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Development of Safety Assessment Technology for Nuclear Facilities against Wind-Borne Missiles

Site-specific wind-borne missile hazard, demand and fragility evaluation for Korean nuclear power plants, with experimental validation

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01

Introduction

Natural-Hazard Events at Korean NPPs (OPIS)

Event type	Kori	Shin-Kori	Hanbit	Hanul	Wolsong	Total
Typhoon	**11**	**2**	**0**	**2**	**2**	**17**
Lightning	4	-	7	1	1	13
Marine organisms	2	-	0	18	-	16
Fire	-	-	-	2	-	2
Heavy rain	3	-	-	-	-	3

Source: OPIS (Operational Performance Information System for NPP) DB, 1978–2022

Why wind-borne missiles?

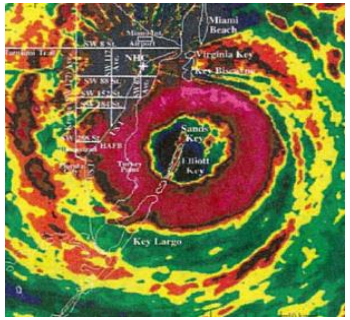
- Typhoon is the most frequent natural-hazard event in Korean operating experience (17 events, 11 at Kori)
- Most consequences were electrical (flashover, short circuit) or debris at the intake
- **Typhoon Maemi (2003):** a wind-borne missile impact the main transformer

Typhoon events at Korean NPPs

- **Maysak (2020)**: flashover of transmission facilities
- **Kong-rey (2019)**: white emergency declared for high wind (wind-speed DB error)
- **Maemi (2003)**: transmission line short circuit, missile strike on main transformer
- **Gladys (1991)**: circulating water system upset by debris ingress at intake
- **Thelma (1987)**: transmission line short circuit, debris ingress at intake
- **Vera (1986)**: insulator flashover, insulator damage by lightning

High Wind Events at U.S. NPPs

Turkey Point NPP · Hurricane Andrew (1992)





Event

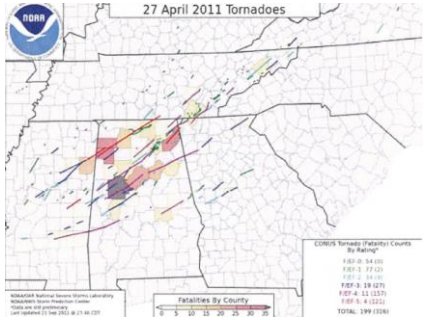
- August 24, 1992: Hurricane Andrew passed directly over Turkey Point
- Category 4 (175 mph, 78 m/s)

Impact

- LOOP (loss of offsite power) for 5 days
- No impact on safety-related SSCs, but minor flooding
- Severe damage to non-safety SSCs
- Structural damage to Unit 1 exhaust stack
- Severe damage to regional infrastructure

Browns Ferry NPP · Tornado outbreak (2011)





Event

- April 25–28, 2011: 200+ tornadoes in 5 southeastern U.S. states
- 15 rated EF-4 (74–90 m/s) or EF-5 (>90 m/s)
- Indirect impact on BFN: transmission towers and lines

Impact

- Loss of 500 kV offsite power
- Reactor trip at 3 units
- Brief loss of cooling at Units 1&2 (EDG oil leak)
- Offsite power restored May 2, 2011

Damage Cases of Wind-Borne Missiles

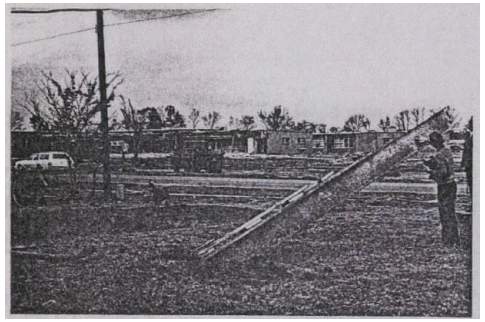
Tornado (rating, year)	Wind speed (m/s)	Missile type	Damage
Texas (F4, 1974)	92–116	2×4 / 2×6 rafter, joist; light channels, angles, timber, plywood	Roof damage (missiles lodged); school roof / wall damage
Louisiana (F4, 1978)	92–116	Light roofing, plastic pipe, steel angle; 2×4 timber	Commercial building damage; penetrated ceiling
Texas (F2, 1973)	50–70	2×4 timber; 2″ pipe	Penetrated into ground
Oklahoma (F3, 1982)	71–91	2×6 timber, utility pole (110 lb); roof chimney	Penetrated concrete block
Nebraska (F4, 1975)	92–116	2″ light steel column; vehicle (overturned)	Vehicle rolled into building
Texas (F3, 1973)	71–91	2″ steel pipe	Penetrated residential wall



Building with broken windows



Roof penetrated by missiles



Timber missile after a tornado

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02

High Wind PRA

High Wind PRA Framework

High Wind Hazard Analysis (WHA)

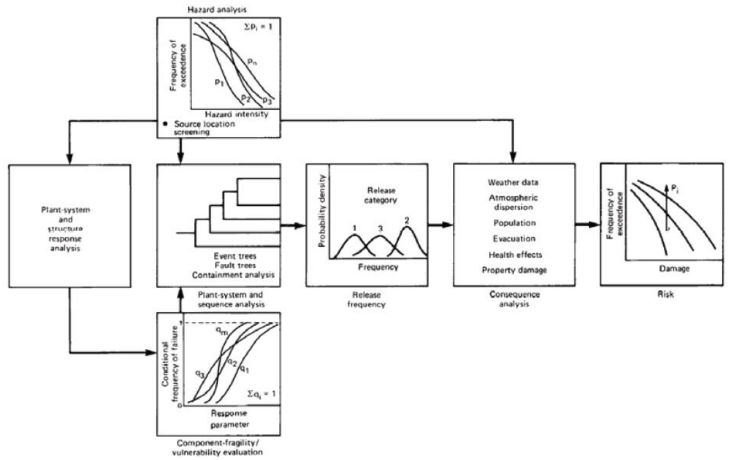
- Annual exceedance probability and frequency for a range of wind speeds at the site

