AMS 10-75 Transmission Line Insulators

2023-27 Transmission Revenue Reset

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1 Executive Summary

This document defines the asset management strategies for the Victorian electricity transmission network's population of transmission line insulators to maintain the safety, quality and security of supply.

Insulators provide a mechanical connection between live conductors and structures whilst insulating the structures from electrical current. Approximately 89,000 insulator strings are in service on the transmission network.

Most insulator strings are comprised of several linked discs made from either porcelain or glass with steel pins to form a continuous string.

There are a growing number of polymeric insulators in operation which consist of composite polymer material that has a fibreglass core with a sheath made from silicone rubber or ethylene propylene diene monomer (EPDM).

AusNet Services has undertaken a large program of targeted insulator replacements which began in 2006. This program responded to increasing trends in disc insulator functional failures in the period between 2000 and 2007. Since then, approximately 25,000 porcelain insulator strings comprising 29% of the total insulator fleet have been replaced with polymeric insulators since 2006.

Since 2017, there have been two failures involving polymeric insulators on the No. 2 500 kV line from Heywood Terminal Station to Alcoa, Portland Smelter. Both polymeric strings were from the same manufacturer (Sediver), all of which have been removed from service. Some of the replaced samples are currently kept in storage for photo documentation and further testing.

Insulators are currently assessed by visual inspection during condition assessment, and line and easement inspections done either from the ground or a helicopter. Thermal cameras which are primarily used to inspect phase conductors and joints can be used on an ad hoc basis to assess polymeric insulators to identify any 'hot spots' caused in internal arcing.

AusNet Services has developed risk-based models to assist with the application of formal risk assessments[1] as required by the Electrical Safety (Management) Regulations 2019. Approximately 2,268 insulator strings (2.6% of the insulator fleet) are forecast for replacement before 2027 due to combinations of deteriorated condition, and high failure consequence locations.[2]

Implementation of this selective replacement strategy, addressing both failure frequency and consequences is necessary to maintain public safety and assist in meeting the safety objectives set out in AusNet Services' MissionZero[3] strategy.

High level strategies recommended for prudent and efficient management of the transmission line insulator fleet are:

1.1 New Assets

- Current policy is to install polymeric insulators as part of insulator replacement programs.
- Polymeric insulators have been known to be attacked by birds if strung under de-energized conditions. Provision will be made to prevent bird attack during project implementation planning.
- Fail-safe design concepts to be applied for insulation systems on new replacement of transmission line structures adjacent to high risk roadways and railways or proof test all insulator fittings prior to installation on towers across roads and railways.

[1] Electrical Safety (Management) Regulations 2009 – Clause 11.

[2] There is an approved project (TD-4197 to replace 1,940 strings) on various transmission lines over two financial years from 2019/20 to 2020/21.

[3] Mission zero is a company health and safety objective which aims at achieving zero injuries, zero tolerance, zero compromise and zero impacts.

- Recent failures including manifestation of high temperatures inside polymeric insulators caused by moisture ingress into the silicone rubber sheath has pointed to the need for more stringent selection of suppliers[4], and/or purchasing products from suppliers with good track records.

1.2 Inspection

- Continue to assess the condition of transmission line insulators during structure climbing inspections conducted at regular intervals and during the annual line and easement inspections.
- Develop policies for inspection, maintenance and ultimate replacement of polymeric insulators considering expected service life.
- Explore the compatibility of existing technologies such as Remotely Piloted Aerial System (RPAS also known as drones) to conduct visual, thermal and corona inspection of insulators.
- Enhance the current use of Smart Aerial Inspection and Processing (SAIP) technology to identify defective insulators.
- Reiterate the import of all relevant technical asset data including date of installation into SAP as part of project close-out for insulator replacement projects.
- Continue to use Field Mobile Inspection (FMI) system as the primary means of capturing condition assessment data and include the asset information, i.e. type of insulator and manufacturer, as part of the data capture process.

1.3 Maintenance

- Replace defective insulator strings as part of corrective maintenance tasks. Complete string replacement is preferred as it is more economic and safer than replacement of an insulator from within a string of insulators.
- Update SAP with the details of the new insulator installed on the tower as part of the close-out process of maintenance activities.

1.4 Replacement

- Selectively replace 2,268 strings which are in high consequence areas and in very poor condition between 2022 to 2027. This quantity represents 2.6% of the insulator fleet.

[4] A methodology, based from an international procedure, is being created to test samples collected from the line that had failures. The objective is to confirm if the failures may be connected to the manufacturing process of the insulator, i.e. improper bonding between silicone rubber sheath and fibre glass rod.

2 Introduction

2.1 Purpose

This document defines the asset management strategies for insulators on lines forming AusNet Services' regulated electricity transmission network. This includes the inspection, maintenance, replacement and inspection/monitoring activities required for the life cycle management of these assets.

This document is intended to be used to inform asset management decisions and communicate the basis for these activities.

In addition, this document forms part of the Asset Management System for compliance with relevant standards and regulatory requirements. It is intended to demonstrate responsible asset management practices by outlining economically justified outcomes.

2.2 Scope

This asset management strategy applies to all transmission line insulators, as well as all associated hardware and fittings, within AusNet Services' regulated electricity transmission network that operate at voltages of 66 kV up to 500 kV in the state of Victoria.

This asset management strategy does not cover:

- insulators operating on the distribution network; or
- insulators and hardware owned by Mondo, AusNet Services' commercial arm.

The strategies in this document are limited to maintaining design capabilities in terms of equipment performance and rating. Improvements in quality or capacity of supply are not included in the scope of this document.

2.3 Asset Management Objectives

As stated in *AMS 01-01 Asset Management System Overview*, the high-level asset management objectives are:

1. Maintain network performance at the lowest sustainable cost;
2. Meet customer needs now and into the future;
3. Be future ready;
4. Reduce safety risks; and
5. Comply with legal and contractual obligations;

As stated in *AMS 10-01 Asset Management Strategy -Transmission Network*, the electricity transmission network objectives are:

- Maintain top quartile benchmarking;
- Maintain reliability;
- Minimise market impact;
- Maximise network capability;
- Leverage advances in technology and data analytics; and
- Minimise explosive failure risk.

3 Asset Description

3.1 Asset Function

The insulator assembly provides the dual function of a mechanical connector and an electrical isolator between the current-carrying phase conductors and the earth-connected support structure, which can either be a steel lattice tower or utility pole made of concrete or steel.

The insulator assembly consists of the insulator string and its associated hardware and fittings. An insulator string can be made from several discs connected in series, or a single unit made from polymeric materials.

Insulator hardware includes the corona ring aka grading ring, which is used to minimise the discharge of corona from the live conductor, and the suspension clamp, which is used as a cradle to support the conductor in a suspension structure[5].

Insulator fittings include the shackles, extension links and turn-buckles which are used to adjust the distance of the conductor from the structure. Termination joints, which are used in strain structures[6], are considered part of the conductor system and are excluded from the insulator assemblies.

3.2 Asset Population

There are 88,851 transmission line insulator assemblies (insulator strings) in service on the regulated transmission network, as at 1 April 2020. Majority of insulator strings are comprised of linked discs made from either porcelain or glass with steel pins to form a continuous string. The number of discs on a string increases with the operating voltage of the line as well as creepage length required for adequate pollution performance[7]. The numbers of porcelain or glass discs required for different voltages are shown in Table 1.

Table 1: Number of porcelain/glass discs per insulator string by voltage

Voltage (kV)	Number of porcelain/glass discs
66	8
220	13 – 17
275	19
330	18 – 20
500	23 – 35

A polymeric string consists of composite polymer material that has a fibreglass core with a sheath made from silicone rubber or ethylene propylene diene monomer (EPDM). Unlike porcelain or glass strings which contain individual insulators joined together in series; polymeric strings contain a single continuous fibreglass core. The number of polymeric sheath rings surrounding the fibreglass core increase along with increasing operating voltage, however, these rings vary in size and distance from one another and number depending on the insulator manufacturer.

