Nuclear Decommissioning Authority

Guide to Technology Readiness Levels for the NDA Estate and its Supply Chain

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Preface

This report has been prepared by Cogentus Consulting Ltd under contract to the Nuclear Decommissioning Authority (NDA). The views expressed and conclusions drawn are those of the authors and do not necessarily represent those of NDA.

Conditions of publication

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Executive Summary

NASA developed Technology Readiness Levels (TRLs) in the early 70's as a means of assessing whether emerging technology was suitable for space exploration. By the 1990's it was in use across many US Government agencies, including the Department of Defense (DOD) and Department of Energy (DOE). TRLs are now in common use in the UK including the NDA Estate.

The NDA document "Technical Baseline and Underpinning Research and Development Requirements" (EGG10) makes specific reference to TRLs and contains guidance in appendix 2. The purpose of this Guide is to expand appendix 2 to include information on what are TRLs, when their use is appropriate, what factors need to be considered when assigning a TRL to a technology and what is established good practice in assigning TRLs.

This Guide is not intended to provide a manual for the assessment of TRLs but to capture the key issues and good practice so that they can be considered in an assessment.

The guide was developed in conjunction with practitioners from across the NDA Estate. Interviews and meetings were held where key issues and best practices were captured. The structure and content was based on the responses obtained.

Several clear messages were received that this guide aims to address. Firstly it explains the benefits of TRLs and provides a detailed definition to ensure that TRLs are used in the right context. It also provides a worked example on how to apply TRLs and examines a range of issues and best practices from the perspective of different stakeholder groups. Since the definitions of the different levels could mean different things to different people there is a range of common examples and their associated TRL to ensure consistency of use across the NDA Estate.

Some key messages from the guide are:

- TRLs are a measure of technical risk where the proposed technology is being introduced into an operating plant at the present time. Care must be taken in interpretation if the technology is being developed for introduction at a future date. TRLs, by themselves, may not always relate clearly to risk, cost and schedule. For instance a technology at a low TRL can mature more quickly than those at a high TRLs. It is also possible that TRLs can go down as well as up if the environment of the project changes.
- TRLs relate to individual plant items. They do not suggest that the individual plant items can be integrated and will work together.
- TRLs do not indicate that the technology is right for the job or that application of the technology will result in successful development of the system.

Keywords

Technology, TBuRD, TRL, Development, Maturation

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1 Background to TRLs

NASA developed Technology Readiness Levels (TRLs) in the early 70's as a means of assessing whether emerging technology was suitable for space exploration. By the 1990's it was in use across many US Government agencies, including the Department of Defense (DOD) and Department of Energy (DOE).

In 2006, the US Government Accountability Office (GAO) initiated a review of DOE projects to assess the relationship between technology maturity and project cost growth and schedule extension (1). Based on this review the DOE produced a Technology Readiness Assessment Guide (2). This guide focuses primarily on the formal assessment of technology readiness. The definitions of readiness are described on pages 15 to 18 and it is these definitions that are used in the current issue of EGG10 Appendix 2 (3).

The purpose of this particular guide is to put Technology Readiness Levels in a UK context with specific regard to nuclear decommissioning.

Interviews, meetings and desktop research were used to capture key issues and best practices. The guide was then developed in conjunction with practitioners from across the NDA Estate and wider industry.

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2 What are TRLs?

TRL stands for Technology Readiness Level. In the context of nuclear clean-up the definitions are:

Technology

This refers to a technological process, method, or technique such as machinery, equipment or software needed for the plant, facility or process to achieve its purpose.

Readiness

This refers to time. Specifically it means ready for operations at the present time.

Level

This refers to the level of maturity of equipment. Equipment that is already being used for the same function in the same environment has a higher level of maturity than equipment that is still being developed. The levels are a nine-point scale based on a qualitative assessment of maturity.

Technology Readiness Level (TRL) measures how ready equipment is for use now in an operating plant.

- **Items that are not directly associated with plant operations do not have TRLs**. That means that not all R&D activities can be assigned a TRL. Work that is being carried out to support technology development such as front end studies, optioneering studies, report writing, simulations, modelling, etc. do not have TRLs. They may use TRLs in their assessments but the work package itself does not have a TRL.
- **TRLs are time specific**. Technologies are assessed based on their introduction into an operating plant at the present time. They explain what risk there might be if the technology is to be used today. They do not necessarily convey accurate information about the future.
- **TRLs are context specific**. A technology that is mature in one operating plant cannot be assumed to be as mature in a different one. Even those that appear the same might have significantly different operating conditions.
- **The TRL scale is an ordinal scale**. The ratings are in order but the distinction between neighbouring points on the scale is not necessarily always the same. You cannot for instance infer that it “only takes about 10% of effort to move from one level to another level. It is not a “grade”.
- **The TRL scale is qualitative, not quantitative. It is textual not numerical**. Although it is common to refer to the numbers, you cannot use the numbers arithmetically. You can’t for instance say that TRL8 is twice TRL4 or that an average of TRL4 and TRL6 is TRL5.

3 Benefits and Limitation of TRLs

3.1 Benefits

The benefit of using TRLs is that they clearly communicate whether a technology is ready for use in plant operations.

In doing so they offer a common understanding of technology maturity that is applicable across the NDA Estate.