High Wind Fragility Analysis (WFR)

- Response and capacity of SSCs → failure probability
- Loads: high wind pressure and wind-borne missile impact

High Wind Plant Response Model (WPR)

- PRA model integrating high wind hazard and fragility → core damage frequency



Overview of external hazard PRA [1, 2]

Scope of this work

- Fragility analysis (WFR), focused on the wind-borne missile load
- Missile strike frequency (hazard) + damage given a strike (fragility) for exposed SSCs

[1] EPRI, High Wind Risk Assessment Guidelines, TR-3002003107, 2015
[2] NUREG/CR-2300, PRA Procedure Guide, 1983

Wind Fragility Model and the Missile Problem

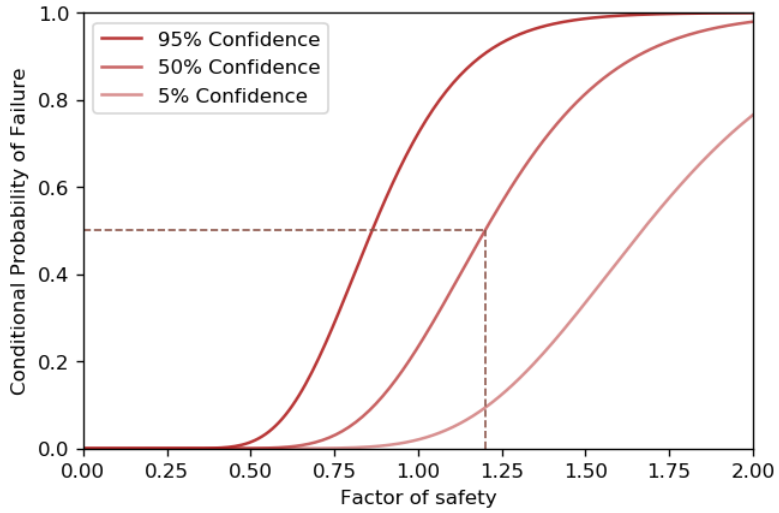
Wind fragility model (lognormal)

$$f = \Phi\left(\frac{ln(\frac{v}{v_m}) + \beta_u \Phi^{-1}(Q)}{\beta_r}\right)$$

- $\Phi(\cdot)$: Gaussian cumulative distribution function
- v: wind speed variable
- v_m: median capacity wind speed
- β_r: aleatory variability
- β_u: epistemic variability
- Q: confidence level

$\boldsymbol{v_m = v_d \cdot \sqrt{F_s \cdot F_d \cdot F_p}}$ (simplified fragility model)

- v_d: design wind velocity
- F_s: strength factor
- F_d: structural ductility factor
- F_p: pressure variability factor



Fragility curves at 5 / 50 / 95 % confidence

Wind-borne missile hazard and fragility

- Strike probability depends on wind intensity, target surface area, and the number and type of missiles
- Evaluate impact frequency (hazard) and failure probability given a impact (fragility)

Missile Impact Hazard: Ψ

Factors affecting missile impact frequency

- Missile type
- Exposed area of the target SSC
- Area from which missiles can originate

Normalization of missile impact probability [1]

$$\Psi = \frac{\text{Probability of missile impact}}{\text{Missile} \times \text{Unit area} \times \text{Tornado}}$$

- Ψ = impact probability per missile, per unit target area, per high wind event
- Generic Ψ by Fujita scale (table): lower bound for shielded / higher-elevation targets, upper bound for unprotected / lower-elevation targets

Intensity (F-scale)	Ψ – lower bound (shielded or higher elevation)	Ψ – best estimate	Ψ – upper bound (unprotected or lower elevation)
0	1E-12	2E-11	8E-11
1	2E-12	4E-11	2E-10
2	3E-12	6E-11	3E-10
3	2E-11	2E-10	6E-10
4	3E-11	3E-10	1E-9
5	4E-11	1E-8	3E-9
6	5E-11	2E-9	5E-9

Hit Probability and Missile Population

Target hit probability

$$\text{Target hit Probability} = \Psi \times SA_T \times N$$

- Ψ: normalized missile impact probability
- SA_T: exposed target surface area
- N: missile population

Why a walkdown is required

- Actual walkdown counts may be 5-10 times higher than the generic values
- A site missile survey is required for an accurate missile fragility

Missile population N – generic values [1]

Site condition	Conservative estimate	Reasonable estimate
Operating plant / no forested area	50,000	10,000
Under construction / forested area	250,000	150,000

What drives N

- Construction sites have loose materials everywhere
- Trees in a forested area are a missile source
- N is the largest uncertainty in the hit probability
- Reasonable estimate (150,000) is used for the CST case study

Missile Impact Fragility: Damage Given a Hit

Exposed equipment

- Conditional damage probability of 1.0 generally assumed (conservative)
- Derived by analysis for steel-plate tanks such as the CST

