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Development of a PIE-PIT for ITER and Selection of Bounding Event Sequences

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Abstract

A method has been developed for displaying the outcome of systematic accident identification studies for the ITER design. It consists of a matrix that shows the potential impact of every Postulated Initiating Event (PIE) identified in earlier studies by Failure Modes and Effects Analysis (FMEA). This matrix is called the PIE-Potential Impacts Table (PIE-PIT).

By considering the significant inventories of radioactive material present in the ITER tokamak, and the confinement barriers and functions that protect them, a set of twelve Plant States are defined that characterise all conditions in which some release to the environment is in principle possible. These form the columns of the PIE-PIT, there being one row for every PIE. The table cells are then filled with sequences of codes representing the aggravating failures that would have to occur for the PIE to result in the defined Plant State. A blank cell means no sequence is possible.

Although developed as a presentational tool, the PIE-PIT has value in its own right. The selection of twelve Plant States is in itself of interest, and a further set of Plant States are identified in which one or more confinement barriers remains intact, so that there is no release. A total of 32 Plant States characterise all possible conditions in the ITER tokamak. Further, the PIE-PIT can be used as a basis for the selection of bounding event sequences, to be the study of more detailed analysis. A probabilistic ranking scheme is proposed for this, although an initial selection has been made based on purely deterministic considerations.

It is argued that of the twelve Plant States, six can be identified as Bounding Plant States, characterising all types of release from the plant and all significant pathways for this release. From these, a set of six Bounding Events have been selected. Although selected by this independent approach, these six correspond to the scenarios of six of the 25 Reference Events previously analysed in ITER safety studies, including all but one of the events which result in non-trivial releases (the other is considered enveloped by those that have been included).

Thus the PIE-PIT provides not only a useful presentational tool for the result of event identification studies, but has also yielded a new limited set of Bounding Events proposed as the basis for future event analyses. The correspondence with earlier event selections gives confidence in the justification of the selection.

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Tables

1 Introduction

1.1 Origins

The purpose of this document is to present the development of a new presentation of information from ITER safety studies, related to the identification of potentially hazardous events and event sequences. In the course of safety assessments of the ITER designs during the Engineering Design Activities (EDA), a large number of potential events were considered. Through comprehensive component-level studies of the main plant systems, using Failure Modes and Effects Analysis (FMEA), a catalogue of Postulated Initiating Events (PIEs) was generated. Each PIE represented a group of identified events that could initiate a similar sequence. The consequences of these were assessed, with selected event sequences analysed in detail.

The volume of information generated by these studies was large and did not present a transparent view of the main challenges to safety. Although a global top-down view of potential hazards was presented by a master logic diagram (MLD), this had no link to the component-level studies, and led to list of event initiators that was maybe confusing. Thus there is a need for a new presentation of the identified event sequences, giving a clear view of potential impacts of each identified initiating event.

This presentation is called the PIE Potential Impacts Table (PIE-PIT). It has the possibility to be more than just a presentational tool, by assisting in the selection of plant states and event sequences which characterise the complete set of potentially hazardous states and the sequences that may lead to them. In this report it is shown how the PIE-PIT for the ITER tokamak (i.e. excluding the tritium plant, hot cell and ancillary buildings) can lead to the selection of a set of just six bounding event sequences.

1.2 Objectives

The principal objectives of the development of the PIE-PIT are:

- To link the PIEs identified in the FMEAs with unacceptable plant states that may result (i.e. states that could lead to an excessive release of radioactive materials);
- To identify the challenges to confinement barriers and to enable the selection of a bounding set of confinement challenges;
- To identify a limited set of bounding event sequences that could lead to an excessive release of radioactive materials.

In satisfying these objectives, the PIE-PIT must also meet some requirements:

- The presentation must be transparent;

- The table should be as compact as possible;
- The coverage of potential events should be comprehensive.

2 History

2.1 Background

The origins of the Postulated Initiating Event Potential Impacts Table (PIE-PIT) was a discussion at an ITER Safety Meeting in November 2000. It was considered desirable to be able to see clearly the potential impact on the plant of every identified initiator. The descriptive text of each PIE in GSSR Vol.X [1] already presents the potential impact of each initiator. Event trees, if they were constructed for the current design, would also provide a comprehensive assessment of the potential impact of each PIE. But clearly this was not what was being requested. A *simple transparent view* was needed of the potential for each initiator to lead to some kind of hazardous condition.

2.2 Development of the first PIE-PIT

The first attempt at satisfying the requirement was by a matrix that linked PIEs, from the existing list, with hazardous outcomes – plant damage states. A matrix was built that had a row for every PIE, and a column for every plant damage state with the intention of putting a check mark in the matrix cells everywhere that a PIE could initiate an event sequence leading to the plant state.

But it was noted that information going into the table could be related qualitatively to the information provided in event trees (ETs). Instead of just a check mark in the relevant cells, a list of the aggravating failures in the sequence could be indicated. This is what was done in the first version – the columns became the plant states corresponding to those from the old (1998) ET analyses (i.e. not just *damage* states), and the cells were populated with codes indicating the sequence of failures as provided by the ET branching.

Because the old ET analyses were only for cooling water systems, and because of design changes, it was necessary to introduce additional plant states and aggravating failure codes, and modify some of the sequences. Some PIEs did not lead to any plant states and conversely some plant states could not now be reached from any PIE, so these were eliminated.

The resulting list of plant states that comprised the column headings were an unstructured and incoherent list. So they were then grouped together according to the inventory at risk and the confinement boundary being challenged, and also the release pathway. The table was thus restructured, containing the same information as before.

The new column headings began to look like a top-down view of the hazards and their release potential, i.e. like the Master Logic Diagram (MLD). However there was some confusion between the boundary being challenged and the release pathway, and there was some duplication. So the column structure was rationalised in the table that finally appeared in GSSR Vol. X [1].

The column headings are shown in Figure 1. There are three levels, the inventory (i.e. source term), the confinement barriers challenged in the event sequence, and the pathway postulated for the release.

2.3 Top-down/bottom-up linkage

As mentioned above, the column heading structure has something of the flavour of the MLD. Although the levels are different, the idea of starting with the inventories at risk and then breaking down by confinement challenges is precisely what the MLD does. Roughly, these are Level 4 (Release Species) and Level 5 (Loss of Confinement) in the present MLD.

There have long been problems with interpretation of the lower levels of the MLD. One of these is that some initiators appear in more than one place in the boxes at the MLD lowest level, and logically feed up the tree in two or more branches simultaneously. For example, an in-vessel LOCA could give rise to both failure of primary confinement *and* T mobilisation through temperature rise, which appear in different branches of the MLD.

This could possibly be resolved by constructing a matrix that would connect initiating events (as rows) with the bottom of all the branches in the MLD (as columns), with check marks indicating the connections. Such a matrix would bear a close resemblance to the PIE-PIT now being developed.

Another, related problem with the bottom levels of the MLD is that not all the items listed in that lower level are initiating events. While some of them *are* initiators (e.g. "first wall loss of flow"), others are actually sequences themselves (e.g. "ex-vessel coolant leak and in-

Inventory at risk	Confinement barriers challenged		Pathway for Release		Plant State Code
In-vessel dust, tritium, ACPs of PFW/DV/NB HTS	VV + VVPSS + penetrations + HTS piping	cryostat building + VDS	cryostat or penetration failure/bypass	Boundary leak	VV1-B1
					VV2-B1
				VDS failure	VV1-B2
					VV2-B2
			Boundary leak		VV1-C1
					VV2-C1
			VDS failure		VV1-C2
					VV2-C2
		HX	HX leak		VV1-V0
		TCWS vault	VDS failure		VV1-V1
			Boundary leak		VV1-V2
(PFW, DV, NB) HTS - ACP& Tritium	HTS piping	HX	HX failure		PL-V0
		TCWS Vault	Vault breach		PL1-V2
			VDS failure		PL1-V1
		cryostat Building	boundary leak		PL1-C1
			VDS failure		PL1-C2
VV HTS - ACP and tritium	VV HTS piping	HX	HX failure		VL-V0
		Building	building bypass		VL2-B1
		TCWS Vault	Vault leak		VL1-V1
			VDS failure		VL1-V2
In-VV dust, tritium, and ACPs of VV HTS	VV	cryostat	boundary leak	cryostat failure	VV3-B1
			boundary leak		VV3-C1
fuel cycle tritium	Process piping	Secondary enclosure	VDS failure		T-S1
			boundary failure		T-B1
Hot cell - dust, ACP, tritium	Cell		VDS failure		HC-S1
			Cell breach		HC-B1
Maintenance - in-vessel dust and tritium	VV and cask boundary	Port cell/path	VDS failure		VV-B1
			Port cell or building boundary failure		VV-B2
		Cryostat	VDS failure		VV-C1
			Port cell or building boundary failure		VV-C2
None	cryo-stat		boundary failure		CRY

Figure 1 Column headings of the table as in GSSR Vol.X.

vessel breach"), while others are statements of something undesirable without a mechanism for their occurrence (e.g. "excess tritium from walls"). The labelling of this level in subsequent versions of the MLD have shown this difficulty – the final version in GSSR Vol.X calls the bottom level "Initial Failure Sequence".

The PIE-PIT is capable of providing the linkage between the detailed initiating event catalogue from bottom-up studies and the loss-of-function view of the top-down MLD approach. The top-down view would not be developed down to the troublesome "initiator" level, but would stop at the level that has identified all the confinement functions that might be challenged. These become the column headings of the PIE-PIT.

2.4 Improving the column headings

The column headings of the table in GSSR Vol.X (Figure 1) has a confusing structure due to two problems:

The first is that a number of separate inventories are referred to, in various combinations. So there is dust + tritium, ACPs + tritium, dust + ACPs, dust + tritium + some ACPs, and so on. In fact dust + tritium + ACPs appears in three separate columns, meaning something different each time. All this needs rationalising, with something that (a) makes it clear what inventory is being addressed and (b) ensures that no feasible combinations are ignored.

The second problem with the existing column headings is confusion between "confinement barriers challenged" and "pathways for release". The first refers to barriers that are challenged but remain intact, the second refers to the postulated failures. Both are of importance, but are different aspects of the same thing. The confusion is typified near the beginning by columns spanned by both "cryostat" and "building + VDS" as confinement barriers challenged, which are then broken down into "boundary leak" and "VDS failure" as release pathway, with or without "cryostat or penetration failure/bypass".

If the table *only* shows confinement barriers challenged, but not sequences in which some barriers have failed, it may be hard to illustrate the challenging of secondary barriers. One proposal is that two separate PIE-PIT tables are needed: one showing confinement challenges, the other showing release pathways. But it is likely that some rationalisation will allow this to be done in a single table – this remains to be determined during the process of developing the PIE-PIT.

The requirement to be comprehensive and complete is satisfied by *considering* all possible challenges while building the table and by including events even if they are of very low frequency.

Seeing the column heading structure as a kind of top-down diagram of the plant hazards is an important insight into its construction. But recalling that the original

MLD ran to many pages, the requirement to keep the PIE-PIT compact demands some careful rationalisation. It might be necessary to divide the table up into clearly separable areas, for example a separate PIE-PIT for the tokamak, the tritium plant, hot cell, etc.

The development of this top-down column heading structure may lead directly to the fulfilment of one of the objectives, the identification of the bounding challenges to confinement barriers.

3 Source Terms

3.1 Introduction

The column headings of the PIE-PIT start with the source terms, or "inventories at risk" for the challenges/sequences represented by the entries in the matrix. While it is import to be comprehensive (as always), it is also desirable to have a relatively compact table. This will keep it readable and present an easily-assimilated view of the main challenges and sequences. It is also intended to use the PIE-PIT to identify a *limited* set of event sequences that could be taken as characterising the complete set of events. This might start with a *limited* set of plant states that characterise the range of possible states in ITER.

