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TURBINE MISSILE IMPACT ASSESSMENT OF SAFETY RELATED NUCLEAR STRUCTURES

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ABSTRACT

This paper provides description of the overall safety assessment process of the nuclear structures of a generic NPP subjected to turbine missile impact. The relevant turbine failure modes is defined and failure probabilities is performed based on the relevant good practices (RGP), followed by defining the generic turbine missiles considering possible failure modes. Then, missile impact trajectory is determined considering the missile ejection angle, ejection velocity and the distance between the turbine and the target structures subject to the assessment. Finally, finite element analysis based on the missile target interaction procedure is assessed.

INTRODUCTION

Nuclear power plants contain pressurised components and rotating machinery (e.g. turbine-generators, diesel generators, pumps, fans, blowers, compressors) that can fail disruptively and cause missiles with destructive kinetic energy for the surrounding SSCs. There are historical examples showing that fragments of different sizes and shapes can be ejected in the event of the failure of rotating equipment. Stress concentrations, structural discontinuities, defects in materials and other factors can all affect the failure process and influence the type of fragments formed.

A turbine disintegration is a catastrophic event that could generate missiles of different type however, due to the weight, rotational velocity and kinetic energy, the turbine rotor disc fragments generated during an overspeed event are taken as the bounding case for these potential missiles. It is the last stage of a turbine moving parts that are most at risk from failure during turbine operation. Low pressure turbine discs are the critical component in any steam/gas turbines and corrosion fatigue has caused most of the damage in that part of the turbine. In terms of the overspeed scenario, the low pressure cylinder last stage disks/blades are longest and massive and therefore at most risk from tensile failure in an overspeed event. This paper provides description of the overall safety assessment process of the nuclear structures of a generic NPP subjected to turbine missiles impact.

STUDY OF RELEVANT GOOD PRACTICE

Nuclear power plants contain large items of equipment that have parts that rotate at high speed during operation, such as the steam turbines. These rotating parts can attain a considerable energy of rotation, which in the event of their failure can be converted into translational kinetic energy and become missiles.

Since rotating machinery usually has a heavy stationary structure surrounding the rotating parts, consideration is given to the energy loss after failure due to the energy absorbing characteristics of the stationary parts (e.g. static casing). Energy loss in the penetration of such structures is invariably a complex process, owing to the configuration of the structure and the characteristics of the missiles. To the extent practicable the calculation of the energy losses should be based on empirical relationships developed in tests of similar, carefully defined structures.

Advances in the design of steam turbines have improved the reliability and availability, which has been based on a large amount of learning from experience. Some of this learning from experience has been as the result of several failure events. There have been numerous causes of steam turbine failures worldwide. The highest frequency events have been loss of lube oil incidents while the highest severity events have been overspeed events. Typically, higher frequency and higher severity events have been blade/bucket failures, particularly in the low pressure (LP) section of the turbine where the blading experienced a number of failure mechanisms (stress corrosion cracking (SCC), erosion, foreign object damage (FOD)) which ultimately lead to failure.

The most destructive event for a steam turbine is an overspeed event, as the steam turbine and its driven equipment are usually catastrophically damaged. These events, while infrequent, continue to occur on both small and larger steam turbines regardless of the vintage, technology level, application, or type of control system (digital, analogue, hydro-mechanical, mechanical) associated with the steam turbine, requiring design and operational provisions to be made.

The table below contains a list of relevant steam turbine failures events that have progressed the understanding of the accident fault sequence. The documentation referenced provides analysis of the root causes of each accident, providing useful learning from experience and informing the RGP.