Structures

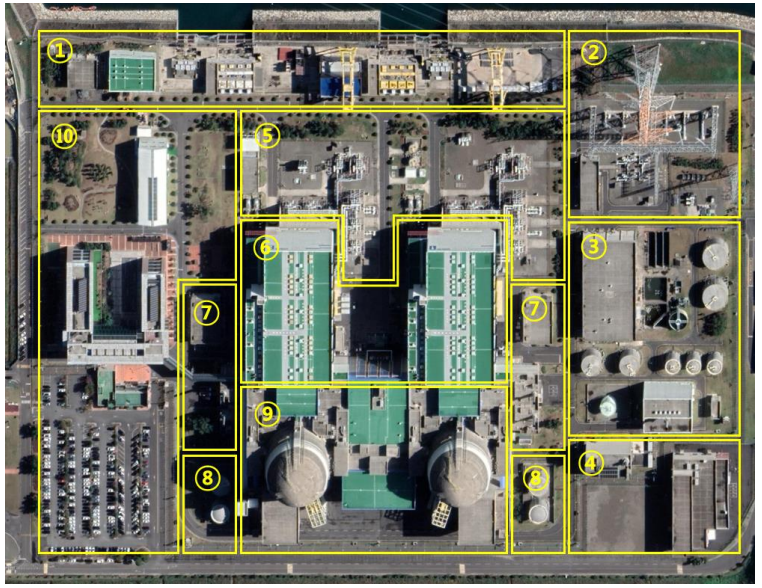
- Vulnerable structures: penetration probability 1.0
- Major structures: 18″ or thicker concrete → no missile penetration
- Openings (doors, louvers, penetrations): penetration probability 1.0

Equipment inside structures

- Inside a vulnerable structure: treated as if no wall; use the equipment surface area
- Inside a major structure: damage probability through openings

Default rule Damage given a hit = 1.0 unless the target can survive. The CST is a steel-plate tank, so its conditional damage probability is derived by impact simulation.

Missile Survey at a Korean NPP Site: 10 Zones



Survey zones (numbers match the table)

Target zone

- Zone 3 holds the condensate storage tank (CST) and real missile sources

No.	Zone	Potential wind-borne missiles
1	Intake structure	ESW intake exterior stairs, drums, containers
2	Switchyard	Stored items in the switchyard
3	Water treatment / CST / aux. boiler	Tank exterior steel stairs, aux. boiler exterior piping
4	AAC DG / LILW storage	Containers outside the AAC DG building
5	Transformer	–
6	Turbine building	Exterior windows broken by high wind
7	CCW HX / EDG	Stored items outside the EDG and CCW HX buildings
8	Hold-up / RMWT	–
9	Containment / aux. building	–
10	Other (incl. off-site)	Fences, lights, trees; off-site PV panels, yard storage