These requirements suggest that the list of inventories at risk should be kept as short as possible. But, for the sake of completeness, let us begin with a complete list of source term types.

3.2 Basic source terms

Radiological source terms are basically tritium and activation products. These break down in a number of ways:

Tritium

- Elemental T in the fuel cycle and plasma
- HTO and T2O where the potential for oxidation exists
- Surface contamination T on components
- Co-deposited T layer on PFCs
- T generated in materials through reactions such as $^{9}Be(n,t)^{7}Li$
- T generated in test blanket modules.

Activation products

- Activated fixed solid materials
- Activated mobile solid materials (i.e. dust, flakes)
- Activated coolant fluids
- Activated corrosion products within coolants
- Activated gases (e.g. NB insulator gas, if any)

Other, non-radiological, hazards could also be included, but are probably best left for future development of the use of PIE-PIT. As examples, these include:

Toxic hazards

- Beryllium, particularly dust and flakes
- Certain insulator fluids, if used
- Cryogenic fluids (possible asphyxiation hazard)

Flammable hazards

- Hydrogen gas (including deuterium and tritium)
- Conventional fire hazards (building materials, insulators, transformer oils, standby generator fuel, etc. etc.)

Some of these hazards (e.g. in-vessel beryllium) are protected by the same confinement barriers as some radiological hazards, so the PIE-PIT may be readily adapted. Others, e.g. fire hazards, are the subject of completely different safety measures, although they need to also be considered as potential initiators of sequences challenging confinement of the other source terms.

For the time being, it is proposed that the PIE-PIT will be developed for radiological hazards only.

3.3 Inventories at Risk

For the purposes of the PIE-PIT column headings, the source terms listed above need to be grouped together into "inventories at risk". Each such inventory comprises all sources *whose release could be enabled by the same sequence of confinement failures*. The term "confinement" here is in the most general sense, so that a failure that promotes mobilisation, for example, is included as a confinement failure.

The first stage in forming this grouping of sources is to list those that are present in each distinct confinement volume. This is done in Table 1.

Table 1 Confinement volumes containing significant radiological source terms

Volume	Source terms	Comments
Vacuum vessel and its extensions	• Un-burnt T in plasma • T on PFC surfaces including co-deposited • T within PFCs • Dust and flakes (APs and absorbed T) • Solid APs in PFCs • T in cryo-pumps • T generated in blankets and test blanket modules • Activated gases (e.g. impurity gases injected for divertor operation)	Small quantity. May need temperature transient and air or steam ingress to mobilise. Not readily mobilised. Not readily mobilised.
Tokamak cooling water system – primary FW/blanket/divertor loops	• ACPs • T in coolant • Activated water (i.e. ^{16}N)	Very short-lived.
Tokamak cooling water system – primary vacuum vessel loops	• ACPs • T in coolant	] Much lower level than in PFC loops.
Vacuum pumps	• T in roughing pumps • Activated gases (e.g. impurity gases injected for divertor operation)	
Fuelling system including pellet injector	• T	
Tritium plant process equipment and piping[1]	• T • Activated gases (e.g. impurity gases injected for divertor operation)	
Hot cell[1]	• T • Solid APs in components • Dust and flakes	
Radwaste store[1]	• T • Solid APs in components • Dust and flakes	

[1] These volumes should be subdivided later.

The T plant, hot cell and radwaste store have each been left un-expanded in Table 1 because these could each be the subject of a separate PIE-PIT. This can only be done if the events and challenges on each separate PIE-PIT are independent, i.e. events in one system have no interaction with those in another. It is proposed that the initial PIE-PIT focuses only on the tokamak itself, so only those inventories above the thick line in the table are included.

The first item in Table 1, "vacuum vessel and its extensions", could be further expanded. For example "PFC surfaces" includes not only surfaces literally facing the plasma, but all surfaces of the vessel *and its extensions* that might have tritium and APs. For example, the surfaces of the NB system in its chamber, and the beam line duct connecting it to the plasma chamber, are all included. When a NB cryopump is being regenerated, the inventory in the volume could be treated separately, as there may be different challenges to its confinement. But for a NB in normal operation, the inventory in the system that forms part of the vacuum vessel volume can logically be considered a part of it, because it is vulnerable to the same challenges.

The "comments" column of Table 1 notes that some of the sources listed have lower risk of mobilisation, or represent a source of smaller magnitude. But the PIE-PIT is not quantitative: by nature it will only indicate possible sequences/challenges that could lead to a release, but not the size of the release. Nevertheless, it is reasonable to exclude from the PIE-PIT those sources that are too small or too immobile to be capable of exceeding project release guidelines. In ignoring small source terms, however, one must be certain that there are no combinations of multiple small sources that could be mobilised together to constitute a significant hazard.

More important than the differing magnitude of source terms is their different vulnerability to mobilisation. In particular, those inventories that require some additional event to promote their mobilisation. Surface-implanted tritium, for example, in plasma facing components, may only be mobilised in a temperature transient resulting from the under-cooling of the component, or from an additional heat input such as from steam interaction with beryllium after a coolant leak, and the mobilisation could be promoted by the presence of air or steam in the vessel by oxidation and isotopic exchange.

3.4 In-vessel inventory grouping

From the above discussion, the sources in the in-vessel inventory can be functionally divided into the groups listed in Table 2.

Table 2 Grouping of in-vessel inventories

Inventory group	Contributing sources	Comments
Mobile activation products	Dust and small flakes	Confined only by physical barrier
Mobile tritium	Unburnt T in the plasma T within dust and flakes T on surfaces of hot Plasma Facing Components (PFCs) T on cryopump panels	Confined only by physical barrier
Vulnerable activation products (APs)	APs in the surface layers of PFCs	Confined by physical barrier and also needs temperature transient or chemical reaction to liberate
Vulnerable tritium	Co-deposited T T absorbed within PFC materials	Confined by physical barrier and also needs temperature transient or chemical reaction to liberate
Fixed APs and tritium	The bulk of shielding blanket material	Assume these cannot be mobilised in any event.

In the "mobile tritium" group, the term "hot PFCs" refers to those components from which a significant quantity of adsorbed tritium can be expected to be liberated in normal conditions. These include hot surfaces such as the divertor dome, for which, during normal plasma operation, there is an equilibrium between tritium being deposited on the surface and tritium being mobilised from it – when the plasma stops there is a net outgassing of tritium for a period.

3.5 Inventories at risk for PIE-PIT column headings

The breakdown of in-vessel inventories in Table 2 makes a suitable categorisation of the inventories at risk in that volume (omitting the benign final category, fixed APs and T). But since the mobile tritium and activation products face identical challenges to their confinement, in terms of physical barriers, the first two can be combined into the same group. The two "vulnerable" categories are protected by the same physical barriers, but require additional failures, or different event sequences, to be available for release. Whether or not this vulnerable inventory is involved in an event will lead to a large quantitative difference in the material that could be released, but in all cases the types of source term are the same: a mixture of tritium and activation products. Thus for the PIE-PIT column headings, all four groups labelled "mobile" and "vulnerable" in Table 2 can be combined into a single inventory at risk, namely

mobile and vulnerable tritium and activation products. The differences in the potential to mobilise these inventories will emerge in the confinement challenges identified in the PIE-PIT.

Four other volumes containing inventories within the tokamak are listed in Table 1. In each case, either there is only one type of source term is involved (**tritium in vacuum pumping system** and **tritium in fuelling system**) or the mixture of source terms are vulnerable to the same challenges (**tritium and activation products in first wall/blanket/divertor primary coolant** and **tritium and activation products in vacuum vessel coolant**). In previous accident sequence identification studies for ITER, it has been normal to separate the first wall/blanket loops from the divertor loops. But each of these loops faces the same types of challenge, even if the component-level detail differs. We have ended up with, for example, a list of divertor loop PIEs that duplicate the FW/blanket loop PIEs. For the PIE-PIT, which attempts to be compact, this can be avoided.

So we conclude with a list of five inventories at risk within the tokamak, identified in bold type in the above discussion. To recap, they are listed in Table 3.

Table 3 Significant inventories at risk in the tokamak

1	In-vessel mobile and vulnerable tritium and activation products
2	Tritium and activation products in first wall, blanket and divertor coolant
3	Tritium in the vacuum pumping system (ex-vessel parts)
4	Tritium in the fuelling system
5	Tritium and activation products in the vacuum vessel coolant

Note that the vacuum pumping system in no. 3 does not include the in-vessel part of this system, the cryopump panels, which are in no. 1 (except, possibly, during regeneration).

These five inventories are suitable as the top-level column headings in the PIE-PIT. Note that there were eight (including one labelled "none") in the impacts table in GSSR Vol.X (Figure 1).

4 Confinement barriers

4.1 Barriers to be represented

In the column headings for the PIE-PIT, the next level(s) below the inventories at risk list the barriers that protect them from release. Both physical and functional barriers should be included. Generally there are two (or more) confinement barriers, so the structure of the column headings must allow an indication of the combinations that are provided for each of the inventories. Before looking at what complexity this will require, the confinement barriers to be included must be listed.

As with the listing of inventories at risk, there is a strong motivation to minimise the number of confinement barriers to be listed. This can be done by combining functionally equivalent barriers, and avoiding distinction between barriers whose failure would lead to only quantitatively different consequences.

4.1.1 Full list of confinement barriers

The confinement scheme in ITER has been most recently summarised by Charles Gordon in [2], and this has been used to construct the following list of confinement barriers relevant to each of the five inventories at risk listed in Table 3. Some of these would be considered "first" confinements, and others "second", but this distinction is not yet made.

In-vessel mobile and vulnerable tritium and activation products

- Vacuum vessel and its extensions
- Cooling water system: in-vessel pipes, channels and all components.
- Cooling water system: ex-vessel pipes and components, guard pipes, TCWS vault.
- Cryostat and its extensions
- VDS and filtering of rooms around tokamak (where there are VV and cryostat penetrations)
- The Vacuum Vessel Pressure Suppression System (VVPSS) is also listed as having a confinement role. But this is only after an event in which it has been employed and some of the in-vessel inventory, as well as some coolant inventory, has been transferred to it. Its role in a potential event sequence is therefore important in certain sequences.
- Vacuum vessel cooling circuit including heat exchanger.

- Neutral Beam duct, vacuum vessel, bellows, and other components facing the plasma vacuum volume. These are important, but can be included within "VV and extensions", of which they are functionally a part.

- The NB cell and its VDS/filters, including guard pipes around lines which lead outside the cell.

- Other heating and current drive systems (IC, EC and LH), interfaces with plasma volume, i.e. windows. May be functionally regarded as part of "VV and its extensions".

- Rooms housing heating and current drive systems, i.e. at end of ducts sealed by windows – VDS/filters. Also isolation valves in the ducts.

- Diagnostics systems with an interface to the plasma volume: equipment boundaries, windows, vacuum feedthroughs. May be included as part of the "VV and its extensions" boundary; feedthroughs of the cryostat are likewise functionally part of "cryostat and its extensions".

- Test blanket modules cooling circuit and purge gas circuit. These should be functionally equivalent to first wall/blanket cooling water systems, but significant variations may arise, for example if the coolant is helium or liquid metal. For the time being it is proposed to declare this area out of scope of the initial PIE-PIT, and the TBM may be the subject of a separate PIE-PIT later.

- Vacuum pumping in-vessel parts: cryopanel and forevacuum lines, isolation valves. Functionally these are part of "VV and its extensions".

Tritium in the vacuum pumping system (ex-vessel parts)

- Roughing pump system equipment.

- Roughing pump system secondary boundary, glovebox.

Tritium in the fuelling system

- Gas injection equipment and fuelling line from T plant.

- Pellet injector and flight tube.

- Secondary container around equipment, glovebox.

Tritium and activation products in FW/blanket and divertor coolant

- Cooling water system: primary circuit pipes, channels and all components.

- Cooling water system: guard pipes, TCWS vault.