Table 1 Significant Steam Turbine Failures

Date	**Location**	**Event**	**Root Cause**
1969	Hinkley Point A, UK	Catastrophic failure of LP Turbine due to stress-corrosion cracking.	The principal cause of the failure was determined to be intergranular stress corrosion cracking of a low pressure disk in the areas of the keyways, attributed to a concentration of NaOH in the keyways combined with a low fracture toughness of the steel caused by temper embrittling during manufacture [1]
14 Feb, 1980	Yankee Row, USA	Catastrophic failure of LP Turbine due to stress-corrosion cracking.	Two discs in the LP turbine failed catastrophically, one of them due to stress corrosion cracking and the other due to impact from fragments. The turbine housing and stator were not breached [2]
9 Nov 1991	Salem-2,	Catastrophic failure of LP Turbine due to overspeed event.	Failure of turbine overspeed protection due to incorrect maintenance. During a subsequent test the turbine generator overspeed to an estimated 2900 rpm (about 60 percent above the design of 1800 rpm). The shaft vibrated severely and

Date	Location	Event	Root Cause
			turbine missiles (blading) penetrated the 1-1/4-inch-thick carbon steel casing on either side. High shaft vibration caused hydrogen seal failure and a subsequent explosion and fire. [2]
31 Mar 1993	Bulandshahr, Uttar Pradesh, India	The Narora Atomic Power Station suffers a fire at two of its steam turbine blades, damaging the heavy water reactor and almost leading to a meltdown	Rupture of two LP turbine blades due to the accumulation of stress on the blades, which snapped the other sixteen blades, changing angular momentum, inducing vibrations in the turbine blades. This vibration caused a hydrogen gas leak and ruptured lube oil tanks, which ignited and caused the fire. [3]
January 15, 2003	Bridgman, Michigan, USA	A fault in the main transformer at the Donald C. Cook nuclear power plant causes a fire that damages the main generator and back-up turbines	The loss of 5 L-0 blades due to high-cycle fatigue created a severe unbalance condition on the rotor with high vibration causing extensive damage to connected systems. This vibration caused a hydrogen seal failure and subsequent fire damage to main generator/exciter housing. All blades were contained within turbine casing.[4]

TURBINE MISSILE DATA USED IN PREVIOUS REGULATORY ASSESSMENTS

In order to build a picture and draw comparisons with the approaches used in previous regulatory assessments, the following table provides a selection of missile characteristics assumed, focusing specifically on the Generic Design Assessment (GDA) in the UK. A further comparison is shown here, for the 1GWe Westinghouse PWR Indian Point 3 in Buchanan, New York, USA, which suffered a blade failure in 1981.

Table 2 Turbine Missile Data used in Previous GDAs

Reactor	Turbine Type	Operating Speed	Blade Length	Missile Mass Assumed in Assessment
UK EPR	ARABELLE 1700	1500 rpm	LP Stage 69”	Not available [5]
UK ABWR	Hitachi TC6F-54	1500 rpm	LP Stage 54” [6]	4000kg [7]
UK AP1000	Toshiba	1500 rpm [8]	LP Stage 52”	2840kg [8]
Indian Point 3 (non-GDA Reference)	Westinghouse	1800 rpm	LP Stage 44”	Up to 5000lbs (2272kg) [9]

In the UK, ONR Guidance on Internal Hazards - NS-TAST-GD-014 [10] has been recently updated (2019) to include the learning from the GDA programme with UK EPR, UK ABWR and

UK AP1000 turbine assessments, as discussed above, having successfully passed GDA. The guidance refers to RG1.115 as RGP and refers to the failure rate of turbines (10^{-4}) from RG1.15 and the low trajectory criteria for missile ejection within 25^{o} of the plane of rotation. From this, it should be noted that some issues have been passed to the site-specific phase; namely, the potential for turbine missile strikes from adjacent plant.

TURBINE FAILURE MODES AND FAILURE PROBABILITIES

The approach for determining the failure modes for the Generic Turbine is based on US NRC RG 1.115 [11] as well as various studies of the failure modes of the main turbine-generator sets and even aero engine studies. For every missile, two postulated trajectories are considered: low and high. Missiles ejected from the turbine at low and high trajectories are considered along with the likely maximum distance of travel. When considering the range of postulated ejection angles, missiles and distances under the low and high-trajectory cases, this determines the NPP target buildings for consideration in the safety analysis.