They provide a basis by which stakeholders can evaluate component technologies and a framework to understand the process for maturing technology. They help to initiate discussions among the stakeholders to consider other factors in technology development and is a process that can be easily repeated during development activities.

3.2 Limitations

The limitations of TRLs lie mainly in how they are used rather than the concept itself. There is often misunderstanding in what they are and what they are used for. This guide aims to clarify those perceptions. Some key points are:

- They are a measure of technical risk, but only if the proposed technology is planned to be introduced into an operating plant at the present time. They do not necessarily convey accurate information about risk, cost and schedule if the technology is being developed for introduction at a future date.
- TRLs relate to individual technologies. They do not suggest that the individual technologies can be integrated and will work together.
- The TRL does not indicate that the technology is right for the job or that application of the technology will result in successful development of the system.

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4 Rating Scale

The qualitative assessment of maturity uses a nine-point scale. The scale shown in EGG10 appendix 2 (3) is an extract from the DOE Technology Readiness Assessment Guide (2). The table below updates that scale to suit UK terminology and it has removed some of the descriptive text which is included and expanded for specific examples in section 7. The definitions below are designed primarily for active facilities although it is readily usable for non-active facilities if required. It is the addition of the radiological aspect that makes the scale at the top end significantly different from other industries. The progression from inactive to active is often a significant step.

Phase	TRL	Stage	Description
Operations	TRL9	Operations	The technology is being operationally used in an active facility
Deployment	TRL8	Active Commissioning	The technology is undergoing active commissioning
	TRL7	Inactive Commissioning	The technology is undergoing inactive commissioning. This can include works testing and factory trials but it will be on the final designed equipment, which will be tested using inactive simulants comparable to that expected during operations. Testing at or near full throughput will be expected
Development	TRL6	Large Scale	The technology is undergoing testing at or near full-scale size. The design will not have been finalised and the equipment will be in the process of modification. It may use a limited range of simulants and not achieve full throughput
	TRL5	Pilot Scale	The technology is undergoing testing at small to medium scale size in order to demonstrate specific aspects of the design
	TRL4	Bench Scale	The technology is starting to be developed in a laboratory or research facility.
Research	TRL3	Proof of Concept	Demonstration, in principle, that the invention has the potential to work
	TRL2	Invention and Research	A practical application is invented or the investigation of phenomena, acquisition of new knowledge, or correction and integration of previous knowledge
	TRL1	Basic principles	The basic properties have been established

Figure 1: Technology Readiness Level Scale

To establish a TRL, an understanding of BOTH the performance and the intended use of the technology is required

5 Process for applying TRLs

The process for applying TRLs is straightforward and has three steps:

1. Map the system
2. Assign TRLs to the items
3. Plan technology development

5.1 System Mapping

A system is described as an aggregation of end products and enabling products to achieve a given purpose (4). In the context of the NDA Estate, these are the buildings and facilities that will manage the effective and efficient clean-up of the UK's nuclear legacy. Within each building or facility will be a number of processes and plant items and it is to these that TRLs are applied. This also applies to the transfer of materials between buildings.

A system can be mapped in different ways depending on the overall goal. It may be based on a single facility or several facilities linked together. It is this diagram that provides the context to a TRL. EGG10 refers to these as Process Wiring Diagrams (PWD).

To construct a system map, determine the overall purpose and list all the plant items or elements in the facility that are required to produce the end product. In project management terminology, this is referred to as a Product Breakdown Structure (PBS). Then show how each product is created and how they are linked together.

An example for illustration is to consider the Waste Vitrification Plant (WVP) at Sellafield. This is a plant that has been operational for a number of years and its purpose is to vitrify high-level liquid waste. The product breakdown structure shown below is one representation of the parts that makes the final vitrified product.

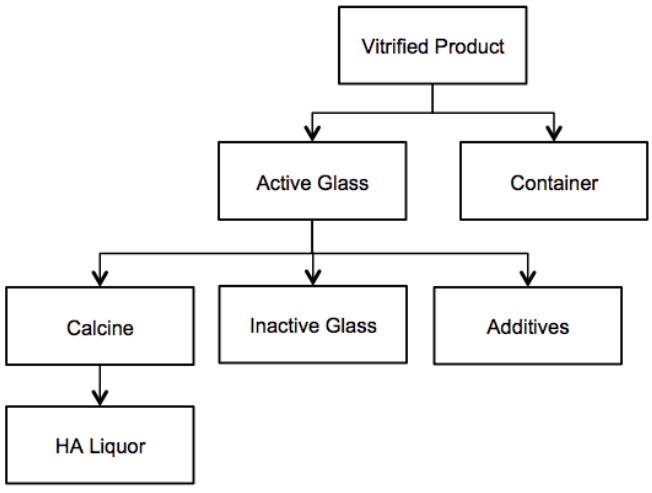

Figure 2: Product Breakdown Structure example

The presentation “Aspects of Process Monitoring” (5) described the individual plant items in WVP and how they are linked together.