- Vacuum vessel and its extensions (following primary circuit leak within vessel)

- Cryostat and its extensions (following primary circuit leak within cryostat volume)

Tritium and activation products in the vacuum vessel coolant

- Vacuum vessel cooling system: pipes and all components, including heat exchanger.

4.1.2 Reduced list of barriers

Some condensation of the above list of confinement barriers is necessary for use as PIE-PIT column headings, in order keep the table as compact as possible. Functionally equivalent barriers may be combined, so that all barriers whose failure could lead to a qualitatively similar event sequence are grouped together. This can be done even where the challenges to them may be different, as this will be represented by the entries in the PIE-PIT matrix itself against different PIEs.

As already noted in the above lists, a number of the specific barriers mentioned are functionally a part of the vacuum vessel and its extensions. Although the challenges that may face, for example, a window in an RF heating waveguide, are different to those that threaten the integrity of vacuum bellows at a port, the consequences are similar in terms of liberating a fraction of the source term into a volume protected by a secondary barrier (not necessarily the same one). Thus they can be grouped together, and the table will have to show how a variety of second barriers may come into play if any part of this primary VV boundary is breached.

There are a number of instances of a room outside the cryostat, together with its detritiation and filtering system, having a role as a second confinement barrier. These are typically at the end of beam lines that (themselves a primary confinement) penetrate the VV and cryostat boundaries. These can be grouped together as a bypass room in which the VDS/filtering performs the confinement function – this is similar to the generic bypass room that was considered in earlier ITER accident analyses.

Finally, it is proposed to combine the two fuelling systems into a single confinement barrier group. Although the detail of the gas injection and pellet injector systems are very different, they perform a similar confinement function when considering the consequences of their failure.

The reduced list of confinement barriers, following this grouping, is given in Table 4, which also identifies in each case whether the barrier acts as a first or second confinement barrier for each of the 5 inventories at risk (from Table 3) that it protects.

The inventory of T and activation products in the primary coolant is, of course, confined by the pipes and components of the cooling circuit itself. However, the in-vessel part of the circuit is not credited with a confinement function, due to the experimental nature of the in-vessel components. Thus this particular inventory (number 4 in Table 3) is considered to be confined by a first barrier comprising the vacuum vessel and its extensions, and the ex-vessel parts of the cooling circuit itself. This is reflected by the entries in Table 4.

Table 4 List of functionally distinct confinement barriers

Confinement barrier	**Inventory protected** (ref. Table 3)	**Confinement level**
Vacuum vessel (VV) and its extensions	1	first
	2	first
Tokamak cooling water system (TCWS): primary circuit ex-vessel pipes and components	1, 2	first
Tokamak cooling water system: guard pipes, vault, secondary circuit pipes.	1, 2, 5	second
Cryostat and its extensions	1, 2, 5	second
Vent Detritiation System (VDS) and filtering	1, 3, 4	third
Vacuum Vessel cooling water circuit	1	second
	5	first
Vacuum roughing pump system boundary	3	first
Roughing system secondary boundary	3	second
Fuel injection system primary boundary	4	first
Fuel injection system secondary container	4	second

It may be noted that the vacuum vessel cooling water system provides the only confinement barrier for its own coolant inventory. This is because of the small inventory involved, and this barrier includes isolation valves that may close in the event of a leak in the air heat exchanger. All other inventories are provided with at least two confinement barriers.

4.2 Combinations of barriers

The information from the above discussion, as summarised in Table 4, may now be used to construct the possible combinations of first, second and - in some cases - third confinement barrier for each of the inventories at risk. This is trivial in all cases except the in-vessel tritium and activation product inventory. Considering each in turn:

1) In-vessel tritium and activation products

For this inventory, two first confinement barriers have been listed in Table 4. The secondary barriers in each case are different, and for a vacuum vessel failure, the relevant secondary confinement depends on the mode of failure:

First confinement: TCWS primary circuit pipes and components
Second confinements: TCWS guard pipes, vault, secondary circuit pipes

First confinement: vacuum vessel and its extensions
Second confinements: cryostat and its extensions, port cell
Third confinement: VDS and filtering

First confinement: vacuum vessel inner shell
Second confinement: vacuum vessel cooling water circuit

2) Tritium in the vacuum pumping system

First confinement: vacuum roughing pump system boundary
Second confinements: roughing system secondary boundary, glovebox
Third confinement: VDS and filtering

3) Tritium in the fuelling system

First confinement: fuel injection systems primary boundaries
Second confinements: fuel injection system secondary containers, glovebox
Third confinement: VDS and filtering

4) Tritium and activation products in FW/blanket and divertor coolant

First confinement: TCWS primary circuit ex-vessel pipes and components
Second confinements: TCWS guard pipes, vault, secondary circuit pipes
cryostat and its extensions (following in-cryostat leak)
Third confinement: VDS and filtering

First confinement: vacuum vessel and its extensions (following in-vessel leak)
Second confinement: cryostat and its extensions
Third confinement: VDS and filtering

5) Tritium and activation products in the vacuum vessel coolant

First confinement: vacuum vessel cooling water circuit
Second confinements: none (for leakage at air heat exchanger)
cryostat (for leak from VV external shell)
TCWS (for leakage within vault)

It should be noted that in the case (4), where the primary circuit leak location is in-vessel, there is the potential to involve the existing in-vessel inventory of tritium and activation products in the release, as well as the coolant's own inventory.

4.3 PIE-PIT Column headings

All this information may now be put together into the proposed column headings of the PIE-PIT. This is done in Table 5.

This has a total of twelve columns in the PIE-PIT matrix, two more than the GSSR version (Figure 1) at the corresponding level (confinement barriers challenged), ignoring those inventories in the fuel cycle and hot cell that are not considered in the scope of this new PIE-PIT. The column numbers are shown in the bottom row for reference later in this report.

Note that columns 3, 4 and 5 are headed by two inventories at risk, the in-vessel T and activation products as well as the T and activation products in the coolant. This is to represent the case that the primary cooling circuit is breached in the in-vessel section, so that some fraction of both of these inventory are combined in the potential release. The in-vessel section of the cooling circuit is not credited with a confinement function, so does not appear explicitly in Table 5. The failure of this barrier will be a typical initiator of events in columns 3 – 5. Columns 3 and 4 represent the overpressurisation of the vessel, and subsequent leakage via a cryostat failure (column 3) or through the vacuum vessel pressure suppression system (VVPSS) in an event in which this has been used (column 4). Column 5 represents both in-vessel and ex-vessel failures of the primary circuit, providing a potential path for release of the in-vessel inventory (the so-called "wet bypass" scenario). Column 6, which involves the same confinement barriers, is concerned only with the coolant's own inventory, as it represents the case that there is only an ex-vessel leakage from the primary circuit.

Table 5 Proposed PIE-PIT column headings

<table>
<tr><td>Inventory at risk</td><td colspan="7">In-vessel tritium and activation products
Tritium and activation products in FW/ blanket and divertor coolant</td><td>Tritium in the vacuum pumping system</td><td>Tritium in the fuelling system</td><td colspan="3">Tritium and activation products in the vacuum vessel coolant</td></tr>
<tr><td>First confinement barrier</td><td colspan="4">vacuum vessel and its extensions</td><td colspan="3">Ex-vessel TCWS primary circuit pipes and components</td><td>vacuum roughing pump system boundary</td><td>fuel injection systems primary boundaries</td><td colspan="3">vacuum vessel cooling water circuit</td></tr>
<tr><td>Second confinement barrier</td><td>cryostat and extensions, or port cell</td><td rowspan="2">vacuum vessel cooling water circuit</td><td>cryostat and extensions, or port cell,</td><td>VV Pressure Suppression System</td><td rowspan="2">TCWS guard pipes, vault,' secondary circuit pipes</td><td rowspan="2">TCWS guard pipes, vault, secondary circuit pipes</td><td>cryostat and extensions</td><td>Roughing system secondary boundary</td><td>fuel system secondary containers</td><td rowspan="2"></td><td>cryostat and extensions</td><td rowspan="2">TCWS</td></tr>
<tr><td>Third confinement barrier</td><td>VDS and filtering</td><td colspan="2">VDS and filtering</td><td>VDS and filtering</td><td>VDS and filtering</td><td>VDS and filtering</td><td>VDS and filtering</td></tr>
<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td></tr>
</table>

5 Plant States

5.1 Labelling of Plant States

The twelve columns of the PIE-PIT identified by the headings shown in Table 5 can be used in two ways. Firstly, if the sequence of confinement barriers noted are considered to have failed, they represent a plant damage state in which some unacceptable fraction of an active inventory has been released outside the site. Secondly, when barriers remain intact, a series of plant states are indicated in which the confinement functions are challenged. Both of these views are interesting, but the second are events in which confinement has successfully prevented escalation to the first. Thus it makes sense to start by listing the plant states that could lead to a release, and then to consider the states in which they are prevented.

To identify the various plant states, a label is assigned to each of the columns, corresponding to the release when all relevant barriers have been breached. But we can then add a suffix to denote the number of confinement barriers that remain intact. The identifier has a form

PS-T*n.#barriers*

Where

T	identifies that this is a plant state for the Tokamak (in the future, PIE-PITs will be developed for source terms in other systems, e.g. the fuel plant);
n	is a numeric column identifier, 1 – 12;
#barriers	indicates the number of confinement barriers that remain fully functional:

0	the plant state in which an unacceptable release may occur;
1 – 3	plant states in which confinement barrier(s) are challenged, but remain intact.

For completeness, we may refer to an additional plant state **PS-TN**, corresponding to normal operation with no abnormalities.

5.2 Plant States leading to a release

In each of the table columns shown in Table 5, between one and three confinement barriers must have been breached to enable the escape of some fraction of the inventory at risk, leading ultimately to an off-site release. Thus a release path is identified, in generic terms. These are listed below for each state. In this list,

#barriers is always zero, since these are the scenarios in which each confinement barrier has been breached.

PS-T1.0	
Inventory:	In-vessel tritium and activation products
Release path:	Leakage of vacuum vessel or an extension into the cryostat, Leakage of cryostat or an extension into a room, Failure of the VDS and filtering systems, leading to release from elevated release point or through leakage from building.
Consequence:	Some off-site release of tritium and activation products
PS-T2.0	
Inventory:	In-vessel tritium and activation products
Release path:	Failure of vacuum vessel inner shell, and leakage into vacuum vessel coolant circuit, Leakage from vacuum vessel cooling circuit to environment (e.g. at air heat exchanger).
Consequence:	Some off-site release of tritium and activation products
PS-T3.0	
Inventory:	In-vessel tritium and activation products *plus* tritium and activation products in FW/blanket or divertor coolant
Release path:	In-vessel leak from primary cooling circuit pipes or components, Leakage from vacuum vessel or its extensions, Leakage from cryostat or its extensions, or port cell, Failure of the VDS and filtering systems, leading to release from elevated release point or through leakage from building.
Consequence:	Some off-site release of tritium and activation products, both from the in-vessel inventory and from that carried by cooling water

PS-T4.0	
Inventory:	In-vessel tritium and activation products *plus* tritium and activation products in FW/blanket or divertor coolant
Release path:	In-vessel leak from primary cooling circuit pipes or components, Bursting of rupture disk to vacuum vessel pressure suppression system (VVPSS), Leakage from VVPSS, Failure of the VDS and filtering systems, leading to release from elevated release point or through leakage from building.
Consequence:	Some off-site release of tritium and activation products, both from the in-vessel inventory and from that carried by cooling water
PS-T5.0	
Inventory:	In-vessel tritium and activation products *plus* tritium and activation products in FW/blanket or divertor coolant
Release path:	Breaches of primary coolant circuit pipes or components in both in-vessel *and* ex-vessel sections ("wet bypass"), Failure of guard pipes, leakage from TCWS vault, or from secondary circuit pipes or components.
Consequence:	Some off-site release of tritium and activation products, including activated corrosion products and tritium carried by primary coolant.
PS-T6.0	
Inventory:	Tritium and activation products in FW/blanket and divertor coolant
Release path:	Leak from ex-vessel portion of primary cooling circuit, Failure of guard pipes, leakage from TCWS vault, or from secondary circuit pipes or components.
Consequence:	Some off-site release of tritium and activation products carried by cooling water

PS-T7.0	
Inventory:	Tritium and activation products in FW/blanket and divertor coolant
Release path:	Leak from primary cooling circuit within cryostat, including failure of guard pipe, Leakage from cryostat or its extensions, Failure of the VDS and filtering systems, leading to release from elevated release point or through leakage from building.
Consequence:	Some off-site release of tritium and activation products carried by cooling water
PS-T8.0	
Inventory:	Tritium in the vacuum pumping system
Release path:	Failure of boundary within vacuum roughing pump system (while isolated from vacuum vessel and tritium plant), Leakage from secondary boundary of vacuum roughing system, Failure of VDS and filtering systems, leading to release from elevated release point or through leakage from building.
Consequence:	Some off-site release of tritium.
PS-T9.0	
Inventory:	Tritium in the fuelling system
Release path:	Failure of boundary of the fuel gas injector or pellet injector system, Leakage from secondary boundary of injection system, Failure of VDS and filtering systems, leading to release from elevated release point or through leakage from building.
Consequence:	Some off-site release of tritium.
PS-T10.0	
Inventory:	Tritium and activation products in the vacuum vessel coolant
Release path:	Failure of vacuum vessel cooling circuit where there is direct path to environment, e.g. within the air heat-exchanger.
Consequence:	Some off-site release of tritium and activation products.