The probability of the Generic Turbine failure is evaluated, based on an established methodology that uses operating experience feedback (US NRC RG 1.115 [10]) and looks at both design and overspeed probabilities together with the frequency of initiating events that can lead to these conditions. Conservatively assuming a failure in the turbine, the next step is to examine what happens in the unlikely case of turbine failure, concentrating on the failure modes and the postulated missile characteristics. Unacceptable failure rates of mostly blades and rotor discs in the early use of turbines (for fossil fuel plants, aero engines and in nuclear power) led to numerous projects to investigate the problems.

The common failure modes of turbines are provided to establish the most likely method of failure. Next, the missile characteristics are discussed to generate the bounding missile type used for the deterministic analysis, along with consideration of the missile ejection angles from the Turbine. Finally, results are summarised and used to identify Target Buildings for further assessment.

There are historical examples that show that fragments of many sizes and shapes can be ejected in the event of the failure of rotating equipment. Test data indicate that for a simple geometry such as a disk, the failure process tends to result in roughly equal disk fragments being ejected. However, stress concentrations, structural discontinuities, defects in materials and other factors can all affect the failure process and influence the type of fragments formed. Bhagi and Vikas work [12] provides a review of investigations and analysis of turbine failure modes. It has been found that Low-Pressure (LP) blades of a steam turbine are generally more susceptible to failure than Intermediate Pressure (IP) and High Pressure (HP) blades [13]. The most common failure mechanisms which occur are corrosion fatigue, Stress Corrosion Cracking (SCC), pitting and erosion-corrosion in steam turbines [14].

A common failure mode for turbines is a high cycle of fatigue of compressor and turbine blades due to high dynamic stress caused by blade vibration and resonance within the operating range of machinery [15]. However, the factors which significantly influence the blade lifetime are corrosion, fretting fatigue, fatigue creep and revolution/rotating speed.

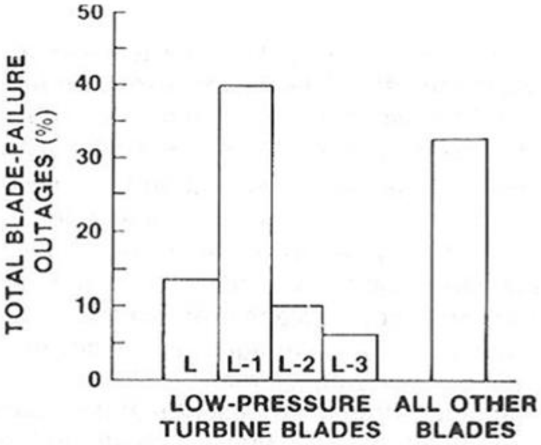

Figure 1: Distribution of blade failure outages in US fossil turbines

GENERIC TURBINE MISSILES AND TRAJECTORIES

There has been extensive analysis and testing on the subject of turbine failure modes by industry bodies, scientific communities and nuclear power operators (e.g. [9], [16] [12], [17] and [18]) which has been taken into account. The conservation of energy from angular to kinetic is key to understanding the damage potential for the missile. In relation to the fragment size, the relative fragment energy for a third-disk segment corresponds to the maximum available energy for the missile fragment. Hence, it is conservatively assumed that a third-disk fragment from the final LP stage is ejected as a missile following the turbine failure.

For the effects of turbine blades, it is usual and realistic to assume that the rotor disk blades are destroyed in the ejection of the disk from the casing. This is conservative given the impact resistance of the blades and the results seen in tests and turbine failures [17]. Turbine disintegration is a catastrophic event. Due to the momentum of the rotating turbine shaft, losing just one turbine rotor disk will considerably change the rotational speed of the shaft and the rotation axis. Nevertheless, it is assumed that more than one missile is released from the postulated turbine failure.