The population of transmission line insulators include three different types which are identified by materials used in their manufacture, namely porcelain, glass and polymeric. Each different type of insulator displays

[5] Suspension structure - a structure wherein the conductor passes as one continuous unit, without any (or minimal) line deviation.

[6] Strain structure – a structure used when there is a deviation in direction of the line. The conductor is terminated at one side of the tower and connected to the conductor on the adjacent side, using a bridging conductor supported by an insulator bridge assembly.

[7] More discs are required for polluted or aggressive environment such as the vicinity of power stations, near the coastline or within the metropolitan area.

different performance characteristics in terms of corrosion and pollution resistance, tensile strength, and electrical insulation properties.

The population of transmission line insulators operate at five standard voltages, 500 kV, 330 kV, 275 kV, 220 kV and 66 kV.

Figure 1 displays photographs of the different insulator types in service on the transmission network

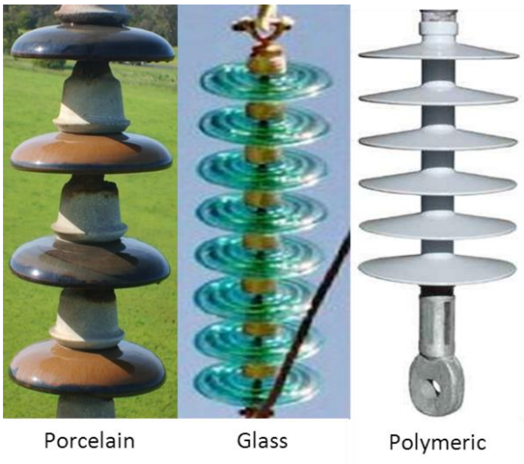

Figure 1: Insulator types

Table 2 summarises the volumes of different types of insulators operating within each of the five voltages.

Table 2: Transmission line insulator strings by voltage and type

Insulator Type	66 kV	220 kV	275 kV	330 kV	500 kV	Total
Porcelain	2,001	19,317	1,236	6,687	26,880	56,121
Polymeric	0	22,110	15	807	2,184	25,116
Glass	252	5,238	45	1,935	144	7,614
Total	**2,253**	**46,665**	**1,296**	**9,429**	**29,208**	**88,851**

Since 2006, deteriorated porcelain and glass insulator strings have been proactively replaced with polymeric insulators. Figure 2 is a graphical representation of the transmission line insulator fleet by type and voltage cohorts.

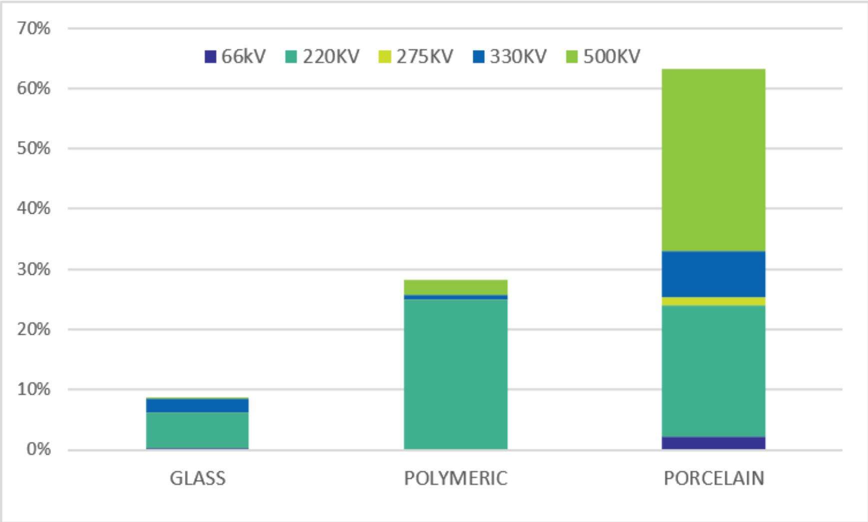

Figure 2: Volumes of insulator strings by type and voltage

3.2.1 Corrosivity Zones

The transmission line network is exposed to varying levels of corrosivity depending on environmental factors. The two factors which have the greatest impact on levels of corrosivity are salt deposition, experienced in coastal regions, and air pollution, caused by emissions from heavy industry.

To manage the effects of corrosion in a prudent manner, corrosivity classifications are assigned to transmission line assets. There are three corrosivity zones: severe (zone 3), moderate (zone 2) and low (zone 1).

Figure 3 shows the proportion of transmission line insulators located in each of the three corrosivity zones. A map displaying a spatial view of transmission line assets within the three corrosivity zones is included in Appendix B.

From the figure, 36% of the transmission line insulators are situated in the low corrosivity zone (zone 1), while approximately 64% are in the moderate corrosivity zone (zone 2) and only 0.5% are in the severe corrosivity zone (zone 3).

The HYTS – APD 500 kV lines' last 28-structures are situated in the severe corrosivity zone. These circuits supply power to an industrial plant situated at Portland on Victoria's western coast. Heavy corrosion of porcelain insulators on these lines prompted their early replacement in 2007 after only 26 years of service. This is also the location where two polymeric insulators failed after only 10 years of service life and four polymeric insulators have manifested elevated temperatures in its core. All these insulators were from the same manufacturer (Sediver) which have since been replaced with NGK brand insulators which are more resilient to aggressive environment.[8]

[8] To assure supply reliability, circuit 1 has Maclean insulators while circuit 2 now has NGK insulators

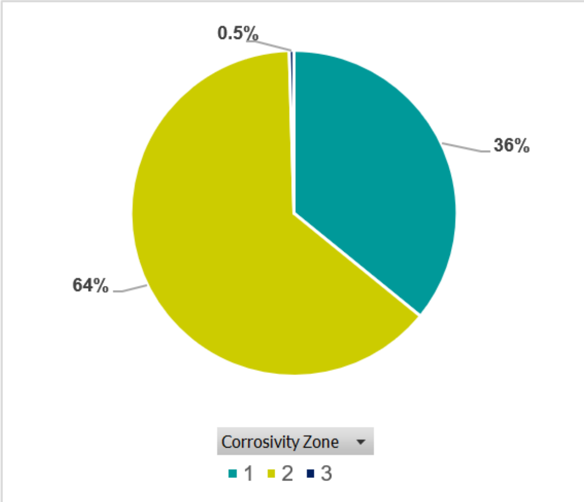

Figure 3: Insulator strings by corrosivity zone

3.2.2 Connection Pins – Porcelain and glass disc insulators

Individual insulators in a string are connected using a “cap and pin” mechanism. The top of each insulator contains a cap and the lower half a steel pin. Insulator pins slot into the cap of the insulator below which allows individual insulator discs to be connected into a string.

The transmission line insulator fleet predominantly contains insulators with three different steel pin diameters: 16 mm, 20 mm and 24 mm. The original insulators used a pin diameter of 16mm which was later increased to 20mm and 24mm. The loss of pin section due to corrosion has a greater effect for the smaller pin diameters.

Figure 4 displays the volume of each insulator pin size against the operating voltage of the line its supporting.

As new insulators introduced into the network since 2006 have been predominantly polymeric strings, the population of disc strings with 16 mm pins have decreased steadily from thirty two percent in 2006 down to nine percent in 2020. For the rest of the fleet, eighty-eight percent of transmission line insulators have 20 mm diameter pin sizes, and only three percent of the fleet have 24 mm diameter pins.