PS-T11.0	
Inventory:	Tritium and activation products in the vacuum vessel coolant
Release path:	Rupture of external shell of vacuum vessel, releasing coolant into cryostat, leakage from cryostat or its extensions, failure of the VDS and filtering systems, leading to release from elevated release point or through leakage from building.
Consequence:	Some off-site release of tritium and activation products.
PS-T12.0	
Inventory:	Tritium and activation products in the vacuum vessel coolant
Release path:	Failure of vacuum vessel coolant circuit within TCWS vault, leakage from TCWS vault.
Consequence:	Some off-site release of tritium and activation products.

5.3 Confinement challenges

Having defined the possible release pathways, through confinement breaches or bypasses, in the above list, the plant states in which some confinement barriers remain fully functional can now be listed. This is done below, starting, for completeness, with the normal operating state, in which all first confinements are continually challenged.

PS-TN	
Inventory:	All
Status:	Normal operation
Confinement challenge:	All first confinement barriers, i.e.: Vacuum vessel and extensions, Primary coolant pipes and components, Vacuum roughing pump system primary boundary, Fuel injection systems primary boundaries, Vacuum vessel cooling water circuit.

PS-T1.2 **Inventory:** In-vessel tritium and activation products **Status:** Breach of vacuum vessel or extension; tritium and activation products within cryostat volume. **Confinement challenge:** Cryostat and its extensions, or (in case of failure of port closure plate) port cell.	
PS-T1.1 **Inventory:** In-vessel tritium and activation products **Status:** Breach of vacuum vessel or extension, *and* leakage from cryostat or extension (or port cell); tritium and activation products within room outside cryostat **Confinement challenge:** VDS and filtering system for room	
PS-T2.1 **Inventory:** In-vessel tritium and activation products **Status:** Breach of inner shell of vacuum vessel; tritium and activation products ingress into the vacuum vessel cooling water circuit. **Confinement challenge:** Vacuum vessel cooling water circuit boundary.	
PS-T3.3 **Inventory:** In-vessel tritium and activation products *plus* tritium and activation products in FW/blanket or divertor coolant **Status:** In-vessel leakage from primary cooling circuit; tritium and activated corrosion products within vessel, pressurisation of vessel but VVPSS not engaged. **Confinement challenge:** Vacuum vessel and its extensions.	

PS-T3.2

Inventory: In-vessel tritium and activation products
plus tritium and activation products in FW/blanket or divertor coolant

Status: In-vessel leakage from primary cooling circuit followed by leakage from vacuum vessel or extension, VVPSS not engaged; tritium and activation products in cryostat.

Confinement challenge: Cryostat and extensions.

PS-T3.1

Inventory: In-vessel tritium and activation products
plus tritium and activation products in FW/blanket or divertor coolant

Status: In-vessel leakage from primary cooling circuit followed by leakage from vacuum vessel or extension, VVPSS not engaged; leakage from cryostat or extension (or port cell, in case of port closure plat failure); tritium and activation products within room outside cryostat.

Confinement challenge: VDS and filtering systems for room.

PS-T4.3

Exactly equivalent to PS-T3.3, and not a distinct plant state.

PS-T4.2

Inventory: In-vessel tritium and activation products
plus tritium and activation products in FW/blanket or divertor coolant

Status: In-vessel leakage from primary cooling circuit, over-pressurisation leading to operation of rupture disk or bleed valve to VVPSS; tritium and activation products in VVPSS

Confinement challenge: VVPSS.

PS-T4.1

Inventory: In-vessel tritium and activation products

plus tritium and activation products in FW/blanket or divertor coolant

Status: In-vessel leakage from primary cooling circuit, over-pressurisation leading to operation of rupture disk or bleed valve to VVPSS, leakage from VVPSS; tritium and activation products in surrounding room.

Confinement challenge: VDS and filtering systems for room.

PS-T5.1

Inventory: In-vessel tritium and activation products

plus tritium and activation products in FW/blanket or divertor coolant

Status: Failure of primary cooling pipe or component in in-vessel section of circuit, *and* failure of the same circuit in ex-vessel section; tritium and activation products ingress into cooling water then, together with tritium and activated corrosion products already in the water, ingress into guard pipe space, TCWS vault or pipe chase, or into secondary coolant circuit (depending on location of ex-vessel breach).

Confinement challenge: Primary circuit guard pipes, TCWS vault, secondary cooling circuit pipes.

PS-T6.1

Inventory: Tritium and activation products in FW/blanket or divertor coolant

Status: Failure of primary cooling pipe or component in ex-vessel section of circuit; tritium and activated corrosion products ingress into guard pipe space, TCWS vault or pipe chase, or into secondary coolant circuit (depending on location of ex-vessel breach).

Confinement challenge: Primary circuit guard pipes, TCWS vault, secondary cooling circuit pipes.

PS-T7.2

Inventory: Tritium and activation products in FW/blanket or divertor coolant

Status: Breach of primary circuit pipe, and guard pipe, within cryostat; tritium and activation products in cryostat volume.

Confinement challenge: Cryostat and extensions.

PS-T7.1

Inventory: Tritium and activation products in FW/blanket or divertor coolant

Status: Breach of primary circuit pipe, and guard pipe, within cryostat, leakage from cryostat or extension; tritium and activation products within room outside cryostat.

Confinement challenge: VDS and filtering system for room

PS-T8.2

Inventory: Tritium in vacuum pumping system

Status: Failure of primary boundary of vacuum roughing pump; tritium within secondary boundary of this system.

Confinement challenge: Secondary boundary of vacuum roughing pump system.

PS-T8.1

Inventory: Tritium in vacuum pumping system

Status: Failure of primary and secondary boundaries of vacuum roughing pump system; tritium in room outside cryostat.

Confinement challenge: VDS and filtering system for room

PS-T9.2

Inventory: Tritium in fuelling system

Status: Failure of primary boundary of gas injector or pellet injector; tritium within secondary boundary of this system.

Confinement challenge: Secondary boundary of fuel injection system.

PS-T9.1

Inventory: Tritium in fuelling system

Status: Failure of primary and secondary boundaries of gas injector or pellet injector; tritium in room outside cryostat.

Confinement challenge: VDS and filtering system for room

PS-T11.2

Inventory: Tritium and activation products in the vacuum vessel coolant

Status: Rupture of external shell of vacuum vessel, leaking its coolant into cryostat; tritium and activation products in cryostat volume.

Confinement challenge: Cryostat and extensions.

PS-T11.1

Inventory: Tritium and activation products in the vacuum vessel coolant

Status: Rupture of external shell of vacuum vessel, leaking its coolant into cryostat; leakage from cryostat or extension; tritium and activation products within room outside cryostat.

Confinement challenge: VDS and filtering system for room

PS-T12.1

Inventory: Tritium and activation products in the vacuum vessel coolant

Status: Failure of vacuum vessel coolant circuit within TCWS vault.

Confinement challenge: TCWS vault

Note that plant states PS-T3.3 and PS-T4.3 (which are equivalent) represent the state in which there is in-vessel ingress of primary coolant, from a leak in a pipe or cooling circuit component. These states are not readily identified in Table 5 because the in-vessel components are not credited with a confinement function. However, the plant state is clearly different from the normal state PS-TN, hence their inclusion in this list, even though formally the same confinement barriers are being challenged.

Thus 32 distinct plant states are identified, including normal operation.

6 Ranking schemes

6.1 Requirements of a ranking scheme

If the PIE-PIT is to be used to select event sequences that form a bounding set, or that are the most challenging, or that most warrant a detailed analysis, then a rational basis is required for making that selection. This can be done with a ranking scheme, that applies some quantification to the factors considered important in the selection process, even if these are assigned by judgement. Some requirements for such a scheme are:

- All factors that might influence the selection must be included.
- It must be flexible enough that different factors can easily be included or excluded according to the type of selection being made.
- The quantification levels assigned to a factor must be coarse enough that there are no borderline cases that make the assignment difficult or contentious.
- It should allow a different weight to be given to the contribution of each factor to the final overall rank of a sequence.
- The scheme must be transparent and accord with intuitive expectations.
- Ideally, the outcome of making a selection using the ranking scheme should be only weakly sensitive to the details of the ranking scheme itself.

6.2 Factors to be included in the scheme

The factors that may influence the ranking of an event sequence are those quantities that would contribute to an assessment of the risk associated with the event. These are the frequency and consequence of the sequence, even if a formal probabilistic approach is not being taken. For example, to find the events with the potentially most severe outcome, the consequence-related factors would be used. These are everything that affects the severity of the outcome. Frequency-related factors are the initiator frequency and everything that affects the probability of the final plant state resulting from the initiator.

These are the factors to be considered:

Plant State severity.

The development of the list of Plant States, in section 5, was intentionally done without consideration of the magnitude of the release involved. For example, PS-T6.0 refers to any ex-vessel breach of the primary cooling circuit, with subsequent leakage of secondary barriers. Clearly, variations in the size of the breach and of the leakage can result in wide range of potential release sizes, all categorised within this plant state. Nevertheless, there is a relative severity of one Plant State compared to another, without regard to the size of the release. For example, a release of vacuum vessel coolant (PS-T10.0) would generally be regarded as less severe than a release of primary first wall/blanket coolant (PS-T6.0). Thus a severity ranking can be applied to each Plant State, based on the nature of the inventory (or combination of inventories) that are at risk of release.

PIE frequency

This is the initiator frequency. FMEA studies have provided categorisation of the expected frequency of every PIE.

PIE severity

In some cases different PIEs have been used to describe initiating events that differ only in magnitude. For example, small leaks and large pipe-bursts in the same cooling circuit. To account for the variation of impacts of PIEs that differ in this way, a severity ranking can be assigned to each PIE.

Aggravating failure probabilities

For every aggravating failure (AF) in an event sequence, there is some probability of occurrence. This may be the failure probability per demand for a safety system, or for a random event it is derived from the frequency. The term "aggravating failure" includes every branch that would be included in an event tree depicting the sequence. Just as probabilities are assigned to the branches to enable the overall frequency of the sequence to be evaluated in an event tree, so probability ranks can be assigned to the steps in a sequence included in the PIE-PIT. For secondary confinement barriers, these are strongly related to the reliability of the barrier.