To propose the number of rotor disk missiles generated it is necessary to consider the following:

- All turbine rotors (HP and LP stages) will be rotating at the same speed.
- HP casings are thicker due to the pressure differences of the steam and not considered.
- Inner disks of each stage may only be ejected within +/-5° normal to the turbine axis or else they collide with other rotor disks [9];
- End disks of each stage may be ejected within -5 to +25° of the normal to the turbine axis [9];

To assume that all the missile fragments per disk can be ejected in the same direction is overly conservative – because of the angular velocity, missiles are ejected on effectively opposite sides of the plane of rotation. Furthermore, missiles ejected downwards will lose kinetic energy on impacts/deflections with the ground. Nevertheless, each missile ejected is treated as independent from the point of view of the probability of impact onto the target, so it is assumed that all three fragments from each end disk of each LP stage can become missiles. Therefore, the total number of ejected missiles from the Generic Turbine destructive event is 12 for a 1/3 disk fragmentation (16 for a ¼ disk fragmentation).

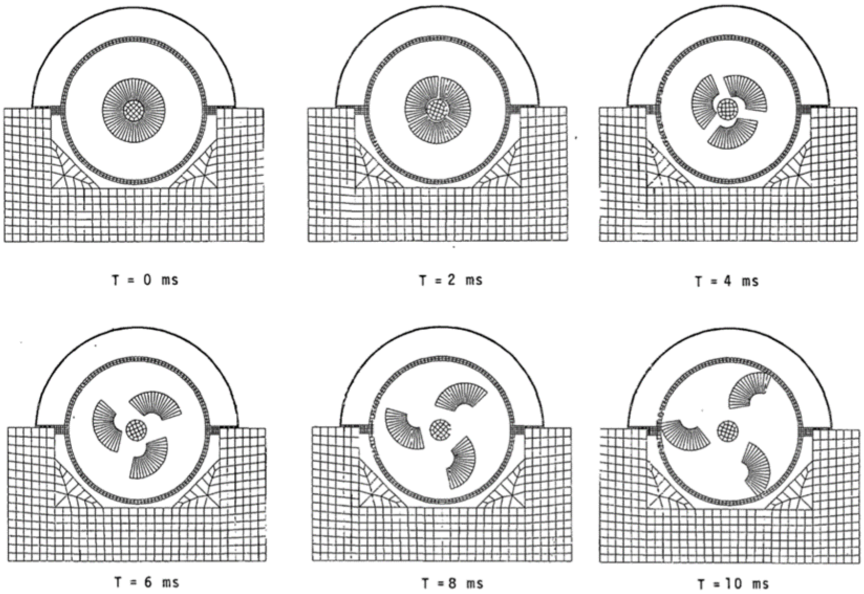

Figure 2: Turbine Disk Failure Sketch (Blades not Shown)

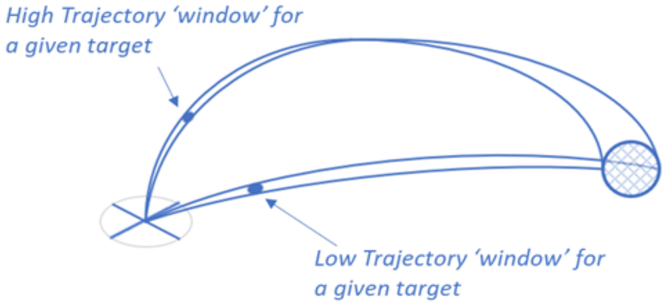

Figure 3: Two Missile Trajectories Postulated from Turbine Failure

STRUCTURAL ANALYSIS

This section includes description of the structural impact analyses of the generic turbine missile into the structures within the scope of protection. The ejected missile represents 1/4 disk fragment (without the shaft). The impact is assumed to happen along high trajectory with impact speed equal to the ejection speed. The air drag (i.e. the air resistance while the missile is flying to the target) is neglected and the impact velocity is assumed to be same as the ejection velocity. Since the air drag leads to reduction of the missile velocity, the outcome of the structural assessment may be considered slightly conservative. The structural assessment is done by the missile-target interaction method, i.e. impact simulation of the model of the missile into the model of the target and the contact between them.