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03

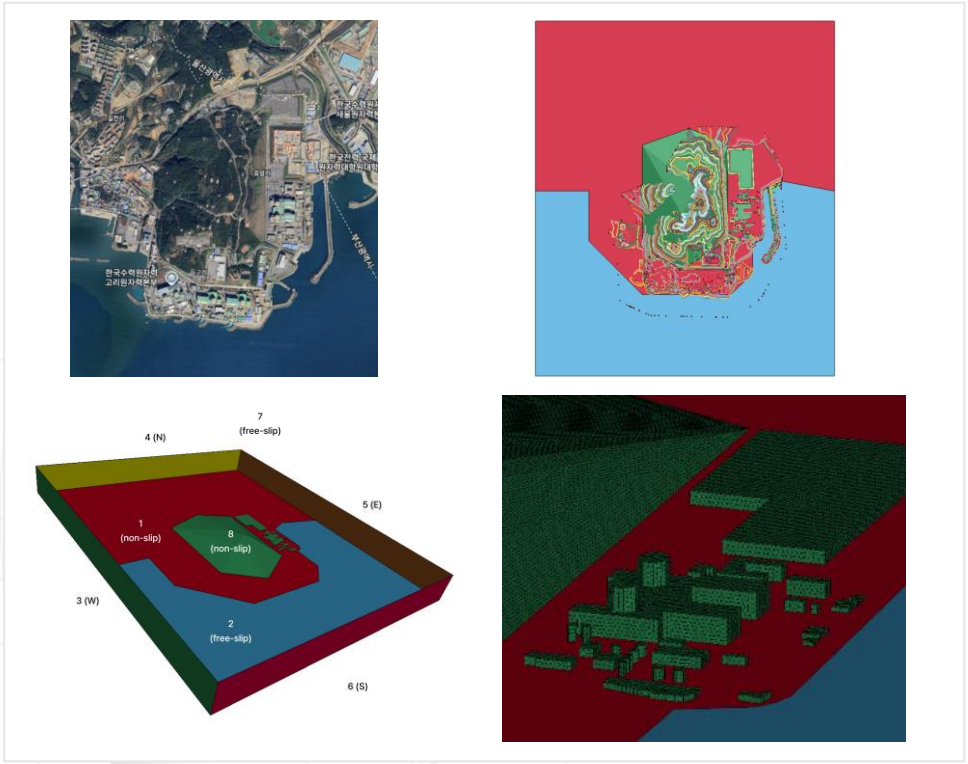
High Wind Demand

High Wind Demand · Site-specific wind amplification

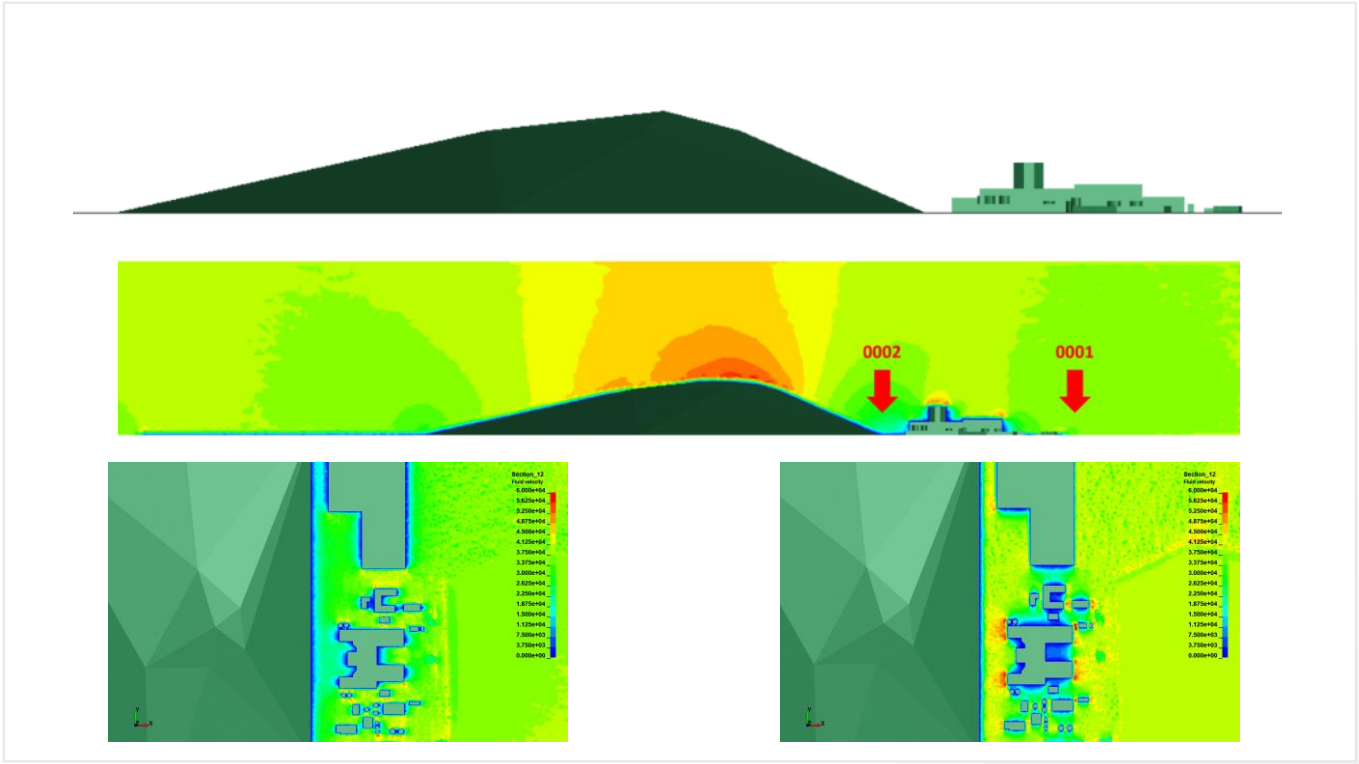
Site CFD Model for Local Wind Speed

Approach

- CFD-based numerical model of a domestic NPP site: terrain + plant buildings
- Local wind amplification by terrain and site layout, evaluated at component height



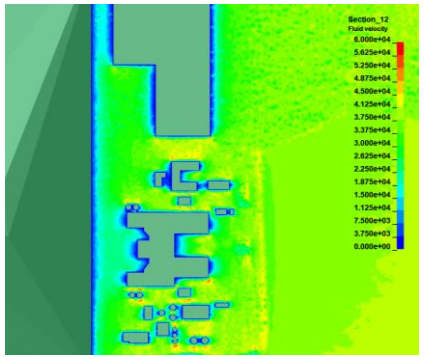
Target NPP site, terrain model, computational domain and plant model

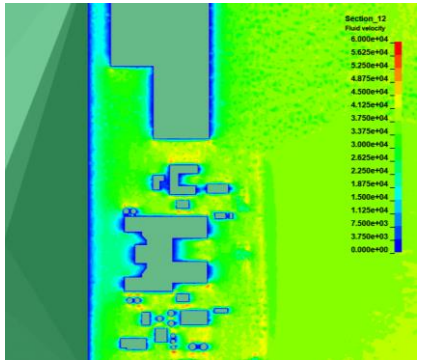


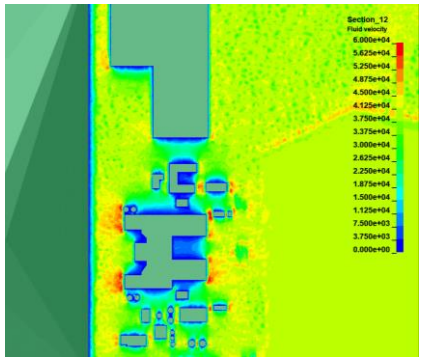
Example results: speed-up over the hill (side view) and around the buildings (plan view)

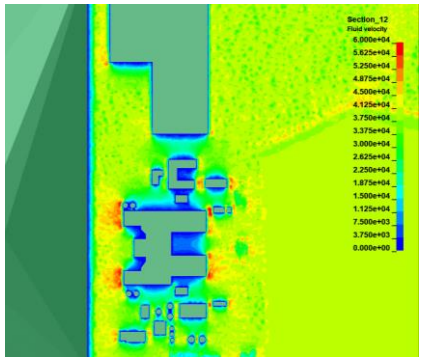
High Wind Demand · Site-specific wind amplification

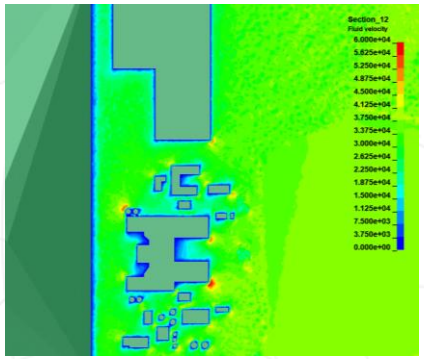
Local Wind Speed by Direction (V = 40 m/s)

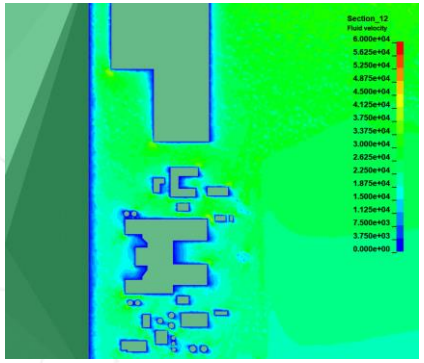

E (V = 40 m/s)