Aggravating failure severities

As with initiators, each aggravating failure may have an associated severity, where there is an issue of the magnitude of the failure. In particular this would apply to physical barriers for which a range of leakage mechanisms may be considered, each with a different leak size. This AF severity is linked to the AF probability, and is also related to the barrier reliability in the case of secondary confinement. For example, a strong barrier may have a very low probability of a large breach, but a greater probability of a small leak.

6.3 Assignment of ranks

As noted in the list of requirements above, a coarse ranking scheme is required, since in the most part the assignment will be by judgement. In the following proposals, a minimum number of levels is used in each case to differentiate between factors of different magnitude. This could, of course, be changed later if more quantitative information is available.

The requirements also mentioned the importance of the scheme according with intuition. This means that the numbering of levels should be such that higher numbers indicate a greater magnitude. Thus if a rank is used for "severity", a higher numbered level should refer to a greater severity. This may seem obvious, but it is in fact the opposite of what has been used previously for some quantities – for example in GSSR Volume X, PIE frequencies are given in four categories, with I the highest frequency and IV the lowest.

In the following list of factors to be ranked, a symbol is assigned to each that will be used in subsequent combination into an overall rank for each event sequence.

6.3.1 PIE Frequency, F_{PIE}

Each PIE included in the table already has a frequency category assigned to it by the FMEA studies. These are on a logarithmic scale, each category spanning two decades. The frequency ranking used here can make use of this directly, but the numbering is inverted so that a higher number refers to a higher frequency. This is clarified in Table 6. There will likely be no events of interest at rank 4, so there are essentially three levels of this ranking.

Table 6 Ranking of PIE Frequency, F_{PIE}

Frequency ranking	GSSR Volume X Frequency Category	Frequency range (yr^{-1})
1	IV	$< 10^{-4}$
2	III	$10^{-4} – 10^{-2}$
3	II	$10^{-2} – 1$
4	I	> 1

6.3.2 PIE Severity, S_{PIE}

This factor is used to indicate the size of the initiator referred to by a PIE. For example, "large" and "small" coolant leaks in the same circuit are included in the PIE lists as separate events, with different frequencies. Two levels of severity are proposed, the larger number indicating the higher severity, see Table 7. Of course, it is to be expected that a higher severity PIE will occur at a lower frequency, so if this factor is combined with the frequency ranking F_{PIE}, the effect will tend to equalise the risk impact of different PIEs.

Table 7 Ranking of PIE severity, S_{PIE}

Severity ranking	Severity
1	Low
2	High

6.3.3 Confinement reliability, R_c

The sequence leading from an initiator to a plant state generally includes a number of stages that have been called "aggravating failures", but which are mostly the failure of a confinement barrier, a confinement function, or some supporting function. As noted above (section 6.2), each of these stages is like a branch in an event tree, and occur with some probability. And like initiating events, in many cases there is a magnitude, or severity, associated with the failure, such as a leak size. Thus two parameters are required to characterise each failure in a sequence.

But to simplify the assignment of ranking, and to make the scheme more intuitive, a single value of ranking is proposed for each barrier failure in the sequence. Furthermore, this is done in terms of the *reliability* of the barrier rather than its *failure probability*. This should be easier to assign, and it also facilitates the combination of several barriers. The term "barrier" is used here to include all relevant confinement functions.

A ranking of three levels of reliability are proposed, a higher number indicating a greater reliability. This ranking should take into account both the probability of failure of the barrier (i.e. probability per demand or independent failure frequency, as appropriate), *and* the magnitude or severity of the failure (e.g. leak size) where this is important. A barrier may have a low probability of a large leak and a modest probability of a small leak – this may all be taken into account when assigning a reliability rank. A matrix showing how the reliability rank can be derived from the failure probability and severity is shown in Table 8.

Table 8 Guide to assignment of Confinement Reliabilty, R_C

Failure probability or frequency	Magnitude or severity of failure	
	low	high
low	3	2
high	2	1

6.3.4 Multiple barrier reliability, R_s

In general a cell in the PIE-PIT matrix will contain a code for more than one aggravating failure, indicating that a sequence contains a series of confinement failures. When each of these has been assigned a reliability rank, the overall reliability of the sequence of failures may be obtained by simply summing the individual ranks, i.e. for *N* barriers in a sequence the overall rank is

$$R_S = \sum_{C=1}^{N} R_C$$

It is the use of reliability, rather than failure probability, as the quantity being ranked that makes this simple sum possible. It also accords with intuition; introducing an additional barrier increases the total reliability rank value, and two weak barriers are broadly equivalent to one strong one, etc.

6.3.5 Plant State severity, S_{PS}

The final plant state has an associated severity, as discussed above (section 6.2). This is related to the severity of the state in general terms, taking into account the characteristics of the inventory vulnerable to release, but not the magnitude of the fraction actually released. Three levels of severity rank are proposed for this, the highest number indication the greater severity (Table 9).

Table 9 Ranking of Plant State severity, S_{PS}

Severity ranking	Severity
1	Low
2	Medium
3	High

6.4 Overall Risk Ranking of a sequence

Having assigned ranks for each component of a sequence, i.e. PIE, aggravating failures, and final plant state, a combined rank for the entire sequence can be obtained. This is the quantification that can be used to identify the "worst" or "most challenging" sequences. The data to be combined are the four values set out above (section 6.3), namely the PIE frequency and severity, F_{PIE} and S_{PIE}, the summed reliability of the barriers which fail in the sequence, R_S, and the plant state severity, S_{PS}.

These ranking values can be regarded as being on a logarithmic scale. Thus whereas a *risk* of an event is defined as *frequency* × *consequence*, in terms of the ranking scheme an equivalent formalism is *risk ranking* defined as *frequency rank + severity rank.* Thus the four ranks that characterised a sequence can be combined by summing, rather than multiplying, the values.

It is important to recall that while larger frequency and severity values, F and S, will *increase* the over risk, larger barrier reliability values, R, will *decrease* it. Thus R will appear as a negative term in the total risk ranking. (The formal reason is that *failure probability* $\propto$ *1/reliability*, so if the rank value is regarded as a logarithmic scale, *failure probability rank* $\propto$ *-reliability rank*).

In combining the values contributing to the overall ranking, weighting factors are used, to allow different emphasis to be placed on the importance of each contributing factor. Each of these weights is in the range 0 – 1. The total ranking score for a sequence is thus:

$$H = W_F \, . \, F_{PIE} + W_{PIE} \, . \, S_{PIE} - W_S \, . \, R_S + W_{PS} \, . \, S_{PS}$$

where

W_F is the weight given to the initiator frequencies

W_{PIE} is the weight given to PIE severities

W_S is the weight given to the reliability of the confinement barriers and functions which fail in the sequence (aggravating failures)

W_{PS} is the weight given to the final Plant State

F_{PIE} is the PIE frequency rank, see Table 6

S_{PIE} is the PIE severity rank, see Table 7

R_S is the summed reliability of the confinement barriers or functions that are assumed to fail in the sequence, see Table 8

S_{PS} is the severity of the Plant State, see Table 9.

Thus it is possible to perform different kinds of selection by different choices of the weights. Setting all weights W to unity provides an approximate probabilistic risk ranking, for example, while setting $W_F = 0$ provides a ranking based on the severity of the sequence.

7 The ITER tokamak PIE-PIT

7.1 Scope

Based on the column headings proposed in section 4.3, a PIE-PIT for the ITER tokamak has been constructed. Although the intention is to be as comprehensive as possible in the coverage of event sequences, it is also important to be clear about the limitation of the scope. The Plant States represented by the column headings, which have been described in section 5, refer only to the tokamak itself. Thus out of the scope are the hot cell and tritium plant, and any other ancillary buildings and plant. It is anticipated that these will be the subject of separate PIE-PITs to be developed later.

A further restriction to the scope of this first PIE-PIT is that it covers only event sequences initiated during normal operation. During maintenance operations, a different arrangement of confinement barriers may be in use, so different column headings and Plant States may be appropriate. This, too, should be the subject of a separate PIE-PIT.

The starting point for the rows of the PIE-PIT matrix is the list of PIEs given in GSSR Volume X [1]. But removed from these are those eliminated by the restricted scope stated above. Specifically, these are:

- those relating to remote handling activities during maintenance, RHMA1, RHMA2, RHBA1, RHBA2 and RHCA2;
- those concerned with the tritium plant, TPL1, TPL2, TSL1, TSL2, TPC1, TPC2, TPH1, TPH2 and TPO3;
- those for events in the Hot Cell, HC01, HC02, HC03, HC04, HC11 and HC12; and
- those for the cryoplant and cryodistribution system LYO1, LYO2.

Those PIEs that were categorised Cat.V (hypothetical) in the FMEA studies have also been removed, as hypothetical sequences are not deemed to be in the scope of this study. These PIEs are LVFVU, and LDC1, and the Plant States that would hypothetically result from them are covered by other PIEs, anyway. LFC1, in-cryostat coolant ingress due to rupture of a coolant pipe within the cryostat, has been promoted from Cat.V to Cat.IV, since the FMEA study assumed guard pipes would protect the pipes in this location – these were subsequently removed from the design.

In the course of constructing the PIE-PIT, several PIEs were found to not lead to any of the twelve Plant States. This is consistent with the descriptions of them given in ref. [1], they are faults that have no consequences in terms of incidents or accidents with a potential for release of tritium or activation products. These PIEs are FV2, FV99, VCW2, TGP4, TVP1, TVP2, MP1 or MP2.

This leaves 76 PIEs for the rows of the PIE-PIT matrix.

7.2 Aggravating Failure Codes

In order to identify the sequences identified in the cells of the PIE-PIT, it was found necessary to use 22 codes for distinct aggravating failures. These are listed in Table 10.

Table 10 Aggravating failure codes used in ITER tokamak PIE-PIT

arc	Failure of magnet arc prevention systems
bps	Failure of back-up power supplies/generators
cri	Failure to isolate of cryogen circuit
cry	Failure of cryostat or extension
dir	Direct (no additional failures)
fps	Failure of fast plasma shutdown system
ivc	In-vessel failure of primary cooling circuit
nbc	In-vessel failure of Neutral Beam system cooling circuit
nbs	Neutral Beam system fails to shutdown
phx	Primary cooling loop heat exchanger failure
psc	Failure of vacuum pumping system secondary confinement
pzr	Primary cooling loop pressure relief failure
sci	Failure to isolate of secondary coolant circuit
tsc	Failure of secondary confinement of tritium fuelling system
vbd	Vacuum Vessel Pressure Suppression System does not function correctly
vds	Vent Detritiation System failure
vlt	Loss of integrity of Tokamak Cooling Water System vault
vpn	Failure of VV and cryostat penetration
vpr	VV cooling loop pressure relief failure
vps	Loss of integrity of Vacuum Vessel Pressure Suppression System
vvc	Failure of VV cooling circuit or heat exchanger
xvc	Ex-vessel failure of primary cooling circuit

Note that "dir" is a special code indicating that the PIE leads directly to the Plant State without any additional failure. This code has been used only for failures in the air heat exchanger of the vacuum vessel cooling loop, where a direct (but small) leakage of tritium and activation products in the vacuum vessel coolant could be released directly to the environment.

Although all other codes indicate additional failures that need to occur for the sequence to result in the identified Plant State, a distinction is drawn between independent additional failures and consequential failures. The latter are failures that occur as a result of the initiating event or some other failure postulated in the sequence. In many sequences, for example, an in-vessel coolant ingress is postulated to result from the initiator as a consequence of damage caused in a plasma disruption.. Such consequential are identified in the PIE-PIT by showing the aggravating failure code in bold face and underlined.

7.3 Construction of the PIE-PIT

Having set up a matrix of columns representing twelve Plant States (section 5) and 76 PIEs (section 7.1), each cell was systematically considered to identify the significant event sequence(s), if any, that could lead from each PIE to each Plant State. Reference was made to the description of each PIE and its effects in GSSR [1], as well as earlier work based on event tree analysis [3], even though this was for an earlier design of ITER.