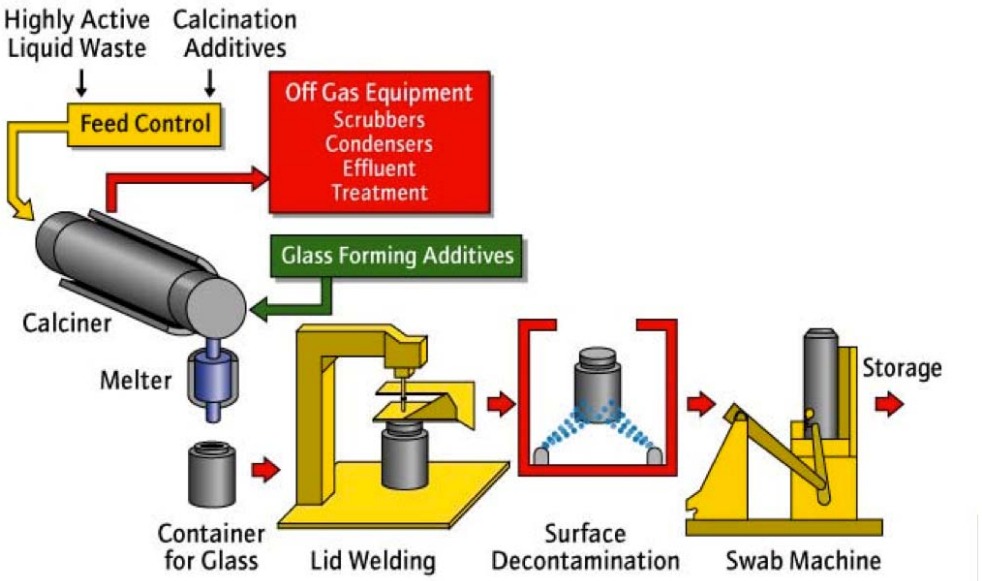

Figure 3: WVP System

For the presentation, graphics were used, but a simple block diagram will be adequate to produce the system diagram. These can be drawn in any number of readily available software packages.

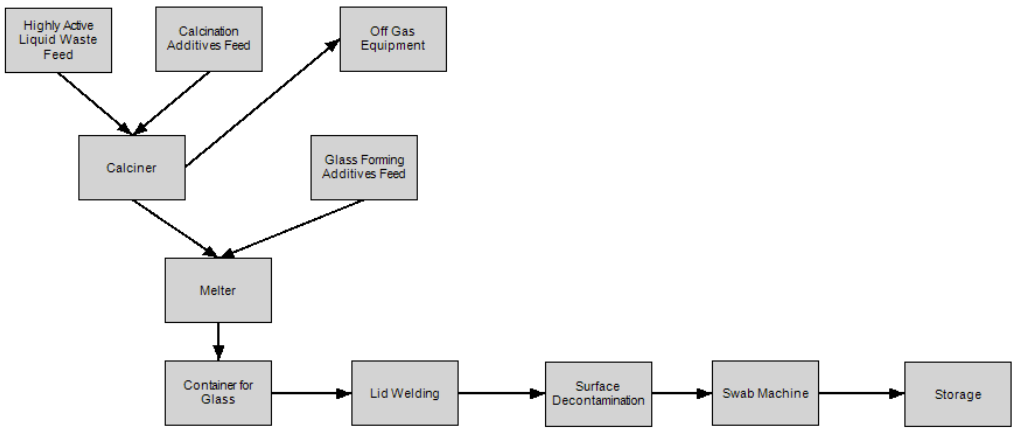

Figure 4: System mapping example

Note, that plant items within the system will, themselves, be made up of smaller components. These are called sub-systems and can also be represented in a diagram if any of the items are particularly complex. Within WVP one of the plant items is the calciner.

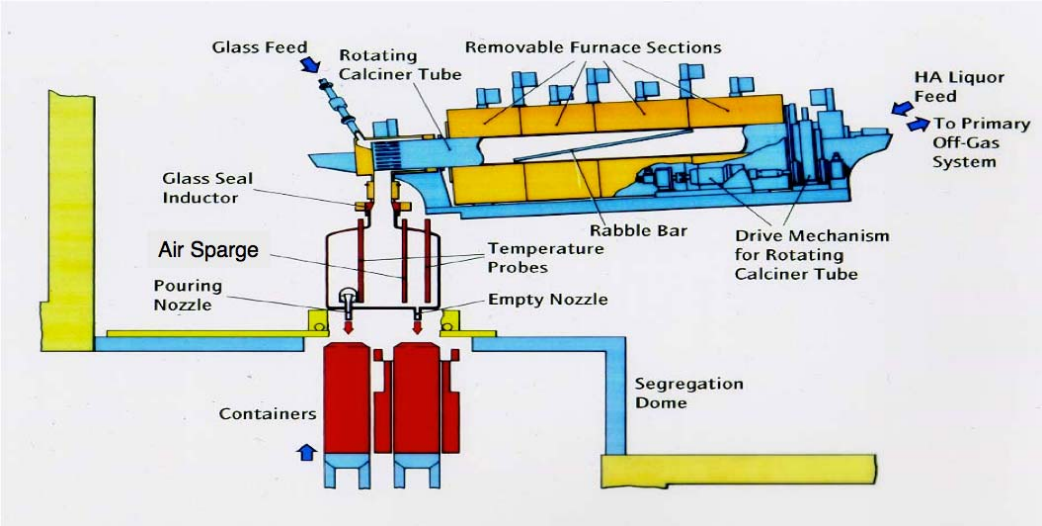

Figure 5: WVP sub-system

A block diagram representation, with the calciner components highlighted in yellow, is as follows:

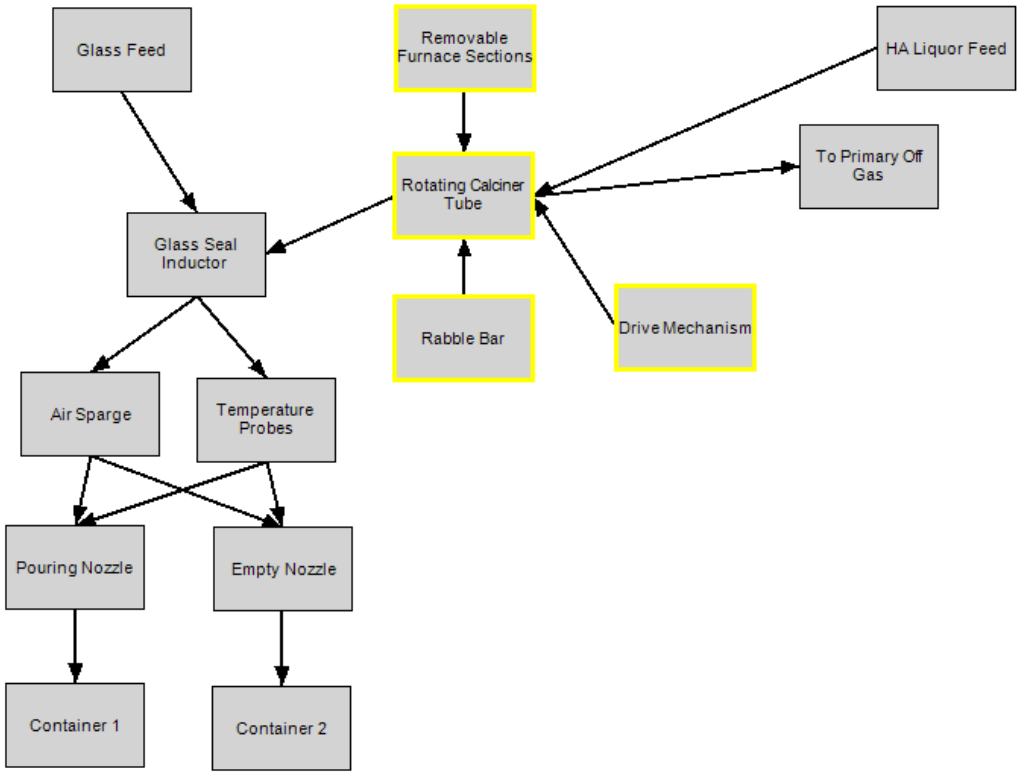

Figure 6: Sub-system mapping example

Similarly, WVP is part of a much larger integrated flow for the whole site. In this case, it is just one facility out of many others. This is called the super-system.

Figure 8: WVP super-system

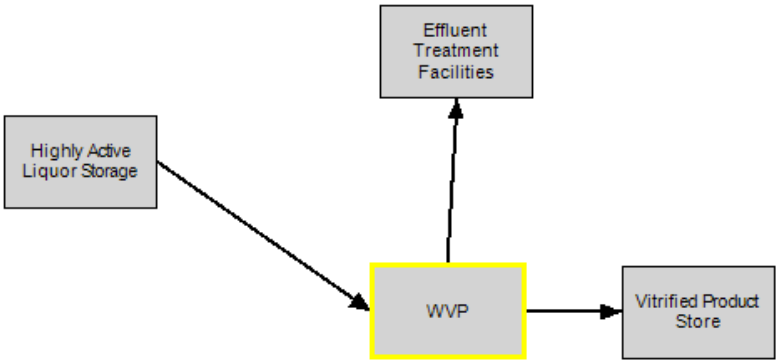

Figure 9: Super-system mapping example

The term Critical Technology Elements (CTEs) is sometimes used in association with TRLs. A technology element is “critical” if the system depends on this technology element to meet operational requirements. If the system mapping approach is followed as above then all the items on the diagram will be a CTE.

The decision regarding the level of detail required for a system map will be dependant on the technologies being developed. In many cases a tiered approach will be required, starting with a super-system diagram and then a system diagram for individual plants or facilities. In some cases – for complex, highly integrated equipment – sub-system diagrams may be required to highlight aspects of a piece of equipment within a plant or facility that require development.

5.2 TRL Assignment

Once the system diagram is complete, TRLs for each item can be assigned by following the descriptions in the table. The method for this is as follows:

Step	Activity
1	Start. Choose a box
2	Assignment. Ask the question: “What stage is the equipment currently at?” This can range from pure research though bench-scale up to large scale as described in Figure 1. It should be recognised that once at large scale, the difference in moving up the scale is environmental context – the highest TRL only applies if the equipment is to be used in exactly the same operating environment and the planned plant/facility.
3	Evidence. Log the evidence used to provide the assessment. For instance *“the rig has been built and successfully run in this environment with this feedstock”*
4	Repeat. Assign TRLs and collect evidence for the remaining boxes in the system diagram.

Where systems are aggregated together to simplify the diagrams, the TRL of the aggregate is given the TRL of the lowest item. Thus, the aggregate system is only as good as its weakest link.