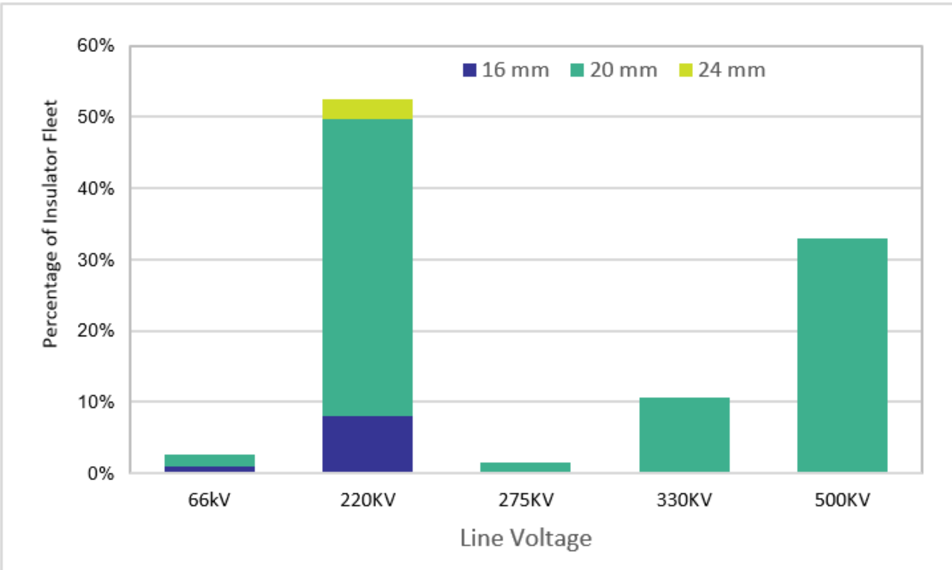

Figure 4: Insulator strings by voltage and size of connection pin

3.3 Age Profile

The average in-service age[9] of the transmission line insulator strings is 35 years as shown in Table 3. This average has been influenced by the progressive replacement of deteriorated insulator strings.

Table 3: Average age of transmission line insulator

Voltage Class (kV)	Average Age
500	40
330	49
275	32
220	13
66	43
All strings	**35**

Figure 5 shows the age of the transmission line insulator population by voltage. There are approximately 8,100 insulator strings with a service age exceeding 55 years; majority of these insulators operate on the 220 kV network, with some strings belonging to the 66 kV, 330 kV and 500 kV circuits.

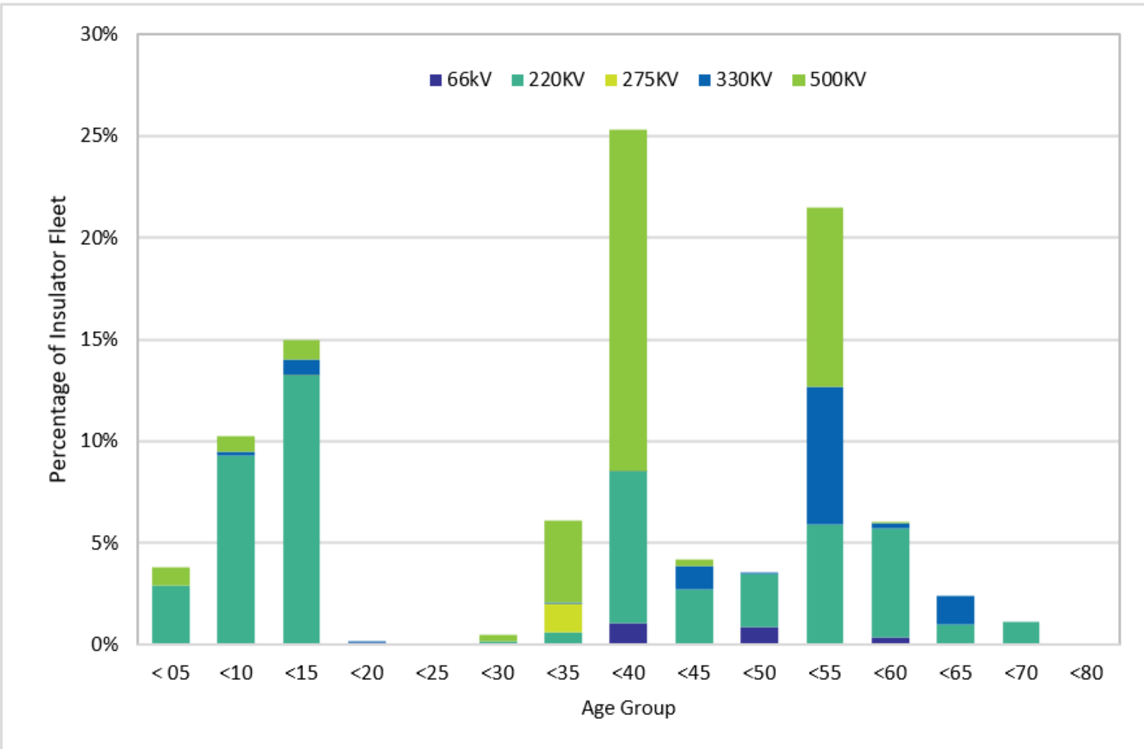

Figure 5: Transmission line insulators Age Profile by Voltage

[9] Note that AusNet Services' asset age data for insulators is based on the asset installation date, not the manufactured date.

Figure 6 shows the age of the transmission line insulator population by type, with the oldest transmission line insulators being either porcelain or glass type.

The majority of insulator strings with an age of 15 years or less are polymeric types, with new porcelain disc strings used only as bridging insulators on strain towers due to its weight, i.e. to keep bridging conductors from swinging too close to the structure during high winds.

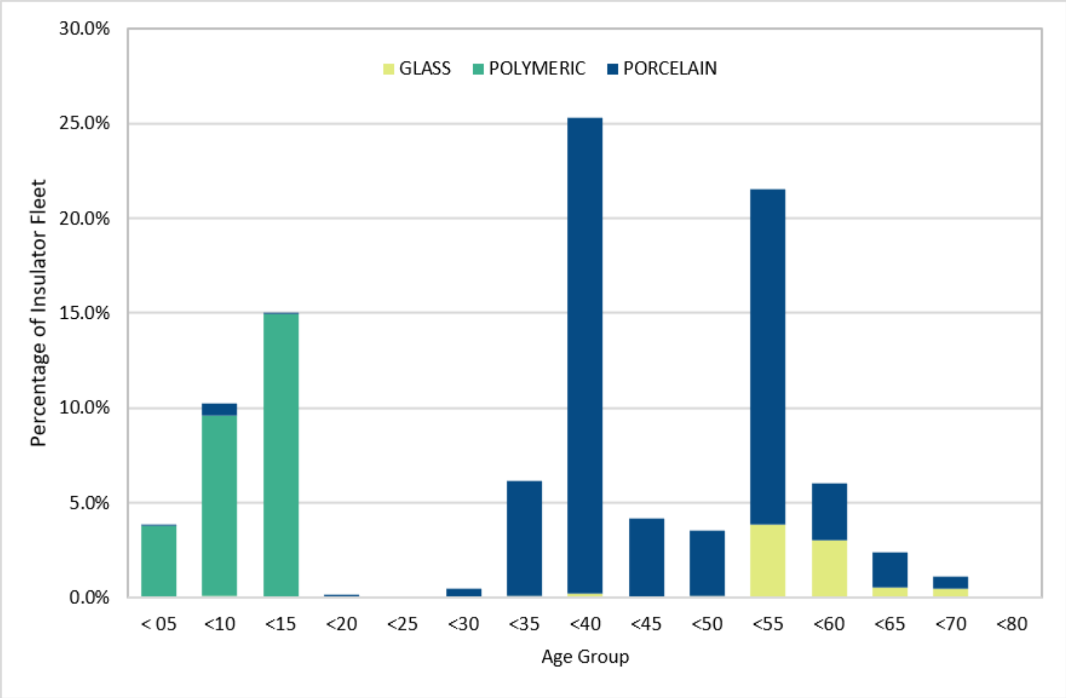

Figure 6: Insulator Service Age by type

3.4 Asset Condition

Condition of transmission line insulators is assessed during regular tower inspections. Insulators are assigned a condition grade from a scale between C1 (best) to C5 (worst) against two different grading parameters, fitting wear and pin corrosion. The worst condition from both parameters is then used as the overall condition grade for each insulator string.

The condition assessment criteria and what it represents is summarised in Table 4. More detail is described in LPP 09-06: *Condition Assessment of Overhead Lines*.