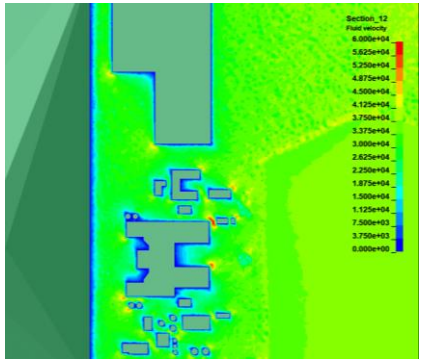

W (V = 40 m/s)

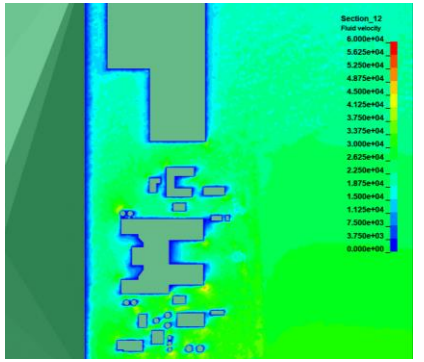

S (V = 40 m/s)


N (V = 40 m/s)


NE (V = 40 m/s)


NW (V = 40 m/s)


SE (V = 40 m/s)


SW (V = 40 m/s)

Maximum local amplification

2×

40.0 m/s design wind → 81.6 m/s local wind

- 8 wind directions, inlet 40.0 m/s
- Buildings shield the yard in some directions and channel the flow in others

Demand increase

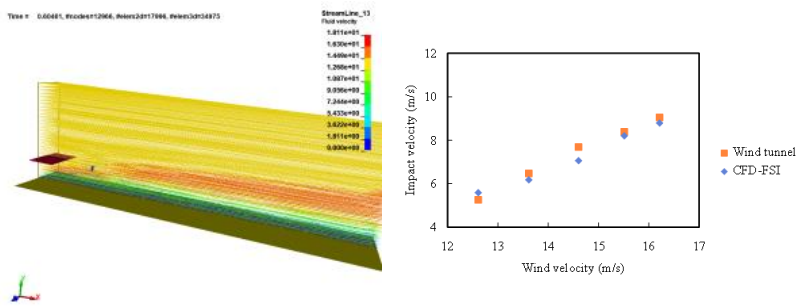
- Site amplification raises the required performance

High Wind Demand · Missile impact velocity

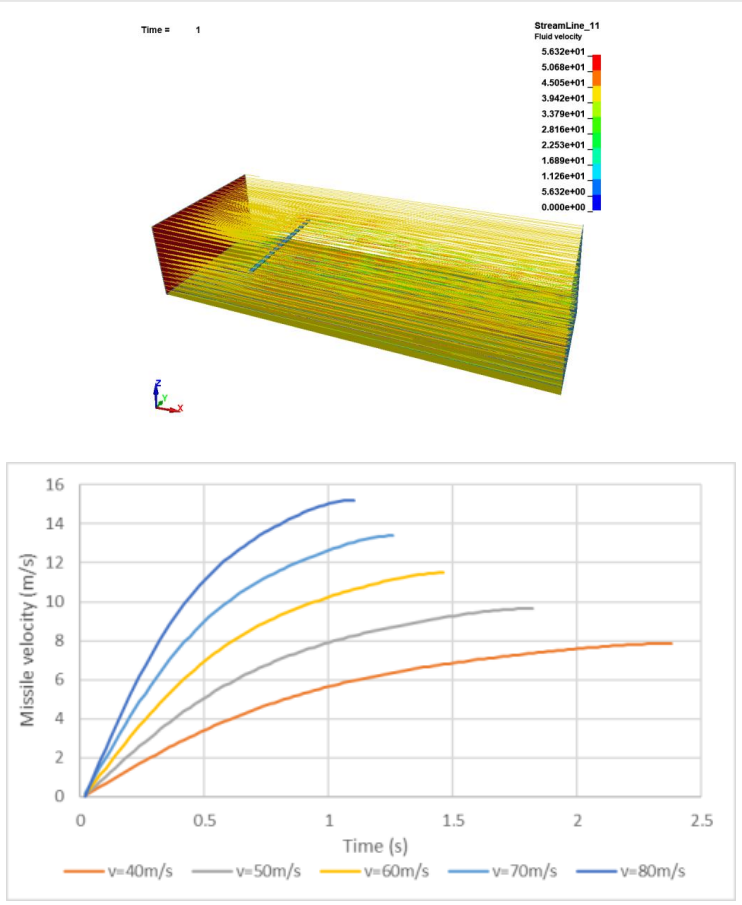
CFD-FSI Missile Impact Velocity



Wind tunnel test for missile behavior



CFD-FSI model and validation against the wind tunnel test



Impact velocity of a 6″ pipe by CFD-FSI (wind 40–80 m/s)

Method

- Wind tunnel test of missile motion
- Coupled CFD-FSI model: missile moves in the computed flow, aerodynamic force updated every step
- Test and model agree well (wind 12–17 m/s)

Re-evaluated impact velocity

30.5 → 7.9 m/s

FSAR bounding value → test-based CFD value

Demand decrease

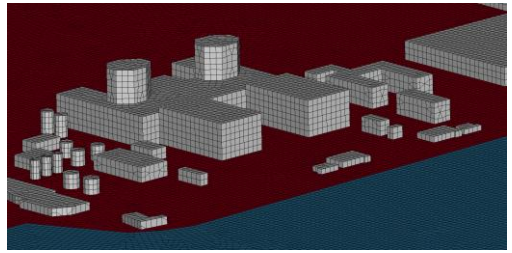
- Realistic velocity lowers the required performance

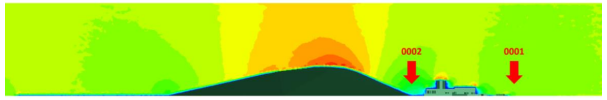
High Wind Demand · Re-evaluation of required performance