It is good practice and good governance to ensure that TRLs are reviewed independently. Since there will be a cost and time implication to any independent review, the degree of independence should depend on the scale and expected oversight of the project. The greater the oversight requirements the further from the project, or organisation the independent reviewers need to be.

5.3 Development Plan

The current TRL of an item does not, of itself, tell you anything about the steps required for it to be mature enough to be used on an active facility. A development plan (sometimes called a maturation plan or a roadmap) is the document that will explain that pathway. The terminology used varies between organisations but at its core are two key aspects:

Strategy: this explains the pathway to get from where you are now to where you want to be. The strategy will describe whether the plan is to mature the technology by moving up each step in the scale one by one or to miss steps out. For instance, it is relatively common to go straight from pilot size to inactive commissioning thereby saving the cost of building a near full-scale prototype.

Plan: this explains how the strategy will be accomplished. Typical contents will include:

1. System Diagram. This will reproduce the relevant system diagram (and if required any sub-system diagrams). The objective is to put the development work into context. It will show the TRLs of the individual items.
2. Technology Scope. This will explain which parts of the system diagram are to be addressed by the plan. It might be to look at a single item or a number of linked items – whatever makes sense for delivery. The objective is to be clear what is included in the plan and what is excluded.

3. Work Scope. This will list the work to be carried out within the plan. For some development, this will be underpinned by traditional project management structures such as schedules, detailed cost estimates and risk registers. If development is following an Agile approach the activities will be reflected as stories or use-cases.
4. Assumptions. This will state the expected operational environment for the technology.
5. Deliverables. This will list the main products from the development plan. These will align with the development strategy in presenting the evidence of moving through the scale.
6. Acceptance Criteria. This will explain the standards to be met in order to declare success and should be based on the functional specification. In many cases, the development will pass through different communities as the project progresses and it is advisable to be clear at what point handover occurs.

6 Guidance for Users

6.1 Top Tip

Question: Which of the scenarios below, showing how two different technologies may mature, is correct?

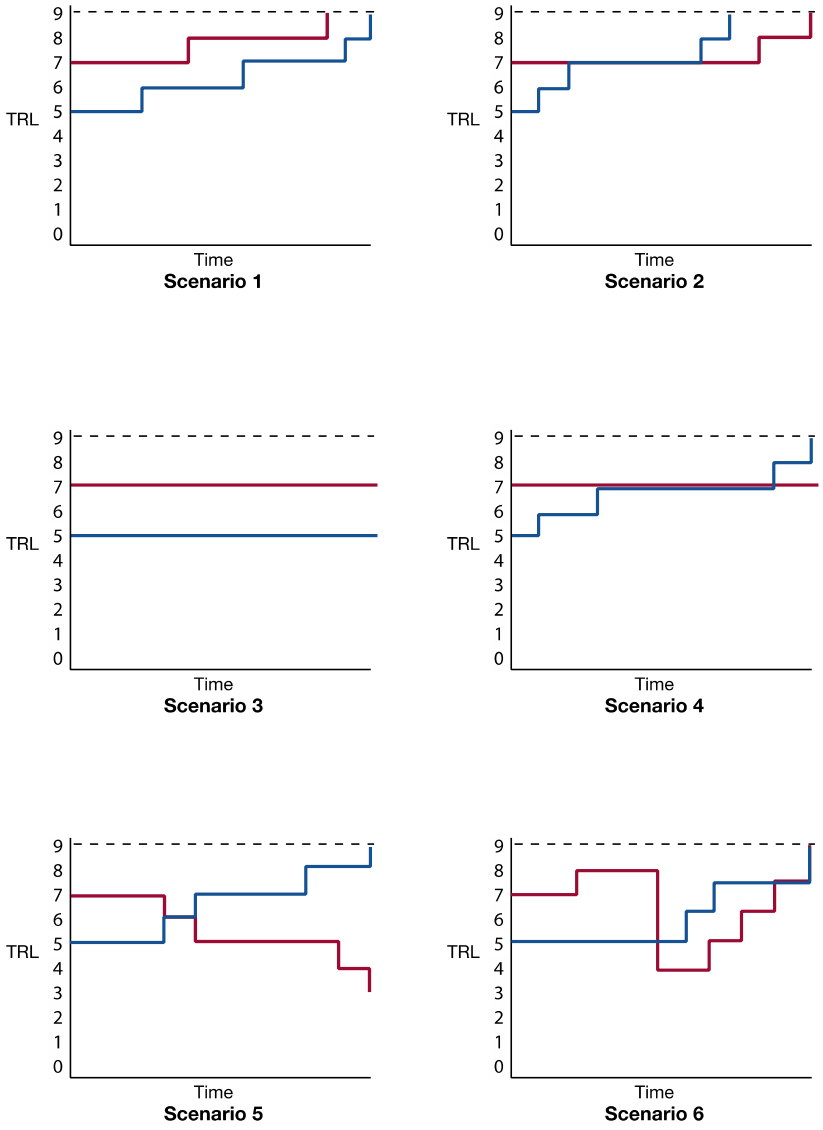

Figure 10: TRL future scenarios

Answer: All of the scenarios are possible, plus an infinite number in between.

