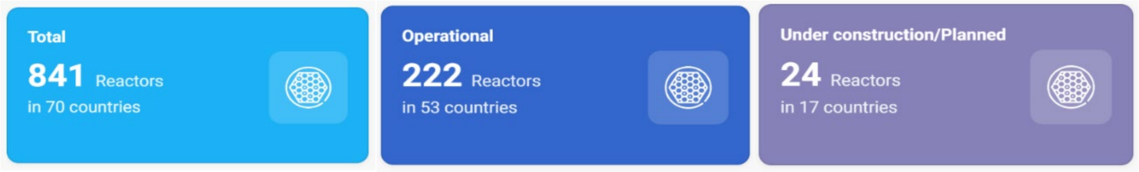
Nuclear Transport Solutions (NTS) has for many decades undertaken all Categories of marine transports in support of critical removal operations in support of the US DOE and other Government stakeholders around the world. In addition to the external shipping operations, NTS also provides a lot of essential expertise and capability to support these operations – such expertise which can easily go unnoticed to the external stakeholders and end customers. NTS' in-house capability provides nuclear shielding and criticality safety analyses for the transport of fissile materials across the globe. The authors have over 45 years of combined experience within the nuclear industry; primarily in the area of criticality safety. This paper will provide insight into the complexity and strategic importance associated with the criticality modelling of fissile nuclear materials proposed for transportation. Transport criticality safety assessments are completed in compliance with international regulatory frameworks (which govern and enable the multitude of global initiatives to remove and transport fissile nuclear materials) in support of security and other associated national prioritisation programmes.

1 Introduction

Research and test reactors provide a global service and are a versatile tool in research; material testing; technology development; education and training purposes; and producing radioactive materials for industry, agriculture, forensics and medicine.

As seen in Figure 1, over 800 research and test reactors have been built to date across 70 countries. Whilst many have been shut down, decommissioned or are undergoing decommissioning, 222 are still in operation in 53 countries, and a further 24 are planned for construction, in 17 countries, which demonstrates a continued demand for their purpose.

Figure 1 RRDB Excerpt of the statistics of Research and Test Reactors (RRDB (iaea.org))


Total
841 Reactors
in 70 countries

Operational
222 Reactors
in 53 countries

Under construction/Planned
24 Reactors
in 17 countries

Due to the intended purpose of research and test reactors to primarily generate neutrons, they are very different when compared to conventional nuclear power reactors. Research and test reactors are typically much smaller with a simpler design, and unlike nuclear power reactors are not intended for electricity generation. As such there are no large turbine halls, generators, or connections to the grid, and the control rooms are usually in the confinement or containment area where the reactor is located.

In fact, the output of research reactors ranges from 0 MW, such as that of a critical assembly, up to 200 MW, with the majority sitting below 1 MW, which is in contrast to the 3000 MW (also denoted as 1000 MW (electrical)) of a nuclear power reactor unit. Due to the low associated power levels, they require no or minimal cooling during short periods after shutdown. In addition, research and test reactors tend to operate at lower temperatures and require less fuel due to the smaller core.

Research and test reactors tend to be of a pool or tank design. Pool design research and test reactors make use of a core immersed in an open pool of water. Several feet of water sits above the core to provide cooling and radiation shielding, and allow for operators to view down and see the top of the core. The tank design reactor is similar but the core sits in a sealed tank The pool of water at the top provides cooling and radiation shielding. Tank-type reactors have a core that is in a sealed tank with water.

The majority of research and test reactors utilise thermal neutrons, as such moderators (such as heavy and light water) are present to slow the neutrons down to thermal energies (note there are a few fast neutron research and test reactors that have existed). In addition, reflectors (such as graphite or beryllium) are present to reflect as many neutrons as possible back into the core.

Within the core, fuel is present in the form of cylindrical or plate/block fuel elements. Historically, research and test reactors have used anywhere between 5 and 93% weight enriched Uranium-235, in comparison to thermal nuclear power reactors, which typically use fuels with enrichments up to 5% weight Uranium-235[1].