Re-evaluated Required Performance

Demand increase

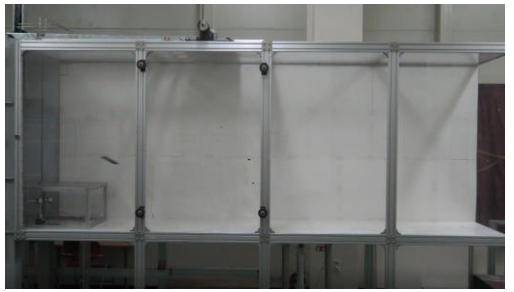
- Local wind speed amplification at the site: up to 2× (40.0 → 81.6 m/s)
- Raises the required performance of exposed, missile-vulnerable SSCs

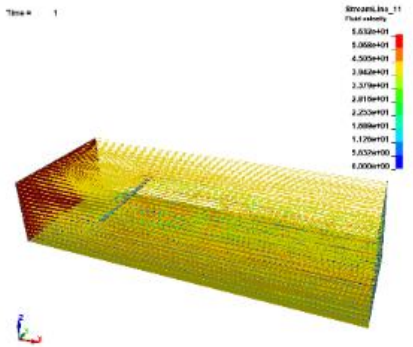




Demand decrease

- Impact velocity from missile tests and CFD-FSI: 7.9 m/s vs. 30.5 m/s in the FSAR
- Lowers the required performance





Result The required performance of on-site missile-vulnerable SSCs is re-evaluated with both effects and applied to the CST fragility

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04

Wind-Borne Missile Fragility

Target Equipment and Hazard: CST

Target equipment: CST

- Located in Zone 3, where potential missile sources were found
- Steel-plate tank → conditional damage probability is derived, not assumed
- Exposed surface area 7,984.9 ft²

Missile impact hazard (generic, conservative)

- Generic value applied (conservative estimate)
- $\Psi = \frac{\text{Probability of missile impact}}{\text{Missile}\times\text{Unit area}\times\text{Tornado}}$ =2E−10
  (for lower unprotected equipment and F1 Fujita scale)
- $\text{Target hit Probability} = \Psi\times SA_T\times N$
  $= 2\times10^{-10}\times7984.9(ft^2)\times150{,}000 = \mathbf{0.24}$
  (N: reasonable estimate for NPP site with forest)

Target hit probability (per high wind event)

0.24

Ψ = 2E-10 (F1, upper bound) × 7,984.9 ft² × N = 150,000

How to read it

- Given a high wind event, roughly one chance in four that at least one missile hits the tank
- So the failure probability given a hit (fragility) decides the result

Fragility Evaluation Approach for the CST

Missile selection

Item	Value
Missile	6″ pipe (design basis)
Diameter D	0.168 m
Length L	4.58 m
Mass	130.2 kg
Impact velocity	30.5 m/s (Shin-Kori 1&2 FSAR max.)

Note

- FSAR velocity (30.5 m/s) is the conservative case; the re-evaluated demand enters through the demand factor

Equipment response

- Impact simulation in LS-DYNA
- Effective stress in the missile impact region

Equipment capacity

- Material strength of the CST plate (SA240 304)
- Ultimate strength 515 MPa

Variability

- β_r (impact angle): derived analytically from simulations
- β_r (impact location): derived analytically from simulations
- β_u (material strength): 0.07 for SA240 304 (EPRI TR-3002012994)
- β_u (model accuracy): 0.05 for a simple structure (EPRI TR-3002012994)

LS-DYNA Missile Impact Model

Target: CST

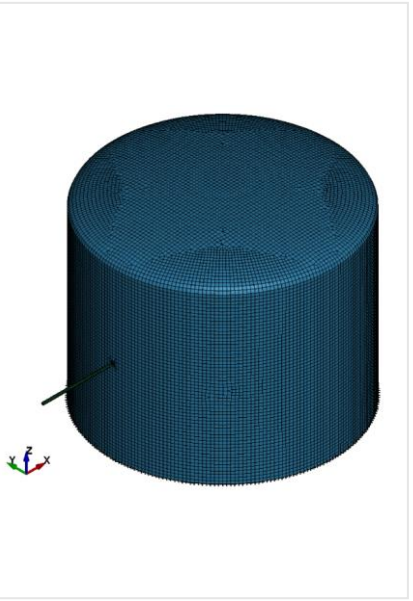
- Material model: plastic kinematic (SA240 304)
- Yield 205 MPa, ultimate 515 MPa
- Shell elements

Missile: 6″ pipe

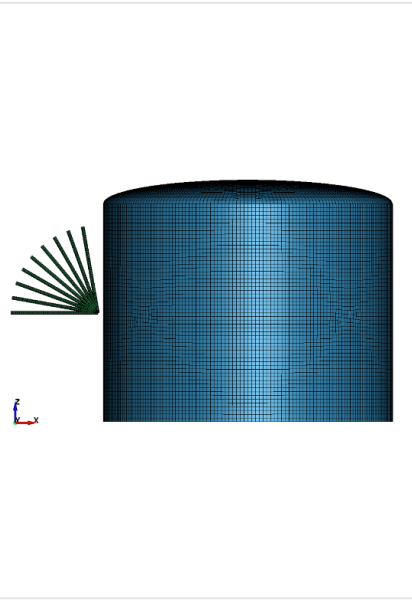
- Rigid material model, solid elements
- Impact velocity 30.5 m/s