Table 4: Transmission line insulator condition grades and descriptions

Condition Scoring Methodology				
Condition Score	**Condition Description**	**Porcelain & Glass Disc**	**Polymeric Long Rod**	**Remaining Life**
C1	Very Good	As new. No issue identified.	As new. No issue identified.	95%
C2	Good	Glazing of disc dulled or gone	Minor discoloration on shed or sheath, First rust.	85%
C3	Average	First rust or first sign of wear	Moderate discolouration of sheds or sheath, Light rusting.	60%
C4	Poor	Light rust, or <10% wear	Minor flashover damage or Minor damage to sheds clear of sheath or Extensive blackening of sheds or sheath, Extensive surface rusting	25%
C5	Very Poor	Extensive surface rust or <20% wear or minor chips or minor flash/ arcing damage	Minor tracking damage to sheath, Sheds split or torn up to sheath, Pellets embedded in sheath Flashed with no evidence of damage to end seals Animal attack, <10% of sheds lost Flaking rust	15%

Figure 7 shows the condition of transmission line insulators by type. More than eighty percent of insulator strings in service on the transmission network exhibit minimal fitting wear or light levels of rust in line with condition grades C1 or C2.

A total of 2,289 insulator strings or 2.6 percent of the total insulator fleet currently belongs to C4 condition which exhibits light rust, or <10% wear. While 291 insulator strings, or 0.3 percent of the total transmission insulator fleet currently exhibits levels of fitting wear or pin corrosion in line with condition grade C5.

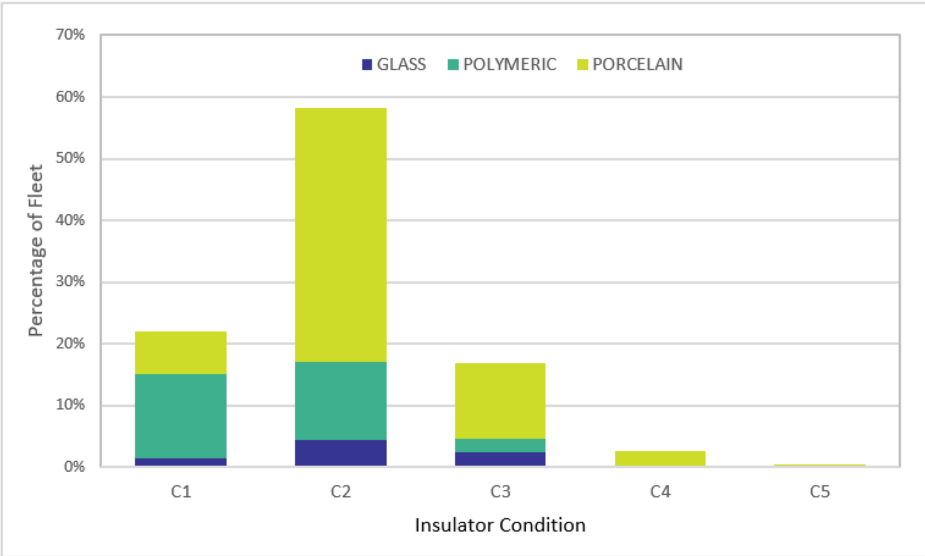

Figure 7 – Insulator condition by type

Figure 8 displays transmission line insulator condition by Corrosivity zones. Thirty-three percent of transmission line insulators which are currently assessed as condition grade C5 are situated in the low to moderate corrosivity zones, while the insulators situated along the severe environment (Corrosivity zone 3) either at C1 or C2 condition.

The insulators in Corrosivity zone 3 were recently replaced with polymeric insulators as these are more resistant to the marine environment. The strings in C1 condition, all located in HYTS-APD #2 circuit were replaced in December 2019 as the previous insulator strings, which were supplied from a particular manufacturer were inadequate for the aggressive environment at Portland, Victoria[10]. The C2 insulators which are installed on the HYTS-APD #1 circuit are from a different manufacturer and is approximately 12 years old.

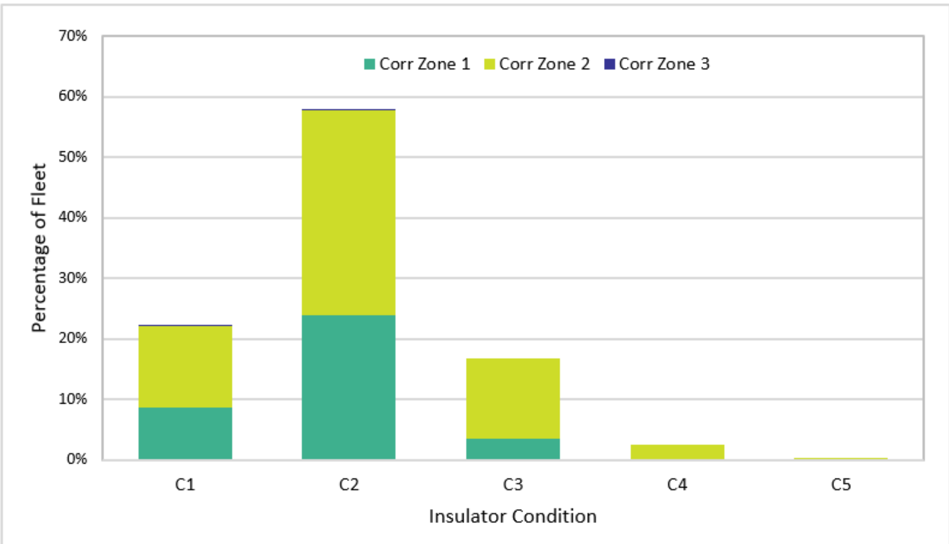

Figure 8 –Insulator condition by corrosivity zone

[10] The failure of a suspension string resulted in a conductor drop event, while the second failure was on a strain tower which fortunately did not result to a conductor drop event.

3.5 Asset Criticality

The consequence of failure of an insulator system is categorised into five bands based on its economic impact. These discrete groups called Asset Criticality Bands are independent of the insulator system's likelihood of failure.

The economic impact is calculated by assessing these components:

- Bushfire ignition
- Health and safety
- Value of unserved energy/ market impact
- Third party collateral damage

3.5.1 Bushfire ignition

Faults on transmission lines can result in explosive failures of insulators which are capable of igniting ground fires due to the expulsion of molten material.

Some transmission lines are situated in easements through high density fuel loads in grasslands and forests. In extreme weather conditions ground fires started close to such fuel loads can develop into widespread bushfires.

Bushfire loss consequence modelling performed by Dr Kevin Tolhurst[11] of Melbourne University has enabled the establishment of quantitative bushfire consequence values for transmission line assets. The bushfire loss consequence model demonstrates that a major insulator failure could trigger a bushfire incident with a maximum risk rating of B as per the AusNet Services risk matrix.

A map displaying the bushfire consequences associated with transmission line assets is included in Appendix C.

In 2007, a small grass was ignited following electrical failure of a porcelain insulator on the ROTS-SVTS No.2 line. A combination of pollution and morning fog on the insulator discs caused a flashover. The flashover caused a small amount of molten metal to fall to the ground resulting in a small grass fire. Moisture on the grass caused the fire to extinguish quickly.

The first incident involving a polymeric insulator occurred in 2017 when a Sediver insulator along the HYTS-APD No.2 500 kV line failed. A defect in the crimping process of the end-seals onto the fibre glass rod caused moisture ingress into the rod causing internal arcing until it failed which resulted for the phase conductor to drop across an arterial road. The conductor contacted a steel fence which caused a small grass fire. The fire was extinguished by the property owner.

3.5.2 Health and Safety Impact

Transmission line easements traverse both public and private land and in many instances, these are shared or located next to other infrastructure such as roads, railway lines, pipes and fences.

Major insulator failures can present health and safety risks to members of the public, AusNet Services' employees or AusNet Services' contractors accessing the transmission line easements. These risks are especially apparent on structures adjacent to roadways or railway lines, as well as areas with various easement use types.

Using the results of a study performed by Vic Roads[12] in 1994, a quantitative consequence assessment of transmission line spans which crosses roads and railways has been completed. The assessment has revealed that a major insulator failure could cause a health and safety incident with a maximum risk rating of B as per the AusNet Services risk matrix.