Thanks to the higher enrichment of the fuels, only few kilograms of uranium is typically required in research and test reactors. In addition, higher enriched fuels can produce higher neutron fluxes and allow for longer timeframes between refuelling. However, with higher enriched Uranium-235 fuels i.e. HEU fuels are associated security risks (with 93% enriched Uranium-235 considered weapons grade enrichment). This is in comparison with the tonnes of material required for thermal nuclear power reactors.

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[1] Low Enriched uranium (LEU) is classed as up to 20% weight Uranium-235; whereas High Enriched Uranium (HEU) is classed as greater than 20% weight Uranium-235.

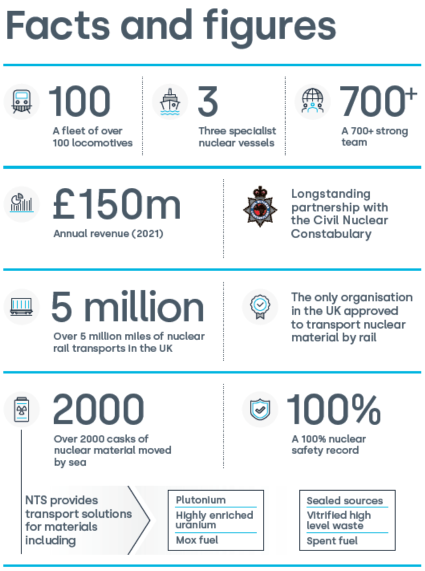
As part of the Reduced Enrichment for Research and Test Reactor (RERTR) programme, many of the research and test reactors that utilised HEU fuel have had their cores converted to utilise LEU fuel.

2 Nuclear Transport Solutions

Responsible transportation of fissile material is incredibly important to minimise any unwanted impacts on the general public and prevent nuclear proliferation or potential misuse of any material. This is especially important when higher enriched fuels are being handled; and pertinent for research and test reactors which are typically based at universities or other civilian locations, and use lower levels of security compared with say weapons establishments.

Nuclear Transport Solutions (NTS) is a wholly owned subsidiary of the United Kingdom's (UK) Nuclear Decommissioning Authority (NDA), a public body which is responsible for ensuring the safe and efficient clean-up of the UK's nuclear legacy.

Figure 2 NTS Facts and Figures



We have over 50 years experience in our technical and operational sections at NTS, and are experts at providing solutions to complex nuclear transport and logistics challenges. NTS is comprised of three subsidiaries:

- International Nuclear Services (INS),
- Direct Rail Services (DRS), and
- Pacific Nuclear Transport Ltd (PNTL).

PNTL are the world's most experienced nuclear shipping company, with 3 purpose-built vessels that have vast international experience transporting a range of nuclear material from across the fuel cycle (including MOX (Mixed Oxide), LEU and HEU fuel; and vitrified high level waste).