The sequences have been noted as a succession of the aggravating failure codes. In most cases a single sequence is given, but where two or more significant sequences were identified, these are all listed, separated by "*or*".

Cells in which no sequence exists to lead to the Plant State have been left blank.

Following the initial population of the cells of the matrix with sequences in this manner, several rounds of review were carried out to ensure that table is comprehensive and self-consistent.

7.4 Ordering of the table rows

After populating the cells of the PIE-PIT, the ordering of the 76 rows of the matrix was altered to gather together events of a similar type. PIE were grouped under the following headings:

- Loss of vacuum;
- In-vessel leakage of cryogenic coolant;
- In-vessel coolant leaks;
- Loss of primary coolant flow;
- Loss of offsite power;
- Loss of heat sink and secondary coolant leaks;
- Ex-vessel coolant leaks;
- Magnet events;
- Loss of cryostat vacuum;
- Leaks from pumping system;
- Leaks from fuelling system;
- Ex-vessel vacuum vessel coolant events.

Ordering the groups in this way yields a broadly diagonal structure to the contents of the PIE-PIT.

The resulting PIE-PIT for the ITER tokamak is presented in Table 11.

Table 11 The ITER Tokamak PIE-PIT

Postulated Initiating Event		PS-T1	PS-T2	PS-T3	PS-T4	PS-T5	PS-T6	PS-T7	PS-T8	PS-T9	PS-T10	PS-T11	PS-T12
	Inventory at risk	in-vessel tritium and activation products				tritium and activation products in FW/ blanket, divertor or NB coolant			tritium in the vacuum pumping system	tritium in the fuelling system	tritium and activation products in the vacuum vessel coolant		
	First confinement barrier	vacuum vessel and its extensions				ex-vessel TCWS primary circuit pipes and components			vacuum roughing pump system boundary	fuel injection systems primary boundaries	vacuum vessel cooling water circuit		
	Second confinement barrier	cryostat and extensions, or port cell	vacuum vessel cooling water circuit	cryostat and extensions, or port cell,	VV Pressure Suppression System	TCWS guard pipes, vault, secondary circuit pipes, VDS and drainage	TCWS guard pipes, vault, secondary circuit pipes, VDS and drainage	cryostat and extensions	roughing system secondary boundary	fuel system secondary containers		cryostat and extensions	TCWS vault, VDS and drainage
	Third confinement barrier	VDS and filtering		VDS and filtering				VDS and filtering	VDS and filtering	VDS and filtering		VDS and filtering	
	Plant state	PS-T1	PS-T2	PS-T3	PS-T4	PS-T5	PS-T6	PS-T7	PS-T8	PS-T9	PS-T10	PS-T11	PS-T12
Postulated Initiating Event	Cat.												
Loss of vacuum													
VVA2 Ingress of Air in the VV - small leakage	III	vds		ivc; vds or ivc; vbd; vds [note 3]	ivc; vps; vds								
VNG1 Large ingress of gas into NB chamber and VV	III	vbd; vpn; vds		nbc; vbd; vpn; vds *or* ivc; vbd; vpn; vds	nbc; vps; vds *or* ivc; vps; vds								
VNG2 Small ingress of gas into NB chamber and VV	II	vbd; vpn; vds		nbc; vbd; vpn; vds *or* ivc; vbd; vpn; vds	nbc; vps; vds *or* ivc; vps; vds								
In-vessel leakage of cryogenic coolant													
VVC1 Large ingress of cryogenic coolant into vacuum vessel (VV cryopump break) [note 6]	III	vbd; vpn; vds *or* cri		ivc; vbd; vpn; vds *or* ivc; cri	ivc; vps; vds								
VVC2 Small ingress of cryogenic coolant into vacuum vessel (VV cryopump leak) [note 6]	II	vbd; vpn; vds *or* cri		ivc; vbd; vpn; vds *or* ivc; cri	ivc; vps; vds								
VNC1 Large ingress of cryogenic coolant in NB chamber and VV	III	vbd; vpn; vds *or* cri		nbc; vbd; vpn; vds *or* ivc; vbd; vpn; vds *or* ivc; cri	nbc; vps; vds *or* ivc; vps; vds								

	Postulated Initiating Event	Cat. (Plant state)	PS-T1	PS-T2	PS-T3	PS-T4	PS-T5	PS-T6	PS-T7	PS-T8	PS-T9	PS-T10	PS-T11	PS-T12
VNC2	Small ingress of cryogenic coolant in NB chamber and VV	II	vbd; vpn; vds *or* cri		nbc; vbd; vpn; vds *or* ivc; vbd; vpn; vds *or* ivc; cri	nbc; vps; vds *or* ivc; vps; vds								
	In-vessel coolant leaks													
LVV1	Large rupture in the internal VV shell	IV	vbd; vpn; vds	vvc		vps; vds [note 1]								
LVV2	Small rupture in the internal VV shell - equivalent break size: a few cm2	III		vvc		[note 2]								
LVVC	Simultaneous coolant ingress from VV circuit into plasma chamber and cryostat	IV	vpn; vds	vvc					arc; cry; vds				cry; vds *or* arc; cry; vds	
LFV1	Rupture of one PFW/BLK segment coolant loop inside VV	III			vbd; vpn; vds	vps; vds								
LFV2	Small PFW/BLK in-vessel coolant leakage - equivalent break size: a few cm2	II			vbd; vpn; vds	vps; vds								
LFV99	Rupture of all PFW/BLK cooling segments inside VV	IV			vbd; vpn; vds	vps; vds								
LDV1	Rupture of one DIV/LIM coolant loop segment inside VV	III			vbd; vpn; vds	vps; vds								
LDV2	Small DIV/LIM in-vessel coolant ingress - equivalent break size: a few cm2	III			vbd; vpn; vds	vps; vds								
LNN1	Rupture of a refrigerated NB component causing large ingress of water in NB chamber.	II			vbd; vpn; vds	vps; vds								
LNN2	Water leakage in a refrigerated NB component causing small ingress of water in NB chamber.	II			vpn; vds	vps; vds								
	Loss of primary coolant flow													
FA99	Loss of flow in all primary loops due to stop of cooling pumps (with coast-down) due to common cause failure	III			ivc; vbd; vpn; vds	ivc; vps; vds	pzr; xvc; ivc; vlt	fps; pzr; xvc; vlt	fps; pzr; xvc; cry; vds					
FF1	Loss of flow in a PFW/BLK coolant circuit due to pump seizure	III			fps; ivc; vbd; vpn; vds	fps; ivc; vps; vds	pzr; xvc; ivc; vlt	fps; pzr; xvc; vlt	fps; pzr; xvc; cry; vds					
FF2	Loss of flow in a PFW/BLK coolant circuit due to pump trip	II			fps; ivc; vbd; vpn; vds	fps; ivc; vps; vds		fps; pzr; xvc; vlt	fps; pzr; xvc; cry; vds					
FF3	Loss of flow in a PFW/BLK coolant channel	II			fps; ivc; vbd; vpn; vds	fps; ivc; vps; vds								

	Postulated Initiating Event	Plant state / Cat.	PS-T1	PS-T2	PS-T3	PS-T4	PS-T5	PS-T6	PS-T7	PS-T8	PS-T9	PS-T10	PS-T11	PS-T12
FF99	Loss of all PFW/BLK cooling pumps (with coast-down)	III			fps; ivc; vbd; vpn; vds	fps; ivc; vps; vds	pzr; xvc; ivc; vlt	fps; pzr; xvc; vlt	fps; pzr; xvc; cry; vds					
FD1	Loss of flow in a DIV/LIM coolant circuit due to pump seizure	III			ivc; vbd; vpn; vds	ivc; vps; vds	pzr; xvc; ivc; vlt	fps; pzr; xvc; vlt	fps; pzr; xvc; cry; vds					
FD2	Loss of flow in a DIV/LIM coolant circuit due to pump trip	II			ivc; vbd; vpn; vds	ivc; vps; vds		fps; pzr; xvc; vlt	fps; pzr; xvc; cry; vds					
FD3	Loss of flow in a DIV/LIM coolant channel	III			ivc; vbd; vpn; vds	ivc; vps; vds								
FN1	Loss of flow in the NB coolant circuit because of pump trip	III			nbs; nbc; vbd; vpn; vds	nbs; nbc; vps; vds								
FN2	Partial loss of coolant flow in a NB component due to plugs in the cooling channels.	II			nbs; nbc; vbd; vpn; vds	nbs; nbc; vps; vds								
	Loss of offsite power													
AOP1	Loss of offsite power for short duration (< 1 hr.)	II			ivc; vbd; vpn; vds *or* ivc; bps; vbd; vpn	ivc; vpn; vds *or* ivc; bps; vpn								
AOP2	Loss of offsite power for long duration (1 < t < 32 hr.)	III			ivc; vbd; vpn; vds *or* ivc; bps; vbd; vpn	ivc; vpn; vds *or* ivc; bps; vpn								
AAP	Loss of all AC power for up to one hour	IV			ivc; vpn	ivc; vps								
	Loss of heat sink and secondary coolant leaks													
HF1	Loss of heat sink to PFW/BLK loop	III			fps; ivc; vbd; vpn; vds	fps; ivc; vps; vds		fps; pzr; xvc; vlt	fps; pzr; xvc; cry; vds					
HD1	Loss of heat sink to DIV/LIM cooling loop	III			fps; ivc; vbd; vpn; vds	fps; ivc; vps; vds		fps; pzr; xvc; vlt	fps; pzr; xvc; cry; vds					
HF99	Total loss of heat sink to all primary PFW/BLK loops due to a large break in Heat Rejection System (coolant discharged in HRS room)	III			fps; ivc; vbd; vpn; vds	fps; ivc; vps; vds	ivc; phx; sci	phx						

Postulated Initiating Event		Plant state / Cat.	PS-T1	PS-T2	PS-T3	PS-T4	PS-T5	PS-T6	PS-T7	PS-T8	PS-T9	PS-T10	PS-T11	PS-T12
HT99	Total loss of heat sink to all primary loops (PFW/BLK, DIV/LIM and NB) due to a large break in Heat Rejection System pipes feeding main pumps from Cold Basin (coolant discharged in HRS room)	III			ivc; vbd; vpn; vds	ivc; vps; vds	ivc; phx; sci	phx						
LHH99	Large rupture of secondary loop in HRS room and consequent multiple pipe break in PFW/BLK heat exchangers	IV					ivc; sci	sci						
LHR1	Large HRS pipe rupture inside TWCS vault and consequent multiple pipe rupture in HX of divertor primary loop	III			fps; ivc; vbd; vpn; vds	fps; ivc; vps; vds	ivc; vlt	vlt						
LHR99	Large rupture of secondary loop inside TCWS vault and consequent multiple pipe break in PFW/BLK HXs	IV			fps; ivc; vbd; vpn; vds	fps; ivc; vps; vds	ivc; vlt	vlt						
Ex-vessel coolant leaks														
LFO1	Ex-vessel coolant ingress due to large rupture of PFW/BLK cooling circuit pipe inside TWCS vault	III					fps; ivc; vlt	vlt						
LFO2	Ex-vessel coolant ingress due to small rupture of PFW/BLK cooling circuit pipe inside TWCS vault	II					fps; ivc; vlt	vlt						
LFO3	Ex-vessel coolant leakage due to rupture of tubes in a primary PFW/BLK HX	III					fps; ivc; sci	sci						
LDO1	Ex-vessel coolant leakage due to large rupture of DIV/LIM cooling circuit pipe inside TCWS vault	IV					ivc; vlt	vlt						
LDO2	Ex-vessel coolant leakage due to small rupture of DIV/LIM cooling circuit pipe inside TCWS vault	II					ivc; vlt	vlt						
LDO3	Ex-vessel coolant leakage due to rupture of tubes in a primary DIV/LIM heat exchanger	III					ivc; sci	sci						
LNO1	Ex-vessel coolant leakage due to large rupture of NB cooling circuit pipe inside TWCS vault.	IV					nbs; nbc; vlt	vlt						
LNO2	Ex-vessel coolant leakage due to small rupture of NB cooling circuit pipe inside TWCS vault	III					nbs; nbc; vlt	vlt						