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[11] A Bushfire Risk Assessment for the AusNet Services HV Network in Victoria 2014.

[12] Bureau of Transport and Communications Economics (1994) The Costs of Road Accidents in Victoria – 1988.

Easement use types are categorised as urban, rural developed and rural undeveloped. Urban easement segments traverse over built-up private properties and on the other end of the spectrum, rural undeveloped easements are bare country properties. The health and safety consequence of an insulator failure resulting to a conductor drop has been calculated for each easement type.

The 2017 incident involving the Sediver insulator which resulted to a conductor drop was beside an arterial road. As the road is in a country area, there were no road users exposed to the hazards of a downed conductor during the time of the incident.

3.5.3 Unserved Energy / Market Impact

The electricity transmission lines forming the National Electricity Market have high levels of redundancy under average loading conditions. However, at peak loading periods, transmission line failures can constrain generator connections causing a re-scheduling of generators in other states and load shedding may be required to provide network security for a subsequent un-related failure.

The Australian Energy Market Operator (AEMO) conducts a study which identifies the amount customers are willing to pay to assure the reliability of their supply. This amount, called the Value of Customer Reliability (VCR), is used to monetise the consequence of the terminal station not being able to provide the load demand by the market, called the Value of Unserved Energy (VUE).

Another impact of lines becoming out of service is the need for AEMO to re-dispatch energy from a different generator (usually a gas generator) due to a line fault that either impacts the line directly, i.e. line is out of service so connected generator can't export energy to the market, or indirectly, i.e. the line outage constraints a certain part of the network so AEMO has to source power somewhere else to meet the load demand.

Major transmission line insulator failures result in system outages which negatively impact on performance levels within the incentive schemes. Impacts on the schemes are compounded when failures take place on radial lines. Financial penalties likely to be imposed can be calculated using guidelines set out by the Australian Energy Regulator (AER).

3.5.4 Collateral Damage to adjacent AusNet Services assets

The electricity transmission network was built in stages, using technical standards that were current on that period.

Over time built on improved knowledge and industry practice, technical standards are updated to become more appropriate to the weather events, e.g. wind and snow loads, as well as construction and maintenance loads structures and its components will support, e.g. out-of-balance loads, broken conductor loads, etc.

This situation means that assets built using older standards are more susceptible to fail in multiples, especially if these are connected in series, e.g. when a high wind event results to multiple collapsed towers.

The consequence of this event has been monetised by considering the design standards at the time of a particular asset's construction, and the potential damage inflicted on adjacent assets if it fails.

3.5.5 Collateral damage to Third Party property

Third party damage considers the consequence of an insulator failure resulting to a conductor drop. The consequence depends on the easement use which are categorised as urban, rural developed and rural undeveloped.

Urban easement segments traverse over built-up private properties and/or councils while on the other end of the spectrum, rural undeveloped easements are bare country properties. The damage to properties, e.g. fence, roof, shed, swimming pool, tennis courts, etc. owned by third parties have been calculated for individual spans and used in the analysis.

3.5.6 Overall Asset Criticality

The consequences of a major insulator failure can be allocated into five asset criticality bands based on their economic impact as the result of the failure. These asset criticalities, or consequence impacts, are irrespective of the likelihood of the actual failure.

The five asset criticality bands are shown in

Table 5.

Table 5: Asset Criticality Band

Asset Criticality Band	Economic Impact due to a failure
1	<= 0.3 replacement cost
2	0.3 to1 x replacement cost
3	1 to 3 x replacement cost
4	3 to10 x replacement cost
5	>10 x replacement cost

The asset criticality assessment compares calculated consequence cost with replacement cost. Table 8 presents the asset criticality matrix for the insulator fleet. The numbers indicate the quantity of insulator strings which are under a specific condition score and have a consequence of failure as indicated by Table 5.

3.6 Asset Performance

Asset performance of insulator systems involve the application of Failure Mode Effect and Criticality Analysis (FMECA) which aims to understand the various modes of failure of any component of the insulator system, its effect on the system's performance and the criticality of this component to the over-all system. FMECA is an integral part in developing processes and systems towards achieving Reliability Centred Maintenance (RCM) strategies.

3.6.1 Suspended failures

Suspended failures are defects that are detected and repaired as part of preventative maintenance tasks before they cause a functional (or physical) failure such as an outage and or conductor drop.

AusNet Services has adopted strict transmission line and easement inspection policies aimed at objectively assessing asset condition with a particular focus on assets which are not fit to remain in service.

Line insulators deemed not fit for service are replaced by raising ZA Notifications (i.e. condition-based work) in SAP, AusNet Services' Asset Management System. Line insulators replaced via ZA Notifications do not result to a transmission line functional failure and so are classified as suspended failures.

Over the last five years there have been a total of 2,181 suspended insulator failures identified. Most suspended failures were caused by:

- defective insulators[13] (28%)
- broken insulators[14] (24%), and
- pollution on the insulator string (26%).

Defective and broken insulators occur across all three types as they all have issues associated with the insulator itself or its hardware.

[13] Defective insulators include items such as missing, incorrect, obsolete, displaced and loose fittings or hardware.

[14] Broken insulators include items such as chewed, chipped, cracked, torn and broken string, fittings or hardware.

Pollution on the insulator string is caused by local environmental factors such as salt deposition from coastal areas, dust in dry open areas or soot emitted from vehicles on busy roadways. Suspended failures due to pollution can be minimised by washing insulators in exposed areas regularly.

A high volume of dirty[15] insulator strings were identified and washed in 2018, which increased the suspended insulator failures that year as illustrated in the following Figure 9. The increase was the result of the drought the previous two year which caused the vegetation along the easement to die and ground to dry out. The high and frequent winds in the South-West area of Victoria caused airborne dust to rise into the atmosphere and settle on the insulator discs of the HYTS-SESS 275 kV circuits.

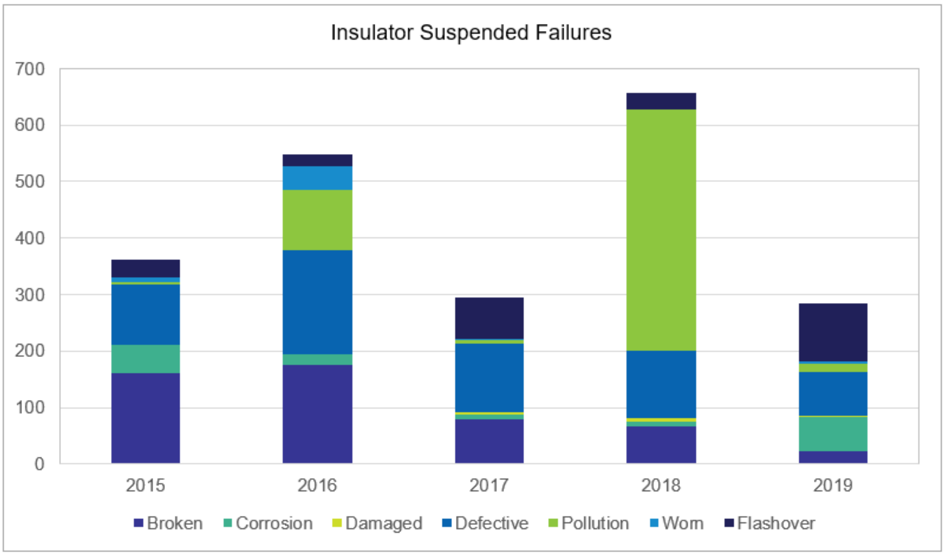

Figure 9: History of suspended insulator failures

3.6.2 Functional failures

A functional failure is a physical failure of an insulator string assembly resulting in either an outage or conductor drop.

Functional failures can be grouped into the following categories:

1. Electrical
2. Mechanical
3. Aggressive environments, and
4. Manufacturing defect.

Electrical failure of porcelain or glass insulator may be due to cracking which creates a path for current to flow through the insulator body or by pollution deposits allowing current to track across the surface of the insulator.