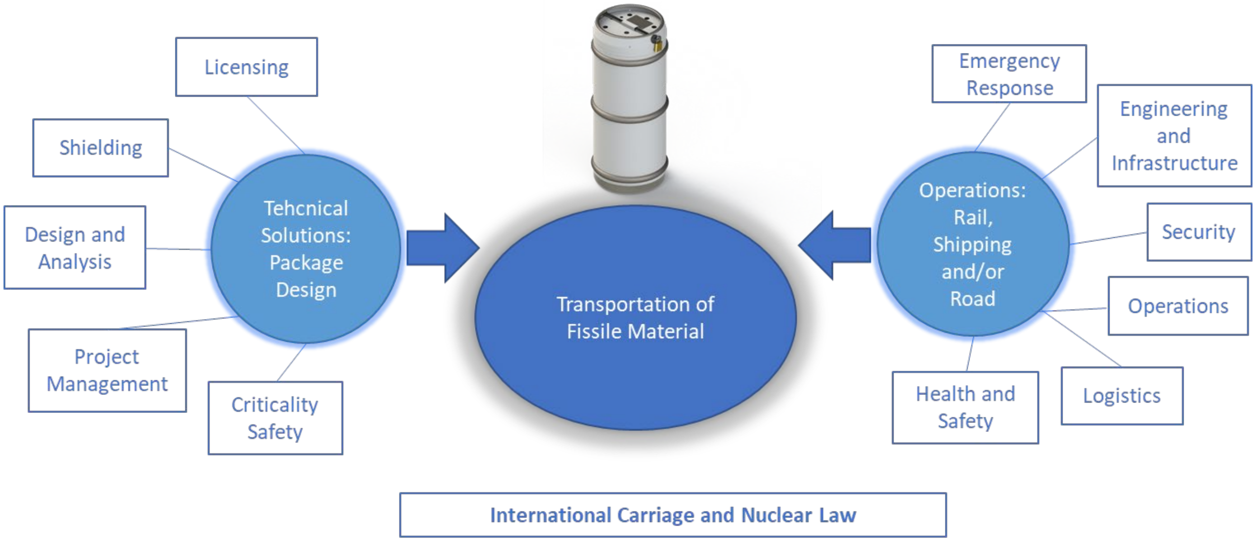
DRS manage a fleet of over 100 locomotives that operate on the UK rail network undertaking nuclear operations frequently. In particular, NTS has vast experience transporting spent fuel by rail from the currently operating Advanced Gas-cooled Reactor (AGR) fleet.

The technical solutions capability (INS) provides the full lifecycle of package design, assessment and licensing, with extensive experience in new and re-purposed packages used to transport nuclear material. We also have existing assets used to transport spent fuel and source terms

3 The Transportation Solution

Whether HEU or LEU fuel is used within research and test reactor fuel, this fissile material requires transportation, for example as either fresh fuel to the research reactor or as spent fuel to a long-term storage facility. The transportation of this fuel depends on a range of experts in various disciplines; these can be split into the operations side and the technical solutions side, as seen in Figure 3. All activities are undertaken in adherence with any carriage, i.e. road, rail, marine or air laws, and any nuclear laws.

Figure 3 The Transport Disciplines



The focus of this paper is demonstrating the wider capability of the technical solutions team. This team includes disciplines such as licensing, shielding, design and analysis, project management and criticality safety. Between these teams, a package could be designed from new or could be one of our existing assets which is repurposed for the client and stakeholder needs.

To adequately carry out the design of a new package or repurposing of an existing asset, the process begins within the licensing team (see Figure 4). Initially, the proposed material for transport is assessed against the IAEA SSR-6 Transport Regulations [1], as to whether it is fissile or not. Where fissile material, as defined in Paragraph 222 of SSR-6 (Ref (SSR-6)) as:

"222. Fissile nuclides shall mean uranium-233, uranium-235, plutonium-239 and plutonium-241. Fissile material shall mean a material containing any of the fissile nuclides."

Upon this determination, the material will also be categorised between a low and high hazard, i.e. fire or corrosive hazard, and the specific activity will be calculated (A1 & A2 values) which are measures of radioactive inventory in Becquerels (Bq).