Scenario 1: the traditional view where the technology increments up the scale with the most mature technology achieving operational maturity first.

Scenario 2: a view where the most mature technology gets "stuck" at a particular TRL for an extended period of time. Meanwhile, a less mature technology proves easier to implement and achieves operational maturity first.

Scenario 3: a view where all technologies get "stuck" for an extended period of time, seemingly not moving up the scale.

Scenario 4: a view where the most mature technology simply cannot get made to work in the operational environment. Meanwhile an alternative technology, though initially at a low maturity, achieves operational maturity first.

Scenario 5: a view where the environmental context of the facility or plant changes. The selected, initially most mature technology, proves incapable of adapting to changes in throughput, feedstock etc. without completely redesigning the equipment which even when redesigned does not succeed. However, a competing technology proves capable of coping with the emerging environment.

Scenario 6: this variation of scenario 5 is that the equipment can be redesigned to work in the new environment. In the view given, this takes the same length of time as developing the competing technology.

In many cases it will take longer to get from TRL 3 to TRL 9 than it will to go from TRL 7 to TRL9. **However, this is not a given**. Care must be taken not to always assume that a technology with a low TRL today is a more risky choice than that of a higher TRL. The Development Plan will help in the understanding of technical risk.

There are several reasons why the traditional view in scenario 1 may not prove valid:

a) Results. The purpose of development is to prove a hypothesis. The reason for carrying out the work is that without this proof there is too much risk to the project. Whilst much development is successful, there is always a possibility that it simply doesn't work. In particular, for the nuclear industry, the conversion of an off-the-shelf technology to work in a nuclear environment can be extremely challenging. For high radiation environments additional shielding or replacement of electronics may be required. In environments

where PVC suit working is required, components may need to be modified to enable operators to maintain the equipment wearing gloves. This can mean the off-the-shelf equipment needs to be substantially modified which can take a long time or even never work as intended.

b) Incorrect Assessment. The TRL given is wrong. This could be due to inexperience or haste of those assigning the TRL.
c) Environment. High TRLs require the technology to be aligned to the operating environment. Information on chemical and physical properties, as well as throughput, will be assumed early in the project lifecycle. Emerging knowledge as the project progresses can mean changes to the environmental context, which may be a reason why the TRL for a technology can stagnate or go down.
d) Functional Specification. Changes resulting from plant design evolution elsewhere mean the functional specification has to change. This therefore can impact on the TRL.

It should be recognised that the x-axis (time) will vary significantly between projects.

The TRL does not indicate that the technology is right for the job or that application of the technology will result in successful development of the system

6.2 Tips for Technology Community

a) Technical Risk Reduction
    a. TRL is a measure of technical maturity and is not an assessment.
    b. The assessment of TRLs is just that - an assessment of readiness. It is best to avoid overly mechanistic processes and be pragmatic. Try to ensure the assessment is based on evidence e.g. trial experiments rather than opinion. It is worth remembering that whilst the TRL is a useful measure it is the development plan that drives technical risk reduction.
b) Assumptions
    a. Since TRLs are context specific it is important that assumptions with regard to environment and feedstock are clearly documented. The wrong assumptions can have a significant impact on a technology's actual TRL and the work required to get to the target.
    b. If possible, verify your assumptions early in your development plan.
c) Awareness of operational conditions
    a. Keep a close eye on technology that requires "nuclearisation". It may appear to some that because it has a high TRL in a non-nuclear application the development will be straightforward and is not an issue. This may not be the case.
    b. Keep a close eye on feedstock changes. This can alter dramatically quite late on and the TRL, as originally assigned, may have changed.

6.3 Tips for Project Managers

a) TRLs, by themselves, should not be used to estimate “risk”
    a. They should not be used directly as a criterion in optioneering studies as a proxy for risk, cost or duration.
b) Do not use TRLs as a tick box of progress. They are there to support the development plan. It is this plan that contains the information on how technical risk will be reduced.
c) TRLs do not indicate that the technology can be successfully developed.
d) TRLs of individual items say nothing about whether the whole system will work together. The integration and interfaces need to be assessed separately.
e) The TRL does not indicate that it is the right technology for the job.
f) Technology at TRL9 may still have room for improvement. The technology will stay at TRL9 unless something is done that changes its functional requirements or operating environment.
g) New technology that is being developed as an improvement (or replacement) to an existing process will be based on whatever TRL is appropriate.

6.4 Tips for Sanctioning Bodies and Procurement

All SLCs use a gated process for sanctioning projects and TRLs are often part of the acceptance criteria for a gate. Sometimes they are used for guidance and sometimes they are mandatory. Occasionally, the procurement community use TRLs in tenders to differentiate between suppliers.

a) Ensure TRLs have been reviewed independently from the project.
b) Do not accept a TRL with caveats. Use the correct TRL. It is the responsibility of the sanctioning body if they choose to accept a lower TRL at a gate than procedures state.
c) Recognise that high TRLs are not necessarily “good” and low TRLs “bad”. Study and review the development plans to understand the technical risk being taken.
d) TRLs can go down as well as up. They are not always a static number that once achieved can only get better.
e) Other industries and sectors have different definitions of TRLs. So, even though the general approach is similar, the details may be different. The GAO report (1) illustrates this well.