The mechanical failure mechanism for porcelain or glass insulators is physical separation caused by a combination of insulator pin corrosion, fitting wear and metal fatigue of the insulator pin.

Mechanical failure of polymer insulator may be due to birds chewing the sheds.

Aggressive environments can degrade the rubber sheath of a polymeric insulator which allows moisture to enter the core of the string, causing internal arcing to occur in the fibre glass rod until it suffers brittle failure.

Manufacturing defects may leave an unwanted gap between the core and sheath material, or introduce a crack on the rod during crimping of the end seals which may allow moisture to reach the core which causes arcing to degrade the fibre glass rod until it fails.

[15] Dirty or polluted insulator discs provide a conductive path which can lead to flashovers between phase conductors and structures. Flashover events can result in conductor drops, like the 2007 insulator incident.

There have been 19 incidents of insulator functional failure over a period of 36 years as shown by Table 6 with the details of the failure events, while **Figure 10** displays the percentage split of total transmission line insulator failure modes.

Table 7: Insulator Failure Details

Line Name	Failure Mode	Failure Mechanism	Insulator Type	Year Failed	Age at Failure (Yrs.)
EPS-TTS 220 kV	Mechanical	Hook fatigue	Glass	1984	29
YPS-ROTS 5 220 kV	Mechanical	Pin fatigue	Glass	1993	37
BATS-BETS 220 kV	Mechanical	Pin fatigue	Glass	1999	37
KTS-WMTS 1 220kV	Manuf. defect	Defective shackle	Porcelain	2001	37
KTS-GTS 1 220KV	Mechanical	Pin fatigue	Glass	2003	39
KTS-WMTS 2 220kV	Electrical	Puncture	Porcelain	2003	39
MBTS-EPS 1 220kV	Mechanical	Hook fatigue	Glass	2004	44
MLTS-TGTS 220kV	Manuf. defect	Fatigue	Glass	2004	47
HWPS-ROTS 1 220kV	Mechanical	Pin fatigue	Glass	2005	39
YPS-ROTS 7 220 kV	Manuf. defect	Defective LL link	Glass	2005	49
ROTS-SVTS 2 220kV	Electrical	Puncture	Porcelain	2007	43
KTS-BLTS 220kV	Electrical	Puncture	Porcelain	2007	38
HWPS-ROTS 1 220kV	Mechanical	Pin fatigue	Glass	2008	42
BATS-BETS 220 kV	Mechanical	Clamp failure	Porcelain	2009	47
CBTS-FTS 1 66kV	Electrical	Flat	Porcelain	2012	44
YPS-ROTS 8 220kV	Mechanical	Bridge Clamp failure	Glass	2013	48
HYTS-APD 2 500KV	Manuf. defect	Erosion of fibre glass rod	Polymeric	2017	9
HYTS-APD 2 500KV	Environmental	Erosion of fibre glass rod	Polymeric	2019	10
YPS-YWPS A 220KV	Mechanical	Bridge Clamp failure	Porcelain	2020	50

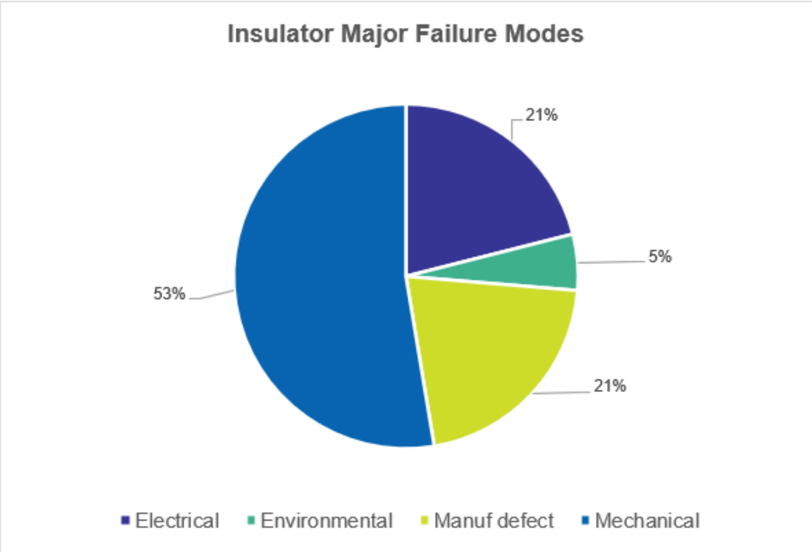

Figure 10: Transmission line insulator failure modes

Among the failure events 10 involved glass insulators, 7 have been from the porcelain cohort and 2 came from the polymeric cohort.

Seventeen of the 19-insulator functional failures occurred on insulators aged between 28 and 50 years, while two failures which belong to the polymeric cohort failed after a decade of service life in the aggressive (marine) environment.[16]

The mean service age at the time of failure for transmission line insulators made from either glass or porcelain discs is 42 years, while the polymeric strings have a mean age of 10 years. Figure 11 shows the distribution of insulator ages at time of failure, as well as the insulator type.

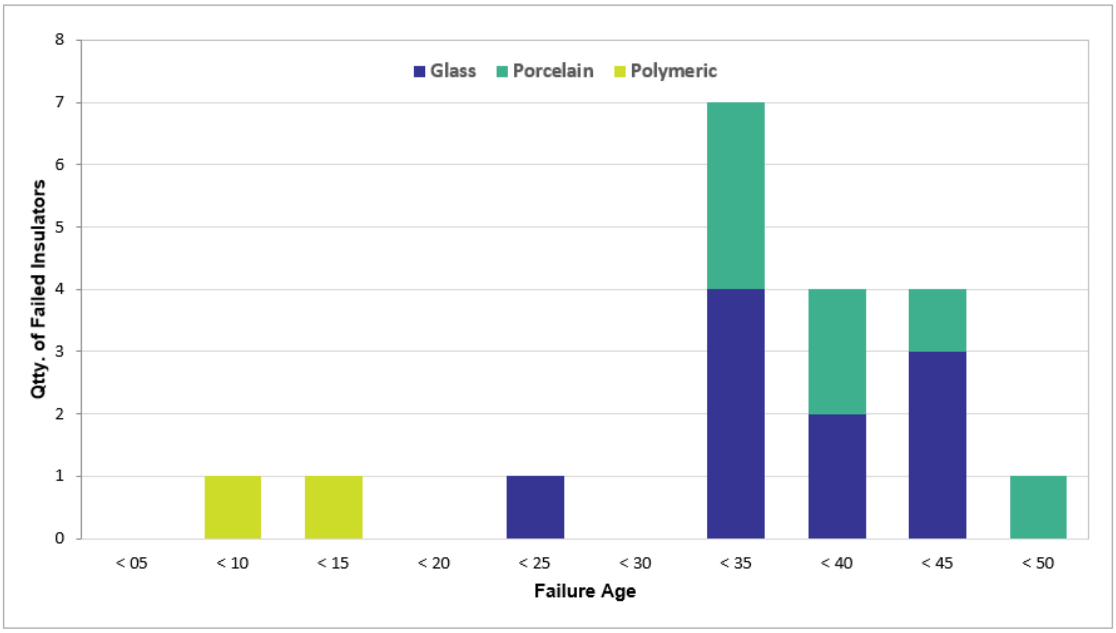

Figure 11: Transmission line insulator age at time of failure

[16] The Sediver polymeric insulators were analysed and determined to be inappropriate for the aggressive environment at Portland – these were replaced with NGK insulators.

3.6.3 Condition Replacements

In 2006, an insulator replacement program was introduced after several insulator failures resulted in conductor drop events.

Investigations on the failed discs indicated that the cohort of disc strings with 16 mm diameter pins, the first type of insulators the State Electricity Commission of Victoria (SECV) used when they built the 220 kV transmission network in the late 1950s to early 1960s, had started to reach their end of life.

The business determined that the risk of failure was beyond its risk appetite and so a program to replace insulators which have the highest risk of failure in the fleet was initiated.