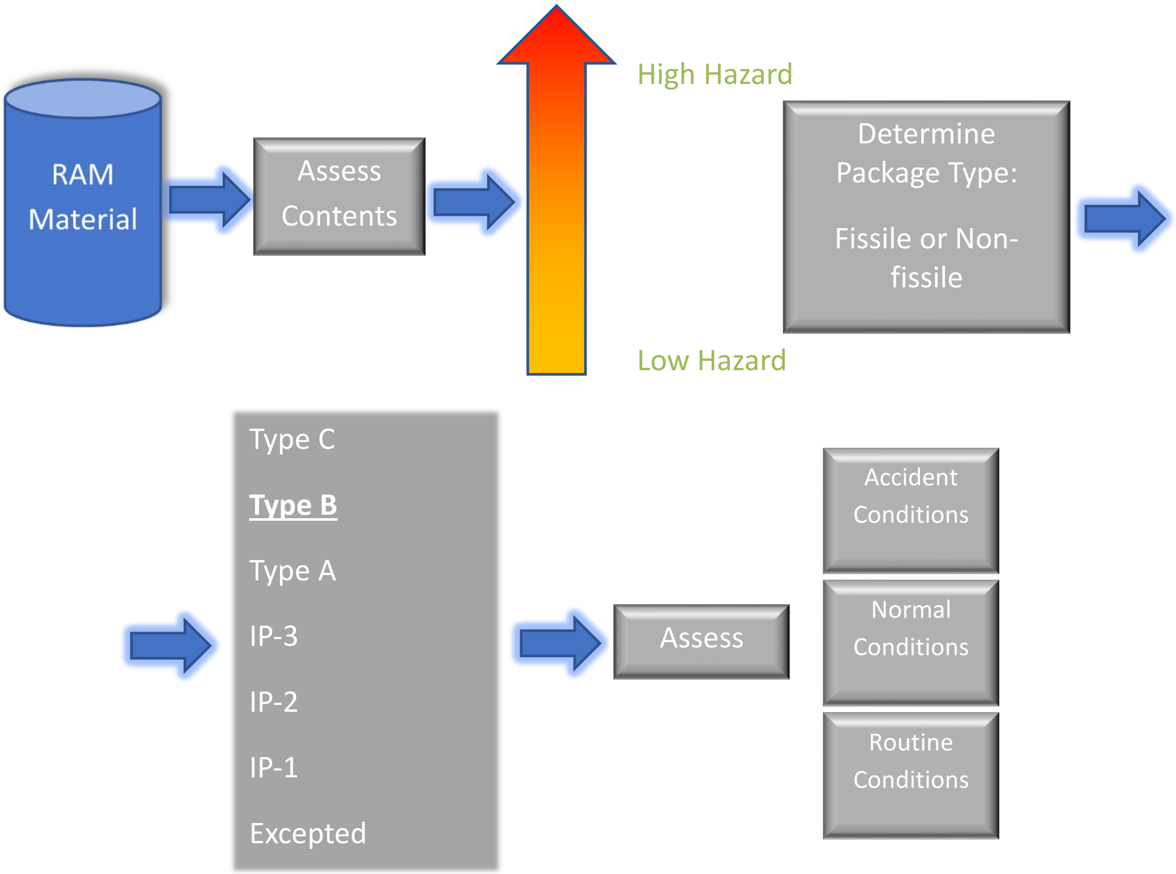
Using this combination of factors, a package will be selected from the list presented in Figure 4. For the example of HEU spent fuel, a Type B package will most probably be selected. Packages used to transport fissile material will need approval by the Competent Authority (CA) in each country they travel out of, into and/or through.

Various conditions will require assessment depending on the type of package used to transport the fissile material, which range across the following:

- Routine conditions of transport cover general requirements for a package and additional pressure and temperature tests if transported by air.
- Normal conditions of transport cover minor accidents such as a fall from a vehicle, exposure to rain, being struck by a sharp object or having other cargo stacked on top.

- Accident Conditions of Transport cover large transport accidents such as a package falling from the back of a train locomotive and being involved in a crash resulting in a severe impact and fire; or a package bring dropped into the sea.

Figure 4 Summary of the Solution to Transporting Radioactive Material.[2]



Typically, the impact, structural, thermal, stress, shielding and criticality teams will assess the engineering and safety aspects of Routine, Normal and Accident Conditions of Transport (RCT, NCT and ACT) prescribed in SSR-6 [1]. The various resulting assessments will be compiled into the Package Design Safety Report (PDSR), which is submitted to the CA of the country or countries of which the package will transit out of, into and/or through.

The CA of the country within which the package will be moved/ the CAs of the countries the package will be moved between must approve the PDSR before any movements can occur.