6.5 Tips for Vendors

Technologies used successfully elsewhere may not be as easy to implement in a nuclear environment as expected. Conversely, technologies at a low TRL may well move quickly to maturity given the right environmental context and drive from the Client and Vendor.

a) Work with the Client to understand the context in which they may want to use your technology. This means understanding the

environment in detail including things such as radiological, chemical, physical, maintainability and throughput amongst others. The functional specification will provide those details.

b) Create a Development Plan that explains what needs to be done to show how your existing technology can be inserted into the active facility.

6.6 Tips for the TBuRD Community

a) Process Wiring Diagrams (PWDs)
    a. Ensure that the boxes in the PWDs can be aligned with a systems approach based on processes and/or plant items. The example shown in EGG10 Rev 5 page 9, Figure 1, has boxes that clearly relate to actual plant items (e.g. “Transfer in Flask” is a device for moving flasks such as a crane and this is followed by “Decontamination” which is a decontamination device).
    b. Do not use colours to illustrate TRLs. This can give a misrepresentation of the technology and imply that a low TRL is somehow “bad”. Colours (e.g. red) should only be used to highlight an issue and therefore may apply to any TRL.
    c. Be clear what the absence of a TRL number means. Is it that the TRL for that process is at 9, that the TRL hasn’t yet been evaluated or that no technology has been selected?
b) R&D Table
    a. You should not assign a TRL to a R&D task that isn’t associated with Technology Development.
    b. You cannot assign a TRL when you don’t yet know the baseline technology.

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7 Common examples for TRLs

Equipment in operating facility/plant	**TRL9**
The item is currently being used in an active operational plant.	
Rationale Since this equipment is being used operationally in an active environment it is at the highest level of maturity. It may not work exactly to the original design but has been handed over to operations and can therefore be assumed to be acceptable. *Evidence* Equipment is fully operational in an active facility	
Development Plan A development plan may be needed if the installed equipment still needs to be improved. In this case it will most likely be covered under operational improvement activities, rather than development.	

Equipment undergoing active commissioning	**TRL8**
The item is currently being tested under active conditions prior to being accepted for active operations.	
Rationale Since this equipment is undergoing active commissioning it is at TRL8. Equipment that is a TRL9 is another plant, even if that plant is exactly the same in every way to the proposed plant, can never be a TRL9. It has to be a TRL8 and go through active commissioning prior to acceptance. *Evidence* Equipment is undergoing active commissioning in the operational facility/plant	
Development Plan The development plan will be part of the active commissioning procedures and changes required will be based on those requirements.	

Testing an existing technology in a new active environment	**TRL8**
The individual item is used commercially elsewhere and is being tested in an active environment. The new active environment is believed to be very similar to the existing active testing environment.	
Rationale The technology is well established, the perceived difference in environment is not believed to be significant and no changes to the technology are envisaged.	
Development Plan The development plan is likely to range from very simple to very complicated. For the simple case, initial R&D may focus on confirming that the perceived difference in environment is not significant for this technology. In more complicated scenarios, if the outcome is that environment is different then the TRL would fall to TRL4 and a new more complex development plan would need to be developed.	

Off-the shelf item Same conditions, different industry	**TRL7**
The item is commercially available and used in a different industry. The operational conditions (such as feedstock, volumes, maintainability, etc.) are however directly comparable to its intended use. Radiation is not expected to pose any issues.	
Rationale Since there is not expected to be any modifications required, and the product is expected to work within the expected operational conditions, then the product would simply require inactive commissioning before entering active commissioning. *Evidence* The supplier should be able to provide evidence demonstrating the technology working with the comparable feedstock in the appropriate environment.	
Development Plan The development plan would be expected to be reasonably straightforward given that there should not be any modifications required. This would involve following standard commissioning practices	

Off-the shelf item Same conditions, same industry	**TRL7**
The item is commercially available and already used elsewhere within the NDA Estate. The operational conditions (such as feedstock, volumes, maintainability, etc.) are directly comparable to its intended use including radiation levels.	
Rationale The item is expected to work without modifications but it will still need to go through inactive commissioning before entering active commissioning. *Evidence* Evidence demonstrating the technology working with comparable feedstock in the appropriate environment should be available from within the NDA estate. Inactive and active commissioning information should also be available.	
Development Plan The development plan would be expected to be more straightforward than using a product from a different industry – essentially following commissioning practices that have been previously tried and tested.	

Off-the shelf item Different conditions but no modifications are required	**TRL6**
The item is in use elsewhere (either a different industry or in the NDA Estate) for a similar function but the operational conditions (such as feedstock, volumes, maintainability, etc.) are different. There is a high degree of confidence that the item will not require modification. No uncertainty.	
Rationale Although the item is not expected to require modification, it will still need to be tested at full-scale with similar operational conditions. *Evidence* Information on the equipment should be available albeit under different operating conditions. For equipment being tested this will be at or near full scale.	
Development Plan The development plan could vary from reasonably straightforward to quite difficult. It will be straightforward if the item operates as expected but less so if not. The scale-up of items to cope with larger throughputs and volumes for instance has proven problematic in the past. It will be a difficult case to convince that no modifications will be required but that's not to say the case can't be made.	