The first insulator replacement program targeted strings that have meet the following criteria:

- Insulator disc has 16 mm diameter steel pin
- Disc string has been given a condition rating of C5, and
- The insulator supports a span that crosses a major road, i.e. freeway or highways.

Successive replacement programs have continued to target the worst condition insulators in the fleet with the highest consequence of failure. For all replacement works, the hardware and fittings used in the insulator string were also replaced so upon completion of the work, the tower has a modern insulator assembly.

Majority of the replacement works introduced polymeric insulators to the tower with the only exception being the bridging insulators used in strain towers. The weight of disc string insulators is required for this application to support and stabilise the bridging conductor from swinging too much during high winds.

Figure 12 shows the cumulative percentage of replaced insulator strings over the number of failures. There is an approved project (TD-4197) to replace 1,940 insulator strings on various transmission lines over two financial years from 2017/18 to 2020/21.

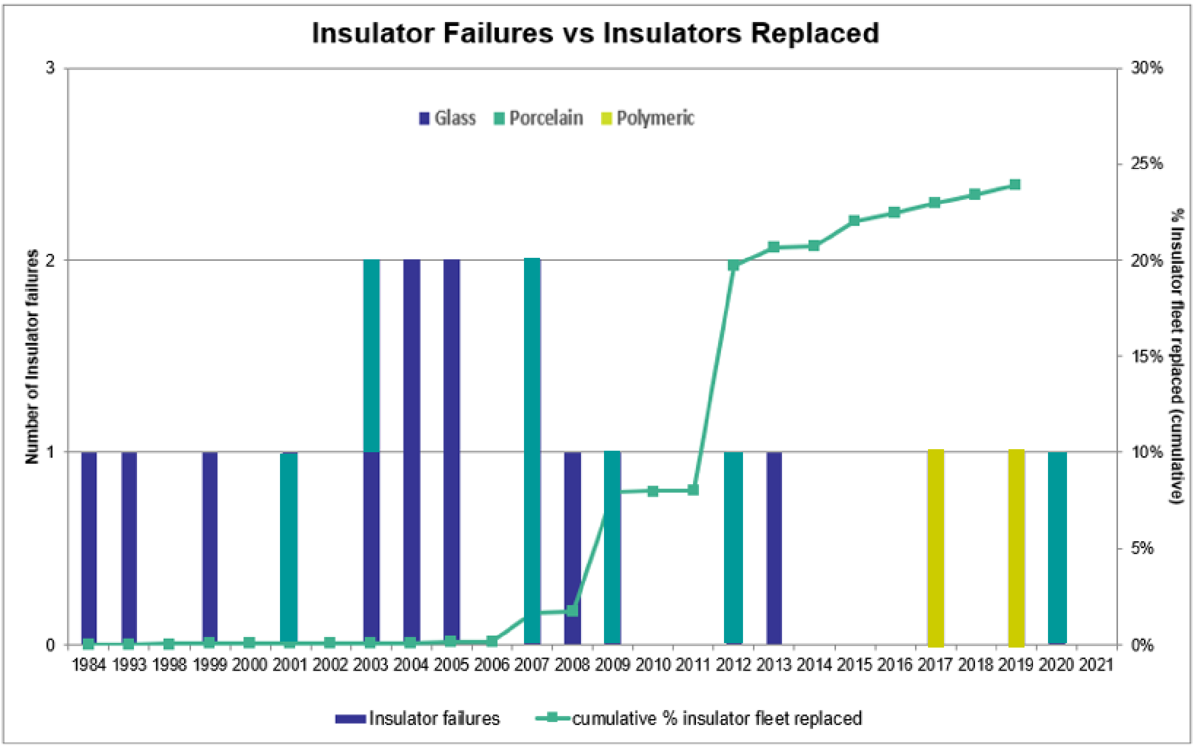

Figure 12: Insulator Failures versus Insulators Replaced

4 Other Issues

The key issues associated with the transmission line insulator fleet are as follows:

- Research to develop cost-effective techniques for assessing the condition and the remaining expected service life of polymeric insulators is ongoing.
- The performance and remaining service potential of polymeric insulators which have been subjected to extreme heat from bushfires need verification by sampling and testing.
- Polymeric insulators which have suffered flash-over damage along mountainous areas where there is high lightning activity are often left undetected due to a combination of ineffective Protection fault location and visual identification.
- New and reliable techniques to determine the dielectric performance of polymeric insulators which had suffered from flashover damage are required to ensure the safety of line workers prior to doing live-line replacement of the string.
- Recent failures of polymeric strings along one of the 500 kV lines at Portland, Victoria demonstrated that not all brands are effective in corrosive environment. This event highlighted the probable need to review the insulator specification to assure similar failures are avoided.

5 Risk Assessment

This section discusses risk assessment relating to the insulator fleet. Quantitative analysis was done to determine the criticality band for each insulator string, then optimisation was undertaken to identity the strings that provide the highest benefit to the business in terms of reducing failure risk costs, while considering the cost of replacement.

5.1 Overview

The Risk Matrix, or Consequence/Likelihood Matrix, methodology is a semi-quantitative analysis using numerical, ordinal or interval scales to rate the consequence and/or likelihood of an event occurring. This type of risk analysis is used to assess overall network risks and specific high-level risks, such as bushfire ignition, health and safety, market impact/value of unserved energy, and collateral damage.

This process brings together asset condition data, asset failure rates and the cost impact of asset failure to determine an economically justifiable level of replacement. This section summarises the reliability modelling of insulator fleet.

Key inputs to this process are as follows:

- asset condition
- remaining service potential (RSP %)
- failure rate and
- failure effects[17].

Insulators situated in the “severe” corrosivity zones have considerably shorter lifecycles when compared to assets in the “moderate” and “low” corrosivity zones.

AMS 01-09 *Asset Risk Assessment Overview* provides more detail in the Consequence/Likelihood Matrix.

5.2 Risk Assessment Methodology

The Risk Matrix analysis was performed. As mentioned in Section 5.1, the following inputs were developed and used in the analysis:

- Insulator condition – based on a scale of 5-point rating where C1 is the “Best Condition” to C5 which is the “Worst Condition”, as per Section 3.4
- Operating environment classification – using three corrosivity zones, as per Section 3.2.1
- Expected life of insulator in operating environment – this is based from experience in operating the transmission network, as well as industry knowledge and bodies of research. A good indication of expected service life for a type of insulator (i.e. glass, porcelain and polymeric) is by looking at the fleet’s service age (Figure 6) and the failure age (Figure 11).
- Characteristic age and remaining service potential calibration – this is derived from the analysis of asset condition versus remaining service potential, to calculate the instantaneous hazard rate for insulators in each condition cohort and comparing the ‘expected failures’ to actual and suspended failures
    - The insulator age (in hours) at the time of functional failure is entered in the program
    - Insulators that are replaced are represented in the analysis by entering its are (in hours) during the time of replacement. These assets are identified as being “suspended failures”
    - The program is made to execute its analysis and the Beta and Eta values are provided

[17] Effect costs were calculated against each of the possible failure effects discussed in section 3.5 including bushfire ignition, health and safety, value of unserved energy and collateral damage. The total failure effect cost for each asset was taken as the sum of all failure effects

- Weibull parameter calibration is achieved by:
  - Calibrate Eta and Beta to arrive at similar number of failures[18] as experienced in practice.
  - All calculations were made using the actual insulator population for each condition score bracket and separately for each corrosivity area.
- The criticality score is assigned to each insulator equipment by adding all the consequences of an insulator failure, then dividing the value by the replacement cost of an insulator equipment, and then grouping this into criticality bands as per Table 5 in Section 3.5.

5.2.1 Insulator Risk Matrix

The risk matrix is presented in Table 8 below. The matrix has considered the on-going insulator replacement project that will be completed as planned by 2021/22 which will have 1,940 insulators changed to C1 condition.

The risk matrix shows that majority of the insulator fleet is in the medium risk levels: 1,533 strings (1.7% of the insulator fleet) are in the Risk Level A; 44,874 strings (50.5%) in Risk Level B ; 40,230 strings (45.3%) in Risk Level C; and 2,214 strings (2.5%) in lowest risk band, Risk Level D

.