The case study consists of impact into two structures with different geometric shape:

- Building I (Typical spend fuel building, roof). The impact into the Building I is considered to be satisfactory provided there is no perforation and no scabbing of the roof slab is observed.
- Building II (Typical reactor with a double skinned dome structure). The impact into the Building II is considered to be satisfactory provided there is no perforation of the external containment observed. It is worth noting that scabbing is allowed on the external containment as the safety-related SSCs are protected by the internal containment.

The turbine failure modes are illustrated in Figure 2. The figure shows that the turbine missile consists of fragments of the disk not including the shaft of the turbine. This is the approach adopted for the current assessment – the model of the missile represents ¼ fragment only of the disk without the shaft. The assumed mass is achieved by adjusting the density of the missile material. The finite element model of the missile can be seen in Figure 4. The number of solid elements is approx. 3480 whereas the mesh size is approx. 50 mm.

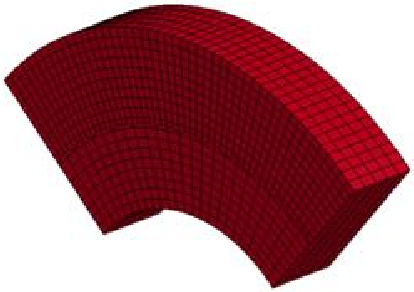

Figure 4: Finite element model of the turbine missile

The LS-Dyna material model used for the turbine missile is MAT_PLASTIC_KINEMATIC (refer to the LS-Dyna Material Manual [40]). The material properties are typical for Nickel-Chromium-Molybdenum steel alloy which is typically used for turbine blades [19]. The assumed properties are given in Figure 3.

Table 3 Material Properties of the Turbine Missile

Modulus of elasticity, [MPa]	Poisson’s ratio	Yield strength, [MPa]	Tangential modulus, [MPa]	Erosion strain, [-]
2.01e5 MPa	0.3	685	750	0.2

Strain rate strength enhancement is considered via the Cowper-Symonds formula with coefficients C = 40 and P = 5 as reported in [20].

To mesh the concrete part, solid element mesh of the target buildings (Building I and II) within the impact location is approximately 0.1x0.1m. The solid element mesh in areas which are not directly impacted is approximately 0.2x0.2m. Appropriate transitions zones are generated between fine and coarse mesh. The purpose of the fine mesh is to adequately capture the stress-strain behaviour within the impacted zone, while the transition to coarser mesh is intended to reduce computational cost. The reinforcement is modelled with beam elements which are constrained into the solid mesh via constraint formulation, i.e. there are no common nodes between the solid mesh

and the beam mesh. The beam element size corresponds to the solid element size, i.e. the beam length is approx. 0.1 m in the impact area and approximately 0.2 m away from the impact area.
The model of Building I also includes the steel supporting beams underneath the concrete roof structure. The steel beams (modelled with shell elements) support permanent steel formwork which is not included in the model.