Parametric cases

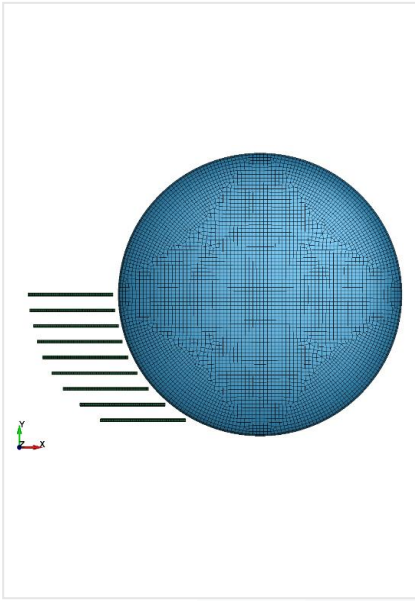
- Impact angle: 0, 10, 20, …, 80° (9 cases)
- Impact location from center: 0, 0.85, 1.69, …, 6.78 m (9 cases)



CST shell model



Impact angle cases



Impact location cases

Why a rigid missile

- All kinetic energy goes into the tank, so the tank stress is an upper bound (conservative on the capacity side)

Stress by Impact Angle and Location

Impact angle (deg)	Stress (MPa)
0	479.0
10	418.0
20	396.9
30	411.1
40	404.1
50	419.1
60	396.1
70	436.6
80	414.5
Median	414.5
Fs, angle	1.24
βr	0.06

Impact location (m)	Stress (MPa)
0	479.0
0.85	407.9
1.69	402.6
2.54	399.8
3.39	393.3
4.23	380.3
5.08	360.7
5.93	341.2
6.78	286.9
Median	393.3
Fs, location	1.31
βr	0.14

Procedure

- Stress for each impact angle and location → median response
- Strength factor Fs = ultimate strength (515 MPa) / median stress
- βr from the scatter of the cases

Impact angle

Fs = 1.24 · βr = 0.06

Normal impact (0°) gives the highest stress, 479 MPa

Impact location

Fs = 1.31 · βr = 0.14

Stress drops from 479 MPa at the center to 287 MPa near the edge; location variability dominates

Wind-Borne Missile Fragility of the CST

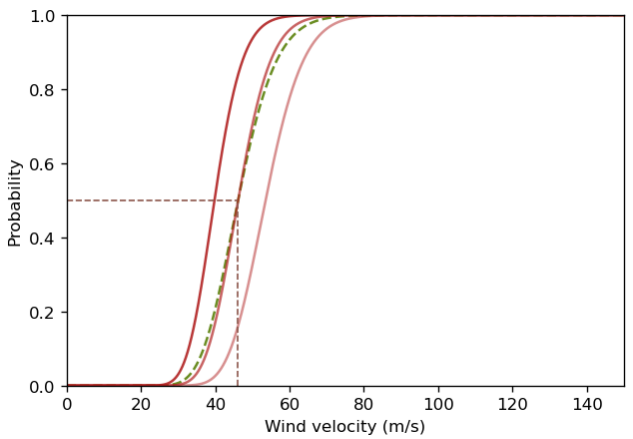
Fragility parameters

$$v_m = v_d \times Fs_{angle} \times Fs_{location} \times Fs_{Demand}$$

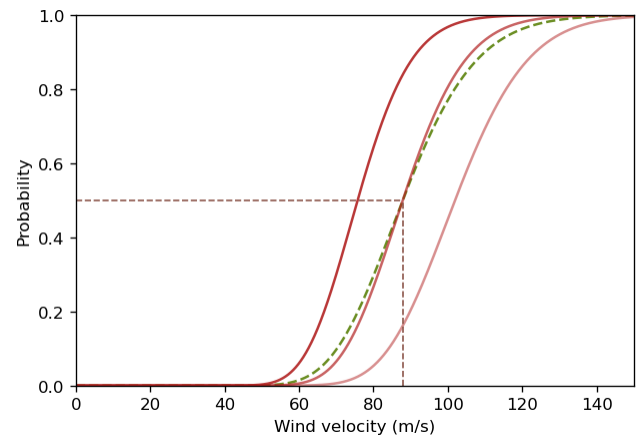
- $v_m = 46.1\ m/s$ (design impact velocity condition)
- $v_m = 87.9\ m/s$ (re-evaluated required performance)

$$\beta_r = \sqrt{0.06^2 + 0.14^2} = 0.15$$

$$\beta_u = \sqrt{0.07^2 + 0.05^2} = 0.09$$



CST fragility – design wind speed condition



CST fragility – re-evaluated required performance

$V_{1\%}$ (wind speed at 1 % failure probability)

31.0 → 59.1 m/s

Design wind speed condition → re-evaluated required performance (≈ 2×)

What the comparison shows

- With the design impact velocity the 1 % failure wind speed is 31.0 m/s
- With site-specific demand (amplification + realistic velocity) it rises to 59.1 m/s
- Demand assumptions dominate the fragility of exposed equipment

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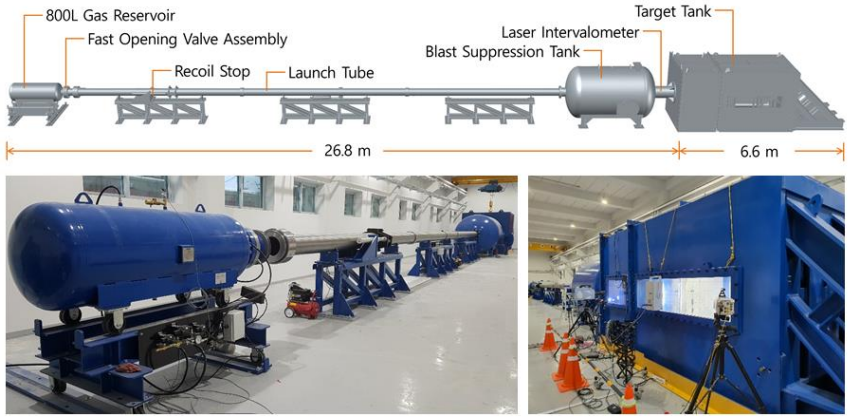
05