4 Why Criticality Safety is important

As highlighted in Section 3, criticality safety is one of the disciplines required to assess various conditions as part of the PDSR. It may seem that operations are the most important part of transportation, however, there are months and even years that go into the design and analysis of a

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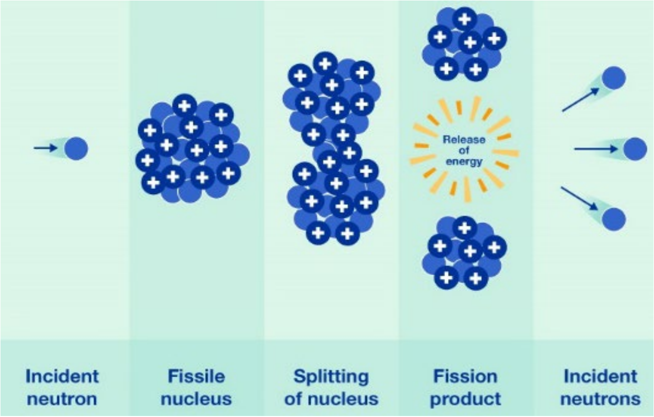
[2] RAdioactive Material (RAM).

transport package. Criticality safety in particular directly impacts operations and the design of the package, which is where the remainder of this paper will focus.

Criticality is defined as a self-sustaining nuclear fission reaction, or more commonly as the splitting of an atom (seen in Figure 5). Uranium-233, Uranium-235, Plutonium-239 and Plutonium-241 area capable of sustaining a nuclear fission chain reaction at any energy.

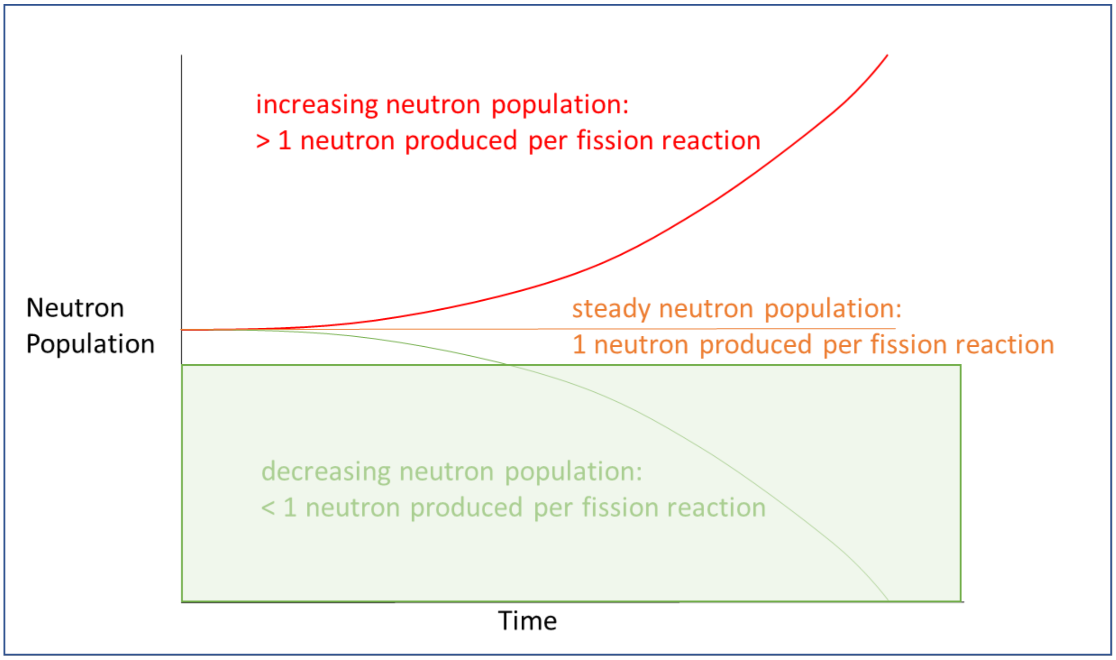
Figure 5 Fission Chain Reaction [2]



Whether a system can sustain a chain reaction of fission reactions is dependent on the neutron balance; the neutron balance is governed by neutron loss or gain, as seen in Figure 6. In summary:

- A supercritical system will be present if there is a greater number of neutrons gained in a system compared to the losses, i.e. there is an increasing number of fission reactions and neutron population is increasing, with an average of greater than 1 neutron produced per fission reaction.
- A critical system will be present if the number of neutrons gained in a system is equal to those lost, i.e. some of the fission reactions ‘die out’, and the neutron population remains steady, at an average of 1 neutron produced per fission reaction.
- A sub-critical system will be present if the number of neutrons gained in a system is less than the number lost i.e. most of the fission reactions ‘die out’ and neutron population decreases, with an average of less than 1 neutron produced per fission reaction.

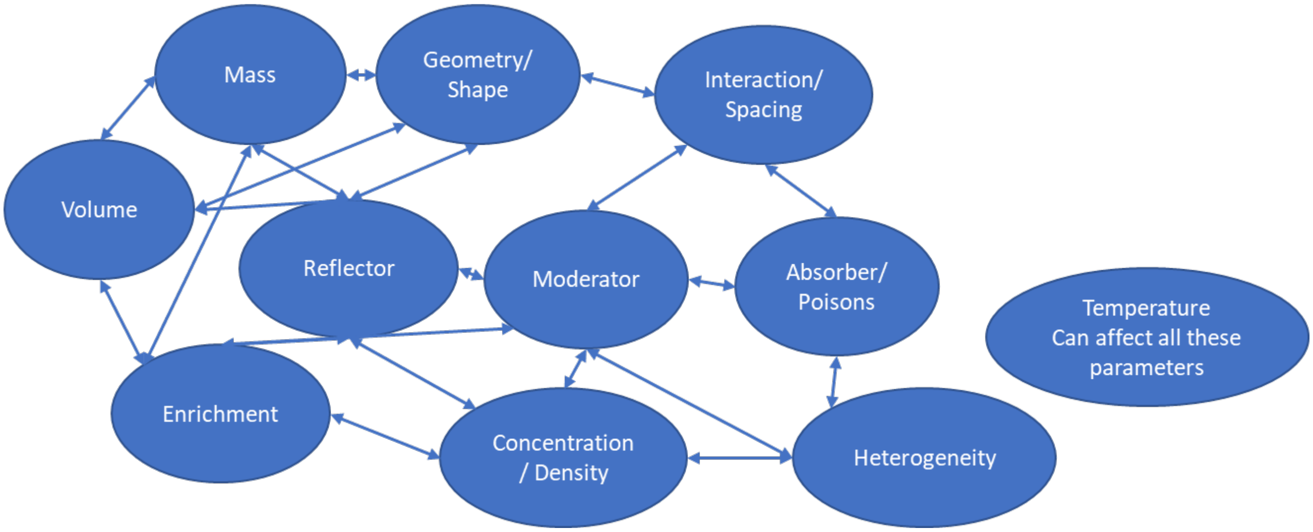
Figure 6 Graphical Representation of Neutron Population



Criticality safety is defined as the prevention or protection against the consequences of an inadvertent nuclear fission chain reaction, preferably by the prevention of the reaction. The neutron population in the package must be decreasing or below a criticality safety criterion (i.e. the neutron population should be within the green box of Figure 6) to ensure criticality safety,

There are several parameters or factors of criticality (MAGICMERV) that can be used to control the neutron balance within a system, as seen in Figure 7. As can be seen, many of these factors are inter-dependent so a small change in one of these can result in potentially huge impacts.

Figure 7 Factors of Criticality



5 The Role of Criticality Safety in Supporting Global Remediation Projects

As noted in Section 4, criticality or the neutron population within a transport package can be controlled via the factors of criticality. For instance, transport packages containing LEU or HEU spent fuel could be controlled via the mass of the fissile material in the package, inclusion of a flux trap or solid poisons or through the geometry of the fissile material present. Furthermore, HEU fuel in in comparison to LEU fuel utilises greater enrichments, which leads to potentially greater constraints on the amount of material that can be transported and the quantity of moderator and reflectors present.