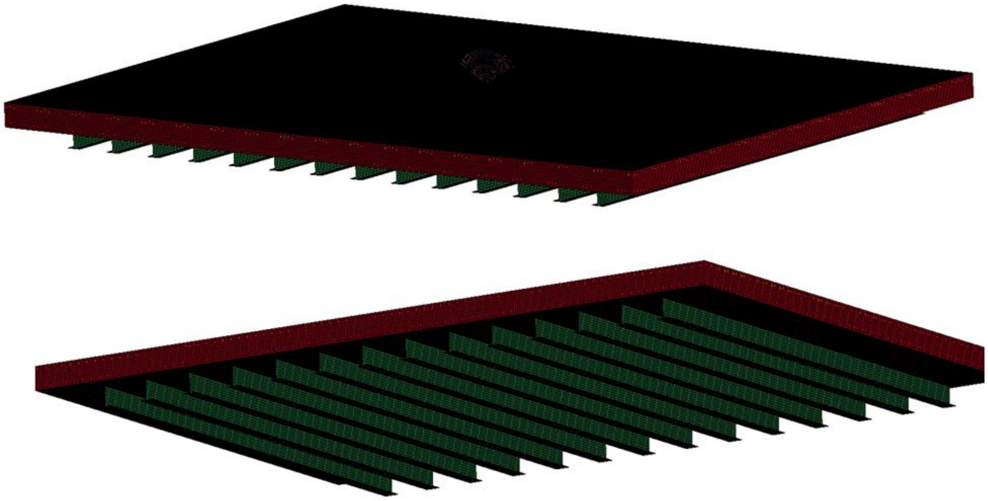

Figure 5: Model of the roof of the Building I

The model used for evaluation of the Building II includes partial models of the outer and inner domes. The models are reduced in order to save computational time.

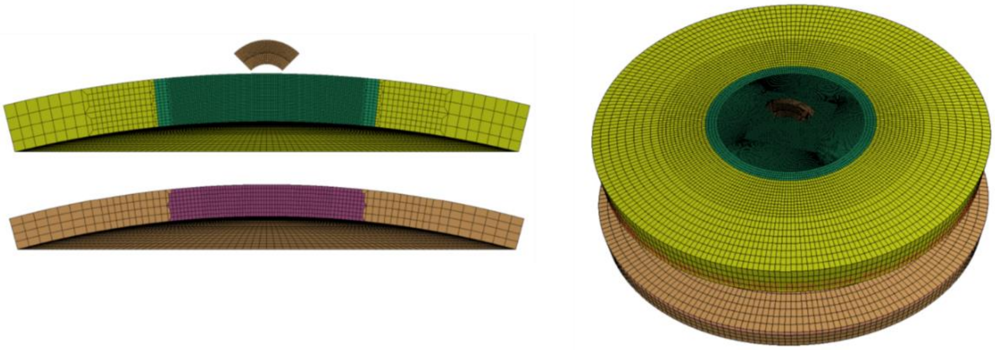

Figure 6: Finite Element Model of Building II

The results of impact onto the Building I include deformed shape of the target structure (Figure 7) and velocity history of the missile (Figure 8). The assessment shows that the roof slab is perforated but the residual velocity is 0 m/s, i.e. the reinforcement of the slab is able to stop the missile. It is assumed that the permanent steel formwork (which is not modelled) will contain the concrete debris from impacting important SSCs. Therefore, the impact scenario is concluded to be satisfactory. Figure 9 and Figure 10 illustrate the outcome of the analysis of the Building II. The missile penetration into the outer shell is shown in Figure . The missile residual velocity is positive as seen in Figure 10, i.e. the missile rebounds at some instance in time. Eroded elements can clearly be observed in Figure 9, i.e. scabbing occurs which will be stopped by the inner containment shell. The analysis results satisfy the assumed acceptance criterion, and the scenario is considered satisfactory.