Off-the shelf item Needs minor modification	**TRL5**
The item is in use elsewhere (either a different industry or in the NDA Estate) for a similar function where the operational conditions (such as feedstock, volumes, maintainability, etc.) are different. It is known that modifications are required but these are well understood. Some uncertainty.	
Rationale The modifications required are well understood; perhaps because something similar has been done elsewhere or the fundamental science behind the change is very well understood. *Evidence* Information on the equipment should be available albeit under different conditions and with known modifications. For equipment being tested it will be at pilot scale.	
Development Plan The development plan could be quite complex since the modifications will alter the operability of the item. It could well take quite some time to move from TRL5 while designs are developed and tested.	

Off-the shelf item Needs extensive modification	**TRL4**
The item is in use elsewhere (either a different industry or in the NDA Estate) for a similar function where the operational conditions (such as feedstock, volumes, maintainability, etc.) are different. It is known that extensive modifications are required and these aren't well understood. High uncertainty.	
Rationale Substantial modifications are required which may affect the final design of the item considerably. Conceptually, however, there's every reason to expect success since the science and engineering is understood. *Evidence* Information on the equipment should be available along with the expected modifications. For equipment being tested it will be at bench scale.	
Development Plan The development plan is likely to be complex since the modifications aren't well understood. However, it could well be that the plan could develop quickly if the initial analysis proves successful.	

Creating a new item using off-the shelf components	**TRL4**
The individual items are used elsewhere (either a different industry or in the NDA Estate) but they need to be brought together for a new function.	
Rationale Although the individual items maybe well known, the merging of them is not well known. *Evidence* Information on the individual equipment should be available along with the expected modifications required for bringing them together. For equipment being tested it will be at bench scale.	
Development Plan The development plan could be reasonably straightforward or extremely complex. It will depend on the number of new items to be fabricated, how modular the original items are and the degree of complexity of control. In straightforward cases the development plan might move very quickly from 4 to 7. In other cases it may take a significant length of time just to move from 4 to 5	

Testing an existing technology in an active environment – different conditions	**TRL4**
The individual item is used commercially elsewhere and is being tested in an active environment. The new active environment is currently considered to be considerably different from the current active testing environment.	
Rationale Although the technology is well established, the perceived difference in environment means that significant changes to the technology are envisaged. *Evidence* Information on the equipment should be available along with the expected modifications. For equipment being tested it will be at bench scale.	
Development Plan The development plan is likely to be extremely complex. Initial R&D may focus on confirming that the perceived difference in environment is significant for this technology. If the outcome is that environment is not different then the TRL would rapidly rise to TRL8.	

University testing an emerging technology	TRL4
The individual item is being developed at a University in their labs.	
Rationale The technology being developed is at bench-scale. *Evidence* Information on the equipment should be available along with the expected modifications. For equipment being tested it will be at bench scale.	
Development Plan The development plan is likely to be detailed and will evolve over time	

University developing a proof of concept	TRL3
The item being developed is a rough prototype in order to prove specific aspects of functionality are feasible.	
Rationale The technology being developed is proof of concept. *Evidence* Demonstration of functionality	
Development Plan The development plan is likely to be detailed and will evolve over time	

University PhD bursary	TRL2
Carrying out research on specific science or engineering aspects linked to a potential technology	
Rationale The technology being developed is still at the research level before an individual item has been created *Evidence* Research papers published	
Development Plan The development plan is likely to be detailed and will evolve over time	

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8 Other Readiness Level Scales

Technology Readiness Levels are for assessing whether individual items are mature enough for active operation but they do not necessarily address other project needs such as integration, transition to operations and manufacturing. TRLs are therefore one of a number of factors that are required by stakeholders to support their decision at various stage gates. Other commonly used readiness level indices associated with projects include:

- **Manufacturing Readiness Levels (MRLs):** A tool which considers the ability of the system to produce a product to the correct quality and of the required throughput (7)
- **Integration Readiness Levels (IRLs):** A tool which considers the maturity of the interfaces between systems or sub-systems (7)
- **System Readiness Levels (SRLs):** A tool which aggregates technology and the interfaces of a system based on TRLs and IRLs (7)
- **Operational Readiness Reviews (ORRs):** A tool which consider whether the plant is ready for active operation from an operability perspective (8)
- **Innovation Readiness Levels (IRLs):** A tool for considering the innovation lifecycle particularly in terms of the market competition (9)
- **Scientific Readiness Levels (SRLs ®):** A tool for considering the maturity of underlying science in predicating behaviour of feedstock on products (10)
- **Project Definition Rating Index (PDRI):** A project management tool that provides a numerical assessment of how well a project is defined and planned (11)

In many cases, interfaces between systems can be covered adequately through TRLs if the systems are mapped appropriately. The “super-system” diagram will include interconnections between facilities/plants and with any complementary systems.

It should be noted that all the above indices have similar issues to TRLs and exactly the same points need to be taken into account:

- Definitions: It is important to understand the exact meaning of the words used in the measurement.
- Rating Scale: It is important that the scale definitions are clear and explained through the use of examples. All scales have the issue that you cannot necessarily infer anything about future costs or schedule. A “high” number may not be better than a “low” number. They are levels at a point in time and will require additional information to explain how the progression is expected to develop.
- Usage: It is important that if a readiness level is used as a threshold (a) it should be independently assessed and (b) acceptance with caveats should be avoided.

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9 References

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