Table 8: Insulator risk matrix

	CONDITION					
Criticality	**C1**	**C2**	**C3**	**C4**	**C5**	Grand Total
5	7,107	14,397	4,758	**417**	**75**	26,754
4	4,491	9,807	3,306	**825**	**45**	18,474
3	6,933	16,131	4,518	909	**129**	28,620
2	918	10,869	1,506	72	**-**	13,365
1	153	1,143	234	66	**42**	1,638
Grand Total	19,602	52,347	14,322	2,289	291	88,851

5.2.1 Quantitative Risk Assessment

Using the failure probabilities for each insulator under a specific condition (C1 to C5), which is located at a particular corrosivity zone (Corrosivity 1 to Corrosivity 3), quantitative analysis was undertaken to identify the optimal option for each insulator (i.e. maximum reduction in risk costs): a) Do Nothing and undertake reactive replacement; or b) Replace insulator during the 2022-27 TRR Period.

From the analysis, 2,268 insulator strings were identified to be replaced during the TRR Period 2022-27 which provides the maximum benefit to the business. This cohort includes strings which currently have a C5 condition and strings which are in C4 condition, located in Corrosivity 2 environment and in high-risk sites or lines.

5.3 Proposed Program of Works

The proposed program of works recommends selective replacement of 2,268 insulator strings (approximately 2.6% of the entire fleet) mainly in Condition 4 and Condition 5 over the five-year period, FY22 to FY27.

Those insulators located on spans which crosses roads and railway lines, urban areas, carry energy from generators to node centres and/or inter-state, become economic for replacement once they exhibit flaky rust (i.e. C4 condition). Other insulators which are situated in areas of lower consequence become economic for replacement when they start to show signs of heavy flaky rust (i.e. C5 condition).

[18] Failures include both suspended and actual failures.

This quantity represents all C5 insulators and the quantities in the red and some strings in the brown band in C3 and C4 condition as shown in Table 8. Insulators proposed for replacement have a Benefit / Cost ratio of at least 2. The number of strings to be replaced excludes the planned replacement of 1,940 insulator strings by 2021/22 under the approved project, TD-4197.

The replacement program for the top 13 circuits by volume, approximately 85% of the insulators proposed for replacement, is shown in Table 9 below. The full program is shown in Appendix D.

Table 9: Proposed Program of Works- top 15 circuits

Circuit Name	220KV	500KV	66kV	Grand Total
MOPS-HYTS 2		624		624
MWTS-LY 1			486	486
TRTS-HYTS 1		174		174
MLTS-TRTS 1		171		171
DPTS-GTS 2	147			147
KTS -WMTS 1	63			63
HWTS-SMTS 2		48		48
ERTS-ROTS 1	42			42
HYTS-APD 1		42		42
HYTS-APD 2		42		42
MLTS-MOPS 2		42		42
LYPS-HWTS 2		30		30
HWTS-SMTS 1		30		30

6 Asset Strategies

6.1 New Assets

- Current policy is to install polymeric insulators as part of insulator replacement programs.
- Polymeric insulators have been known to be attacked by birds if strung under de-energized conditions. Provision will be made to prevent bird attack during project implementation planning.
- Fail-safe design concepts to be applied for insulation systems on new replacement of transmission line structures adjacent to high risk roadways and railways or proof test all insulator fittings prior to installation on towers across roads and railways.
- Recent failures including manifestation of high temperatures inside polymeric insulators caused by moisture ingress into the silicone rubber sheath has pointed to the need for more stringent selection of suppliers[19], and/or purchasing products from suppliers with good track records.

6.2 Inspection

- Continue to assess the condition of transmission line insulators during structure climbing inspections conducted at regular intervals and during the annual line and easement inspections.
- Develop policies for inspection, maintenance and ultimate replacement of polymeric insulators considering expected service life.
- Explore the compatibility of existing technologies such as Remotely Piloted Aerial System (RPAS also known as drones) to conduct visual, thermal and corona inspection of insulators.
- Enhance the current use of Smart Aerial Inspection and Processing (SAIP) technology to identify defective insulators.
- Reiterate the import of all relevant technical asset data including date of installation into SAP as part of project close-out for insulator replacement projects.
- Continue to use Field Mobile Inspection (FMI) system as the primary means of capturing condition assessment data and include the asset information, i.e. type of insulator and manufacturer, as part of the data capture process.

6.3 Maintenance

- Replace defective insulator strings as part of corrective maintenance tasks. Complete string replacement is preferred as it is more economic and safer than replacement of an insulator from within a string of insulators.
- Update SAP with the details of the new insulator installed on the tower as part of the close-out process of maintenance activities.

6.4 Replacement

- Selectively replace 2,268 strings which are in high consequence areas and in very poor condition between 2022 to 2027. This quantity represents 2.6% of the insulator fleet.

[19] A methodology, based from an international procedure, is being created to test samples collected from the line that had failures. The objective is to confirm if the failures may be connected to the manufacturing process of the insulator, i.e. improper bonding between silicone rubber sheath and fibre glass rod.

Appendix A Acronyms

AER	Australian Energy Regulator
EDPM	Ethylene Propylene Diene Monomer
FMECA	Failure Mode, Effect and Criticality Analysis
FMI	Field Mobile Inspection
MIC	Market Impact Component (of STPIS)
MTBF	Mean Time Between Failures
NCC	Network Capability Component (of STPIS)
NEM	National Electricity Market
RCM	Reliability Centred Maintenance
RPAS	Remotely Piloted Aerial Systems
SAIP	Smart Aerial Inspection and Processing
SAP	AusNet Services' Asset Management Information System
SC	Service Component (of STPIS)
SECV	State Electricity Commission of Victoria
STPIS	Service Target Performance Incentive Scheme
TNSP	Transmission Network Service Provider
TRR	Transmission Revenue Reset

Appendix B Corrosivity Zones on the Victorian Transmission Network

[C-I-C]

Appendix C Bushfire Consequences on the Victorian Transmission Network

[C-I-C]

Appendix D Proposed Insulator Replacement Program

Circuit Name	220KV	500KV	275KV	330KV	66kV	Grand Total
MOPS-HYTS 2		624				624
MWTS-LY 1					486	486
TRTS-HYTS 1		174				174
MLTS-TRTS 1		171				171
DPTS-GTS 2	147					147
KTS -WMTS 1	63					63
HWTS-SMTS 2		48				48
ERTS-ROTS 1	42					42
HYTS-APD 1		42				42
HYTS-APD 2		42				42
MLTS-MOPS 2		42				42
LYPS-HWTS 2		30				30
HWTS-SMTS 1		30				30
HWTS-ROTS 3R		30				30
CBTS-FTS 1					30	30
ROTS-TTS	24					24
SMTS-TTS 1	24					24
HWPS-HWTS 2	18					18
HWPS-YPS 2	18					18
NPSD-BLTS	18					18
CBTS-LYD-ERTS					18	18
FBTS-BLTS	15					15
HWPS-HWTS 4	15					15
KTS -WMTS 2	15					15

HWPS-HWTS 3	12					12
MSS -DDTS 1				12		12
YPS -ROTS 7	9					9
YPS -ROTS 8	9					9
CBTS-TBTS 2	6					6
HWPS-ROTS 1	6					6
DDTS-SMTS 2				6		6
HOTS-RCTS	**6**					6
MWTS-LY 3					6	6
YPS -ROTS 6	3					3
HYTS-SESS 2			3			3
KTS -GTS 1	3					3
HWPS-ROTS 2	3					3
HWPS-JLTS 4	3					3
TBTS-JLA 1	3					3
KTS -GTS 3	3					3
CBTS-TBTS 1	3					3
KGTS-WETS	3					3
HWPS-JLTS 3	3					3
ROTS-SVTS 2	3					3
SVTS-HTS 2	3					3
RWTS-TTS R	3					3
DDTS-SHTS	3					3
Grand Total	**474**	**1233**	**3**	**18**	**540**	**2,268**