	Postulated Initiating Event	Plant state Cat.	PS-T1	PS-T2	PS-T3	PS-T4	PS-T5	PS-T6	PS-T7	PS-T8	PS-T9	PS-T10	PS-T11	PS-T12
LNO3	Ex-vessel coolant leakage due to rupture of tubes in a primary NB heat exchanger	III					nbc; sci	sci						
LFC1	In-cryostat coolant ingress due to PFW/BLK coolant line rupture [note 4]	IV							cry; vds					
	Magnet events													
MLC	Break in magnet cryogenic cooling line inside cryostat, inducing an arc between coils and cryostat or VV walls	III							xvc; cry; vds				vvc; cry; vds	
MP3	TF coil over-voltage	II							arc; xvc; cry; vds					
MPO1	CS/PF coil over-current	III							arc; xvc; cry; vds					
MPO2	CS/PF over-voltage	II							arc; xvc; cry; vds				arc; vvc; cry; vds	
	Loss of cryostat vacuum													
MCJ1	Large leakage of cryogenic gas in a penetration towards outside CV	II							arc; xvc; cry; vds					
VCH1	Large ingress of He in the cryostat	II							arc; xvc; cry; vds					
VCH2	Ingress of He in the cryostat - small leakage	II							arc; xvc; cry; vds					
VCA1	Large ingress of air in the cryostat	II							arc; xvc; cry; vds					
VCA2	Ingress of air in the cryostat - small leakage	II							arc; xvc; cry; vds					
VCG1	Large ingress of gas (He and Air) in the cryostat	IV							arc; xvc; cry; vds					
VCG2	Ingress of gas (He and Air) in the cryostat - small leakage	II							arc; xvc; cry; vds					
VCC1	Large ingress of Cryogenic coolant in the cryostat [note 5]	II							arc; xvc; cry; vds					
VCC2	Ingress of Cryogenic coolant in the cryostat - small leakage	II							arc; xvc; cry; vds					
	Leaks from pumping system													
TVP4	Torus roughing pumping system process boundary failure within second confinement	II								psc; vds				
TVP5	Simultaneous failure of torus roughing pumping system process boundary and second confinement	IV								vds				

Postulated Initiating Event	Plant state / Cat.	PS-T1	PS-T2	PS-T3	PS-T4	PS-T5	PS-T6	PS-T7	PS-T8	PS-T9	PS-T10	PS-T11	PS-T12
Leaks in fuelling system													
TGP1 Gas puffing pipe breach within secondary confinement	II									tsc; vds			
TGP2 Double failure of gas puffing process line and second confinement	IV									vds			
TGP3 Failure of a tritium buffer tank	II									tsc; vds			
TPI1 Pellet Injector pipe break within secondary confinement	II									tsc; vds			
TPI2 Double failure of pellet injector process line and second confinement	IV									vds			
TPI4 Failure of pellet injector	II									tsc; vds			
TPI5 Failure of pelletiser cryoline inside pellet injector room	III									tsc; vds			
Ex-vessel VV coolant events													
HV1 Loss of heat sink to VV cooling loop	III										vpr; vvc		
LVC1 Large rupture of VV external shell	IV							arc; <u>cry</u>; vds				cry; vds *or* arc; <u>cry</u>; vds	
LVC2 Small rupture of VV external shell	III							arc; <u>cry</u>; vds				cry; vds *or* arc; <u>cry</u>; vds	
LVO1 Multiple tube rupture in the VV cooling circuit heat exchanger	IV										dir		
LVO2 Single tube rupture in the VV cooling circuit heat exchanger	III										dir		
LVR1 Large rupture of VV cooling circuit pipe inside TCWS vault	IV												vlt
LVR2 Small rupture of VV cooling circuit pipe inside TCWS vault	II												vlt

Notes

1 This sequence involves VV coolant, but **not** the FW/blanket coolant.
2 We assume that the small leak of LVV2 is insufficient to initiate the event noted for the large leak, LVV1.
3 The vbd failure here includes failure of pumps to start up to evacuate non-condensible air from the volume above the water in the VVPSS.
4 In the FMEA study guard pipes were assumed in the cryostat. As the design does not now include guard pipes here, the Category of LFC1 has been changed from V to IV.
5 PIEs VVC1 and VVC2 are new. The frequency categories are estimates.

8 Selection of bounding events

8.1 Approach

Having constructed the ITER Tokamak PIE-PIT (Table 11), a clear view has been achieved of the range of event sequences and potentially hazardous outcomes, coupled with the range of faults and failures that could initiate them. It has been shown that a set of twelve Plant States (section 5.2) characterises all significant conditions in which a release to the environment may occur. Postulated initiating events, grouped into twelve groups of fault types (section 7.4), cover all significant failures that could initiate an event sequence. The PIE-PIT shows how these are linked, and now aids the process of selecting those event sequences that best characterise the full set of identified events.

A limited set of "bounding events" is sought. This set can then form the basis of future accident analyses, and provide confidence that the full range of hazardous consequences of events in the plant have been encompassed. The set will be bounding in the sense that, within the scope set out in section 7.1, no event sequence could have a consequence more severe than those in the set. The set is limited in the sense that the number of events in the set can be the minimum necessary to achieve complete coverage of the hazards. Thus an event sequence need not be included if another has been selected that has similar, but more severe, consequences.

A probabilistic approach to the selection of bounding events has been proposed using the ranking scheme described in section 6. However, here an initial selection of a set of bounding events is made from deterministic considerations. Further consideration using the probabilistic approach may be done in the future.

In the following discussion, it is recognised that the PIE-PIT approach to classifying plant damage states is based on just five inventories that present the potential radiological source terms for accidental releases. These were listed in Table 3 (page 12), and are also the items in the top row of the PIE-PIT itself. In three of the Plant States, PS-T3, 4 and 5, the potential release may include some fraction of two of these inventories (the in-vessel inventory plus that carried by the water coolant), but in all others only one inventory is involved. Thus a total of six types of inventory combinations may be involved in an accidental release. So it is likely that fewer than twelve Plant States can be chosen to characterise all of these.

After selecting bounding Plant States, for each of these an event sequence is selected from the PIE-PIT that presents the greatest challenge to the barriers that prevent it. Where an inventory is protected by more than one set of barriers, as is clear from the PIE-PIT column headings, it may be necessary to select more than one sequence to fully represent the different ways in which a Plant State could be reached.

8.2 Bounding Plant States

As noted above, the twelve Plant States are all based on just six inventories or combinations of inventories, as appear in the top row of the PIE-PIT column headings (top of Table 11, page 40). The overlapping of the two inventory titles above Plant States PS-T3 to PS-T5 indicates that parts of both these inventories may be released in these states. For each of the six inventory combinations, the corresponding Plant States are now considered to see whether a single one can be chosen as representative in each case. This is done with reference to description of the Plant States and the release paths involved, as described in section 5.2.

8.2.1 In-vessel tritium and activation products

The two Plant States corresponding to release of part of this inventory, PS-T1 and PS-T2, relate to quite different release paths. In PS-T1, there is a leakage or bypass of the vacuum vessel boundary and of the cryostat boundary, and failure of detritiation systems operating on volumes outside the cryostat. In contrast, PS-T2 relates to failure of the vacuum vessel cooling water system boundary within the vessel, leading to the potential for some of the in-vessel inventory of tritium and activation products to be carried by the vessel coolant to its air heat exchanger, where a further failure is postulated. The outcome is similar in both cases (except that in PS-T2 the release is augmented by some fraction of the vacuum vessel coolant's own inventory, but this is trivial). But the PIE-PIT shows that many more event sequences can lead to PS-T1, some of which have the potential to release a larger fraction of the inventory than those in PS-T2.

Accordingly, it is proposed that PS-T1 is selected as the bounding Plant State representing release of this inventory.

8.2.2 In-vessel tritium and activation products *plus* tritium and activation products in primary coolant

The three Plant States related to this inventory fall into two categories: PS-T3 and PS-T4 describe a release through a path that begins in-vessel (challenging the vacuum vessel as the first confinement barrier), while PS-T5 corresponds to a path through a breach in ex-vessel parts of the coolant circuit. Both present significant challenges, so it is necessary to select one of each as the bounding Plant States for this inventory. PS-T5 is clearly one of them, for the other a choice must be made between PS-T3 and 4.

The choice between PS-T3 and PS-T4 for in-vessel events can be made after making these observations from the PIE-PIT:

- All PIEs that can initiate sequence leading to PS-T3 can also initiate sequences to PS-T4, while the converse is not true.
- Sequences leading to PS-T4 generally have fewer steps (involve fewer aggravating failures) than do those for PS-T3.

- Almost all sequences leading to PS-T3 involve failure of the Vacuum Vessel Pressure Suppression System to operate (aggravating failure code "vbd"). But since, in the more significant events, this is by passive rupture disks with very high reliability, this failure is very unlikely.

These points lead to the selection of PS-T4 as the bounding Plant State for these in-vessel events.

Thus two bounding Plant States, PS-T4 and PS-T5, are selected as characteristic of releases of this inventory combination.

8.2.3 Tritium and activation products in primary cooling water

Two Plant States correspond to a release of part of this inventory alone, both referring to a leak of primary coolant that eventually reaches the environment, in PS-T6 by a path that starts within the vault or guard pipes outside of the cryostat, in PS-T7 starting within the cryostat itself.

The outcome of PS-T6, coolant leakage into the TCWS vault, is similar to PS-T5, already selected above as one of the bounding Plant States, except that in PS-T6 the in-vessel inventory is not involved. Thus PS-T6 consequences are enveloped by those of PS-T5. On the other hand, PS-T7 is interesting to include in the bounding set, as the PIE-PIT shows that it is the only state in which magnet system faults may have a significant impact, if it is assumed that a magnet arc could lead to damage of a cooling pipe (this is not certain, and is still being assessed).

So it is proposed that PS-T7 is selected as the bounding Plant State to represent release of this inventory.

8.2.4 Tritium in the vacuum pumping system
Tritium in the fuelling system

These are two separate inventories, each with a corresponding Plant State, PS-T8 for a release from the pumping system, PS-T9 for a release from a fuelling system. But they are very similar in nature, both involving a release of elemental tritium from a system with its own secondary boundary within a room having a VDS system. Thus it is proposed to select just one of these two Plant States as characteristic of both.

The fuelling system probably contains a greater tritium inventory than the relevant parts of the pumping system (this is the roughing pump system outside of the vacuum vessel, not the in-vessel cryopumps). Furthermore there may be more potential initiating events that could lead to a fuelling system boundary challenge, since there are both pellet injector and gas puffing systems.

So it is proposed that PS-T9 is selected as the bounding Plant State for tritium release form the fuelling and pumping systems.

8.2.5 Tritium and activation products in the vacuum vessel coolant

Compared with other primary coolant loop inventories, this is small. But there are three Plant States associated with it, PS-T10, PS-T11 and PS-T12, because of the different sets of barriers that confine different sections of the loop.

The most vulnerable part of the loop is the section outside the building, in particular the air heat exchanger. Here there is only one confinement barrier, justifiable because of the very small inventory involved. The failure of this barrier (as an initiating event) would lead to the direct release of a fraction of the inventory, and this is the only place that the PIE-PIT contains the corresponding "dir" code.

Thus it is evident that Plant State PS-T10 should be selected to represent the release of this inventory.