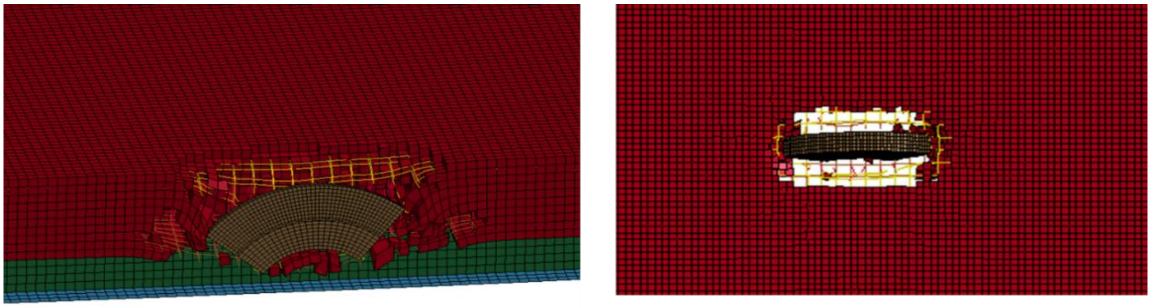

Figure 7: Deformation of the roof structure

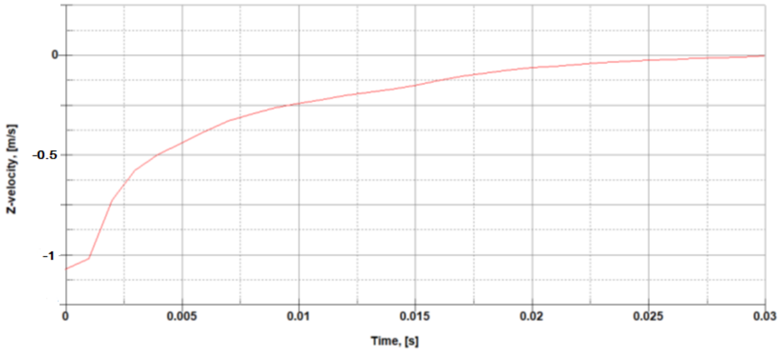

Figure 8: Velocity history of the projectile disk (impact of Building I)

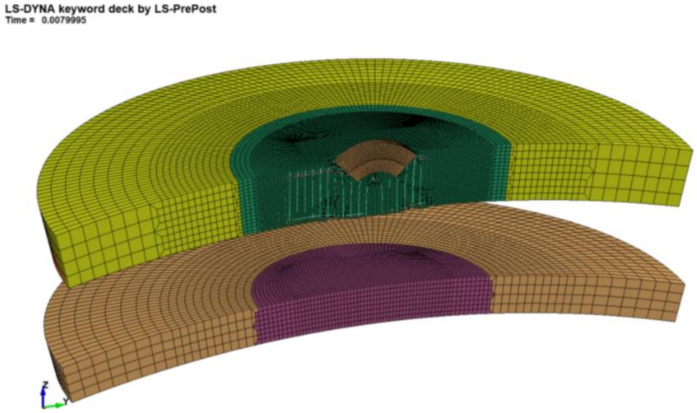

Figure 9: Penetration of the Missile into the Outer Containment Shell

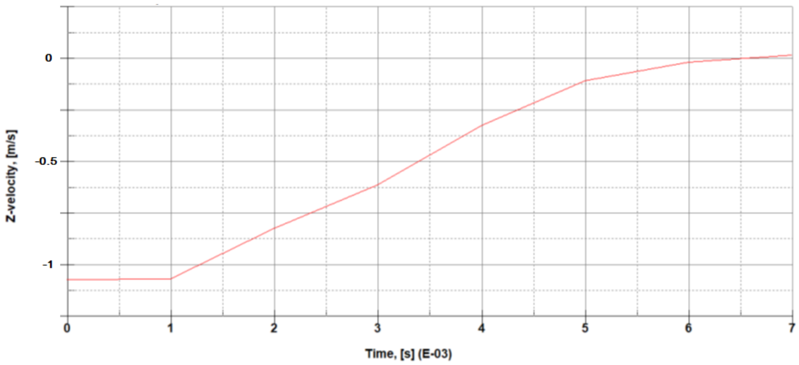

Figure 10: Vertical Velocity Time-history of the Projectile

SUMMARY

This paper attempts to provide a comprehensive description and thought process of the overall safety assessment process of the nuclear structures of a generic NPP subjected to turbine missile impact, covering definition turbine failure modes, failure probabilities, turbine missiles, impact trajectories and assessment approach

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