However, before we determine which factors can be used, the various conditions requiring criticality safety assessment set out in SSR-6 [1] must be considered.

SSR-6 [1] provides the rules behind the transport package design, and for example in the UK, SSR-6 [1] is incorporated into the modal regulations, covering road, rail, air, sea and inland water ways, these are automatically adopted into UK Law and govern the transport of RAM.

Each transport criticality safety assessment works through the prescribed set of requirements set out in SSR-6 [1], and will produce a lot of rigorous deterministic assessment covering various conditions. Ultimately the Criticality Safety index or CSI is calculated which is a number used to provide control against accumulation of packages containing fissile material, which may be transported on a ship, a rail locomotive or road wagon.

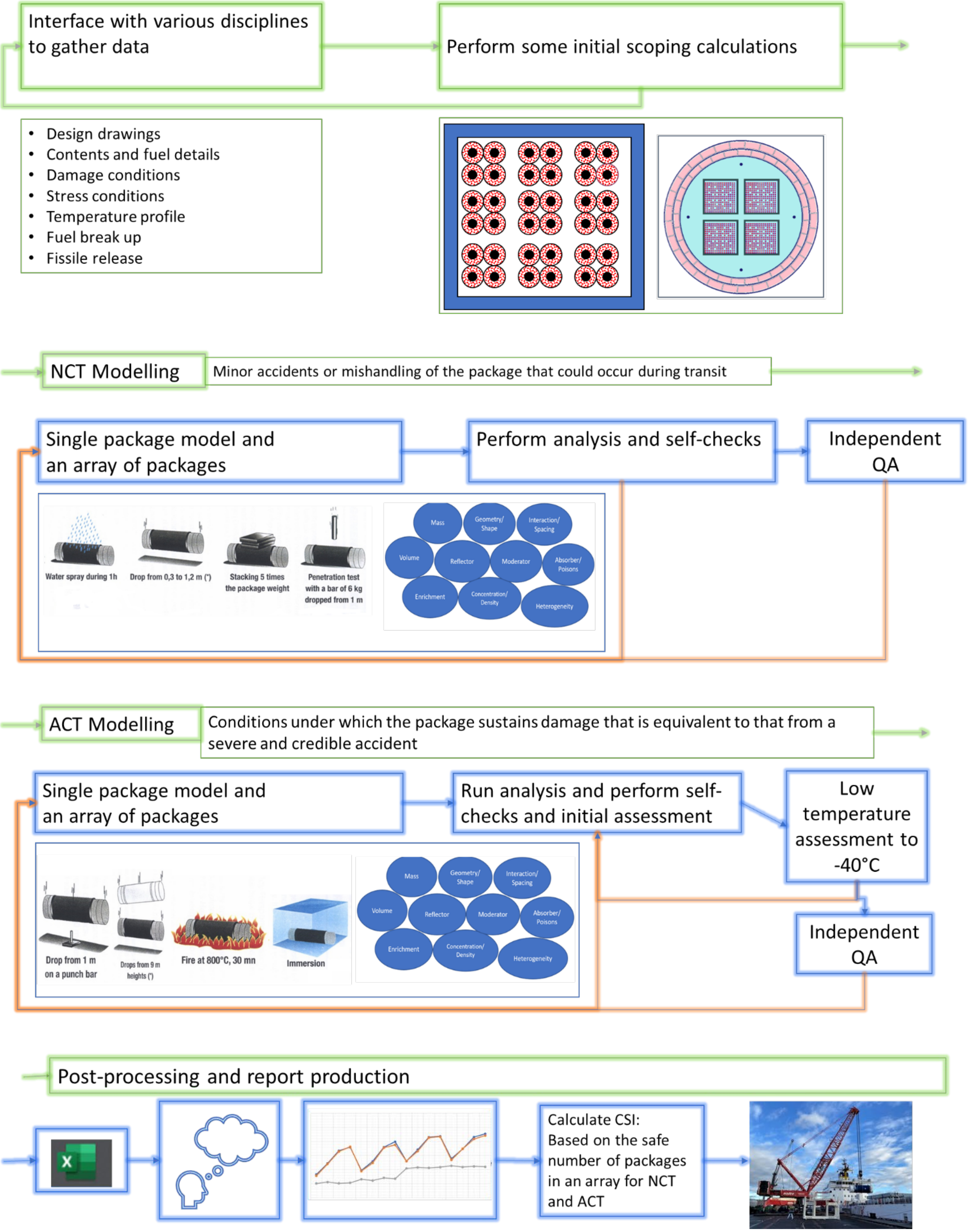
It is worth highlighting that a criticality safety assessment for a plant or reactor site looks very different as they take into consideration probability of faults, whereas transport criticality safety assessments are deterministic and assume worst-case accidents can happen.