8.2.6 Summary of selected bounding Plant States

The outcome of the above considerations is the selection of a set of six Plant States that characterise all twelve as a bounding set. There are listed in Table 12.

Table 12 Bounding Plant States selected for ITER tokamak

Plant state	Description
PS-T1	In-vessel tritium and activation products release through vacuum vessel and cryostat leakage or bypass.
PS-T4	Tritium and activation products, in-vessel plus coolant, released through leakage from Vacuum Vessel Pressure Suppression System.
PS-T5	Tritium and activation products, in-vessel plus primary coolant, released through in-vessel and ex-vessel cooling circuit breaches.
PS-T7	Tritium and activation products in primary coolant released into the cryostat and through leakage from the cryostat.
PS-T9	Tritium release from fuelling system through leakage through its confinement barriers.
PS-T10	Tritium and activation products in vacuum vessel coolant release through air heat exchanger failure.

8.3 Selection of bounding event sequences

8.3.1 Approach

Six Plant States have been defined as a bounding set. By now choosing one or more event sequence from the PIE-PIT column for each of these, a set of bounding event sequences will result. A probabilistic approach could be applied here, but as the intention is to identify event sequences that are the most challenging, the expected frequency of the initiator is not considered. A deterministic judgement can be made, in most cases without difficulty, by examining the PIE-PIT column. This is done below for each of the six bounding Plant States in turn.

8.3.2 PS-T1 : Vacuum vessel and cryostat bypass

All the events in this column of the PIE-PIT are loss-of-vacuum events, including not only leakage of gas into the vessel (and its extensions) but also other fluids, namely cooling water or cryogenic coolant. Coolant ingress into the vessel is adequately covered in PS-T4 (which is potentially more severe because the coolant's own inventory is also involved), so the bounding event sequence for PS-T1 should be a gas ingress.

The most straightforward is from the PIE VVA2, in which air leakage into the vessel occurs through a failure of a penetration line that bypasses both vacuum vessel and cryostat boundaries. This sequence is therefore proposed as the single bounding event for PS-T1. It is equivalent to the Reference Event analysed in GSSR Volume VII [4], section 3.3.2.

8.3.3 PS-T4 : In-vessel and coolant inventory leakage from VVPSS

This Plant State describes the situation reached following an in-vessel coolant ingress and the operation of passive rupture disks to the Vacuum Vessel Pressure Suppression System (VVPSS), and then leakage from that system. There are many initiators that could lead to an in-vessel leakage of primary coolant: the PIE-PIT shows 34 of them. Clearly it can result from a loss of primary coolant, a loss of heat sink or loss of power, as well as due to damage caused by a plasma disruption resulting from some other fault. But the most direct way is by postulating a direct failure of the in-vessel coolant circuit as the initiating event.

Of these in-vessel coolant leaks, the most severe is described by PIE LFV99, which postulates the rupture of many first wall coolant pipes, involving leakage from all loops. This might be postulated as the result of an abnormal plasma termination that deposits excessive energy on a toroidal ring around the entire plasma-facing surface. This sequence is therefore proposed as the single bounding event for PS-T4. It corresponds to the scenario assumed for the Reference Event analysed in GSSR Volume VII, section 3.3.1 (but with the additional aggravating failure of the VDS postulated).

8.3.4 PS-T5 : Ex-vessel and in-vessel cooling system leakage

The events in the PIE-PIT column for this Plant State all begin with an initiator causing an ex-vessel breach of a primary cooling circuit, within the TCWS vault or inside a guard pipe. As before, such a leak can be initiated by various faults such as loss of flow, loss of heat sink, etc., but the most direct cause is a rupture of the coolant pipe itself. As a challenge to the pressure-retaining capability of the TCWS vault, the divertor coolant circuit is more severe than a first wall/blanket circuit, as it operates at higher pressure, has larger water hold-up, and divertor components in-vessel are probably more vulnerable to failure in the event of loss of cooling.

Thus a large rupture in the divertor coolant circuit, within the vault, PIE LDO1, is chosen as the bounding event for PS-T5. This corresponds to the scenario assumed for the Reference Event analysed in GSSR Volume VII, section 3.4.4 (but with additional aggravating failure of the VDS postulated).

8.3.5 PS-T7 : Release of coolant tritium and activation into cryostat

Although the leakage of the active inventory of a primary coolant loop is less severe that PS-T5 (above), which includes part of the in-vessel inventory too, the Plant State PS-T7 has been included in the bounding set because of the different nature of events in the PIE-PIT column initiated by magnet faults. A spontaneous rupture of the in-cryostat cooling pipes (PIE LFC1) is also significant, but the other initiators of PS-T7 are less interesting because they are enveloped by the consequences of PS-T5.

A magnet fault leading to an arc could result in this Plant State if the arc caused damage to a secondary coolant pipe within the cryostat. It is not currently clear if such damage is actually possible as the result of an arc, and this is the subject of ongoing assessments. In principle an arc could also cause damage to the cryostat or a penetration line, thus completing the release path for this Plant State (if VDS failure is also postulated). In the present context there is no distinction between different magnet PIEs that could initiate an arc (MP3, MPO1, MPO2), or indeed other causes of an in-vessel coolant pipe burst (LFC1). So we can describe this event as "primary water coolant pipe break within cryostat", without specifying the initial fault, pending the completion of assessments of magnet events.

The event is similar to that analysed in GSSR Volume VII section 3.8.2, although that also postulates a simultaneous cryogenic helium leak, but does not add the aggravating failure of VDS failure.

8.3.6 PS-T9 : Release of tritium from a fuelling system

This column in the PIE-PIT table contains a number of events that are initiated by a failure of some tritium-confining component of a fuelling system, and aggravated by the failure of its secondary confinement. However, two PIEs, TGP2 and TPI2, describe an initiator that causes simultaneous failure of both confinement barriers. TGP2 is concerned with the gas puffing system, and TPI2 with the pellet injector, in both cases the process line is postulated to be breached.

There is no distinction between these events as far as the sequence to Plant State PS-T9 is concerned, so the bounding event for this state can be described generically as double failure of fuelling system process line and secondary confinement. It corresponds to the scenario assumed for the Reference Event analysed in GSSR Volume VII, section 3.6.3 (but with additional aggravating failure of the VDS postulated).

8.3.7 PS-T10 : Release from vacuum vessel coolant heat exchanger

As noted in section 8.2.5, only one event leads directly to release of the vacuum vessel coolant inventory to the environment, namely failure of the air heat exchanger or the section of the coolant loop leading to it outside the building. Two PIEs correspond to this, LVO1 and LVO2, respectively described as multiple-tube and single-tube ruptures in this heat exchanger. LVO1 being the more severe, it is selected here as the bounding event for PS-T10. In fact any breach of this cooling loop external to the building is equivalent, so this event is the same as the Reference Event analysed in GSSR Volume VII, section 3.4.3, which postulates a large breach in a vacuum vessel coolant pipe outside the building.

8.3.8 Summary of bounding event sequences

The previous sections have selected six bounding event sequences, one for each of the bounding Plant States, as characteristic. These are summarised in Table 13.

Table 13 Selected bounding events for the ITER tokamak

	Plant State	**PIE(s)**	**Description**	**Corresponding reference event[1]**
1	PS-T1	VVA2	Air leakage into vacuum vessel by failure of vacuum vessel and cryostat penetration line.	3.3.2
2	PS-T4	LFV99	In-vessel coolant ingress from multiple first-wall pipe rupture, and leakage from VVPSS.	3.3.1
3	PS-T5	LDO1	Divertor coolant pipe failure within TCWS vault and subsequent in-vessel cooling circuit breach.	3.4.4
4	PS-T7	LFC1	Primary water coolant pipe break within cryostat.	3.8.2
5	PS-T9	TGP2, TPI2	Failure of fuelling system process line and of its secondary confinement,	3.6.3
6	PS-T10	LVO1	Failure of vacuum vessel cooling circuit outside building.	3.4.3

Note 1. Identified by the section no. of GSSR Volume VII [4].

9 Conclusions

The Postulated Initiating Event – Potential Impacts Table (PIE-PIT) has been developed as a method for displaying the complete range of postulated event sequences resulting from systematic accident identification studies. By linking postulated initiating events from component-level FMEA with plant damage states derived from inventory and confinement-barrier considerations, it has elements of both a bottom-up and top-down approach. By the use of aggravating failure codes it also outlines complete event sequences linking initiators to ultimate plant states.

Although originally devised as a presentational tool, the development of the PIE-PIT for the ITER tokamak has produced valuable outcomes directly. These include a list of twelve Plant States (section 5.2, page 20) that characterise all significant conditions in which a release of radioactive material to the environment could occur. In most cases three physical and/or functional confinement barriers have to fail, making the reaching of the final Plant States extremely unlikely. But the intermediate states have also been characterised, by identifying a further nineteen Plant States (section 5.3, page 24) in which one or more confinement barriers remains intact. Thus a total of 32 Plant States, including normal operation, characterise all significant normal and abnormal conditions in the ITER tokamak.

The PIE-PIT for the ITER tokamak (Table 11, page 40) has 76 rows representing PIEs identified in the studies for GSSR Volume X [1] (excluding those relating to maintenance activities). 163 table cells contain codes describing event sequences leading to one of the twelve Plant States.

A probabilistic scheme has been proposed for ranking event sequences on the basis of their frequency and/or severity. However, an initial selection of bounding event sequences has been made from purely deterministic considerations, by observation and judgement, aided by the clear view of the spectrum of events that the PIE-PIT affords.

A limited set of six Plant States (Table 12, page 49) has been chosen which characterise all of the twelve identified. These six envelope every combination of radioactive inventory that could be involved in a release, and each of the main potential pathways for release. From the sequences that could lead to the six states, one has been selected in each case as the most challenging. Thus there are just six bounding event sequences that characterise all identified accident sequences in the ITER Tokamak. These are listed in Table 13.

Although selected through the PIE-PIT approach, and thus on an independent basis from that used for the choice of the 25 Reference Events previously analysed and reported in GSSR Volume VII [4], there is a direct correspondence between each of the six bounding events selected here and one of the 25 Reference Events. In the case of the events selected from the PIE-PIT, the failure of all relevant confinement barriers has been postulated, in order to reach the final Plant State with an environmental release. In the analyses reported in GSSR, at least one functional barrier (e.g. an operating vent detritiation system) was assumed to be intact in most cases, but otherwise the scenarios are identical.

Of the 25 Reference Events analysed in GSSR Volume VII, five relate to maintenance operations, the tritium plant or the hot cell, and are thus not in the scope for the present PIE-PIT development. Of the 20 remaining events, only six result in any non-trivial release (although well below project release guidelines in every case). Of these six, five appear in the list of bounding events selected here. This gives confidence in the justification of the selection processes used. The other Reference Event that leads to a small release is heat-exchanger tube rupture – in the PIE-PIT the relevant Plant State (PS-T6) is one bounded by other States (PS-T5 and PS-T7) that *have* been included in the bounding event list.

Apart from the selection of bounding event sequences in this way, the PIE-PIT may be used for other purposes. It could be used to identify the most challenging intermediate Plant States that do not lead to a release, but which present a challenge to a confinement barrier or supporting safety function. It may also be suitable for aiding the identification of systems that are important to safety, leading to their Safety Importance Classification. And it has proved to be of particular value as a basis for discussion of event sequences, the presentational role for which it was originally envisaged.

There are a number of areas for future work with the PIE-PIT. The probabilistic ranking scheme proposed in section 6 could be applied to the present PIE-PIT, to provide an alternative view of the sequences with the highest assessed risk. Further PIE-PITs can be developed to cover areas that were not in scope in the present work, in particular, PIE-PITs are required for the hot cell, for the tritium plant, and for maintenance activities in the tokamak. Finally the present PIE-PIT for the ITER tokamak should be updated and amended in the light of any future safety assessments and analyses, or in response to any significant changes in the ITER design.

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11 References

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