There are multiple stages to a criticality transport assessment, Figure 8 presents a flow chart of the various stages required. The first phase is the scoping phase, where interface with the engineering, design and analysis and operation teams is performed; data management and flow is incredibly important. This data allows for initial scoping calculations to be performed to key parameters that affect criticality and any areas where further information or and in-depth study maybe required. Importantly, at the end of the initial scoping phase, engagement with any CAs or relevant stakeholders is held if a novel approach is being used.

NCT assessment considers a single package and an array of packages in the various results of regulatory tests or engineered calculations covering minor accidents/ mishandlings during transit:

- A drop off a forklift.
- A package left out in the rain.
- A package dropped off the back of a rail locomotive.
- Or stacking from other cargos.

Figure 8 Flow Chart of the Transport Criticality Safety Assessment Process



ACT assessment considers a single package and an array of packages in the various results of regulatory tests or engineered calculations covering damage equivalent to that from a severe and credible accident during transport, such as:

- Fully engulfing fire (up to 800°C).
- 9 metre drop onto unyielding or flat target.
- 1 metre drop onto a punch bar.
- Immersion in water.

In addition to the NCT and ACT accident regulatory tests or engineered calculations results:

- Tolerances of for example the fuel or package dimensions must be optimised, for example, a larger size doesn't necessarily mean the worst results will be obtained.
- The factors of criticality we saw earlier must be investigated to ensure the worst case models do not breach the criticality safety criterion and are the appropriate array size for transportation.
- A further investigation is required to consider the sensitivity of the individual package to water, in other words, the package is assumed to be fully submerged with water ingress covering fully, partial or differential flooding of the package.
  However, if a Multiple Water Barrier design package is used, which NTS has designed, licenced and operated in the UK, then water ingress does not need consideration.
- Once the bounding conditions have been determined for ACT, then the package must be assessed down to -40°C temperatures, which represents conditions of snow and ice.
- All inputs and outputs are QA'ed by the assessor and independent checker.

All results are post-processed to be in a suitable format for presentation in the PDSR, and the optimised array size for NCT and ACT are determined to calculate the CSI.

6 Concluding Thoughts

Whilst criticality safety is a niche discipline within the technical solutions, the transport criticality safety assessments are a fundamental part of the business. They enable and dictate the carriage of nuclear materials on various modes of transport i.e. ship, rail and road.

At NTS, we have enabled successful transport projects to take place. We have delivered cargo from research and test reactors, and vulnerable locations around the world in support of individual customers' needs and Governmental programmes of material removal.

Finally, transport is an area that is often overlooked in importance, however without transport there is no nuclear industry. The requirement to transport fissile material should be considered in the design phase, and if necessary, engage with CAs and other stakeholders at the earliest possible stage.

7 References

[1]IAEA Safety Standards, Regulations for the Safe Transport of Radioactive Material, 2018 Edition, Specific Safety Requirements, No. SSR-6 (Rev. 1) (ISBN 978-92-0-107917-6).

[2]Website: What is Nuclear Energy? The Science of Nuclear Power | IAEA, accessed 28/09/2022.