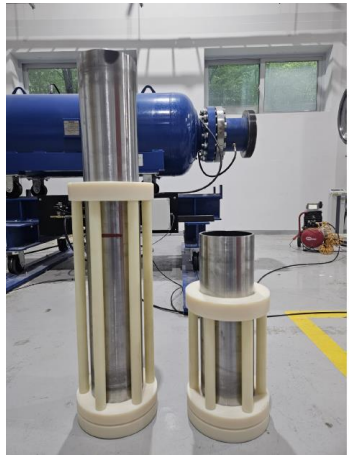
Experimental Validation

Experimental Validation · Test design

Gas-Gun Missile Impact Tests



Medium-speed gas gun impact test facility (Seoul National University)



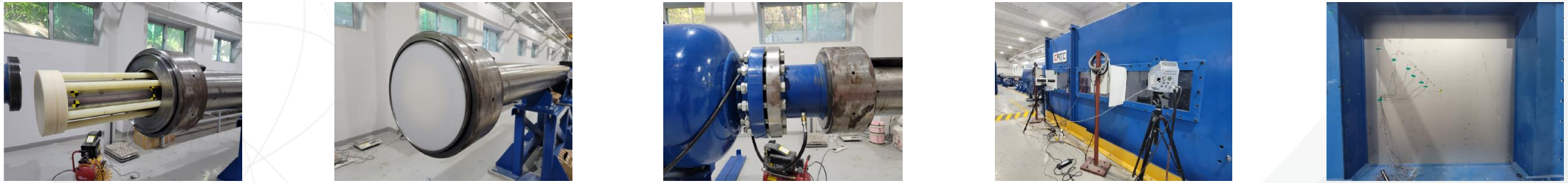
Missiles (1.0 m, 0.5 m)



Target plate (T12)

Test setup

- 800 L gas reservoir, fast-opening valve, launch tube (26.8 m), target tank (6.6 m), laser velocity meter
- Missiles: steel pipe 1.0 m (25.02 kg) and 0.5 m (11.98 kg) · target: steel plate T12 · impact velocity 100–155 m/s

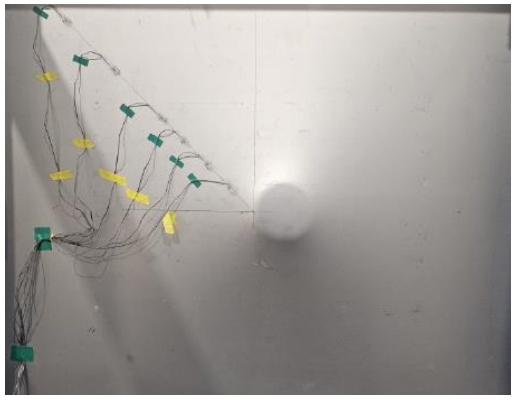


Launch tube, missile loading, target chamber and high-speed camera setup

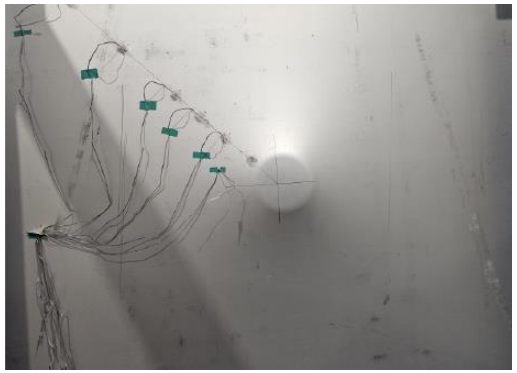
Test Results: Penetration Depth

Case	Length (m)	Mass (kg)	Velocity (m/s)	KE (kJ)	Penetration depth (cm)
NRC RG 1.76	4.58	129.43	41.0	108.8	–
Case 1	1.00	25.02	100.5	126.4	6.7
Case 2	0.50	11.98	131.0	102.8	7.0
Case 3	1.00	25.02	155.5	302.5	12.2

NRC RG 1.76 design-basis pipe missile shown for reference (same kinetic-energy order as Cases 1–2)



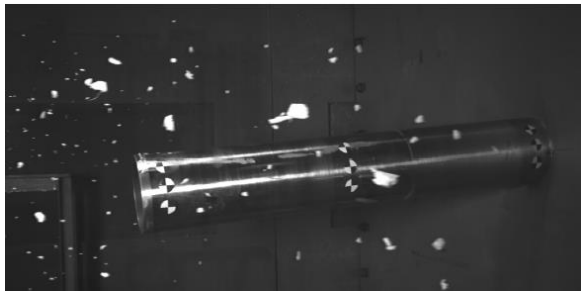
Case 1: target plate after impact



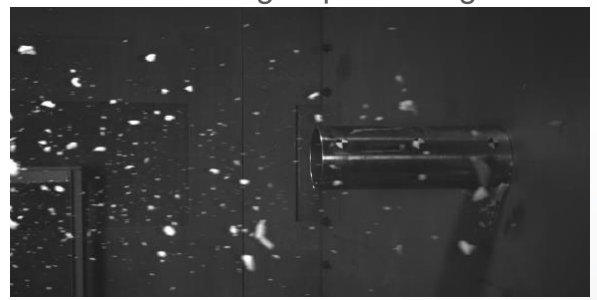
Case 2: target plate after impact



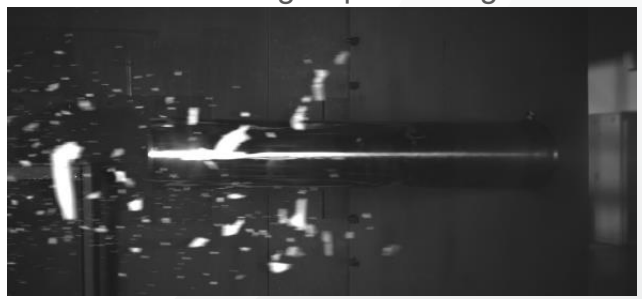
Case 3: target plate after impact



Case 1: high-speed image

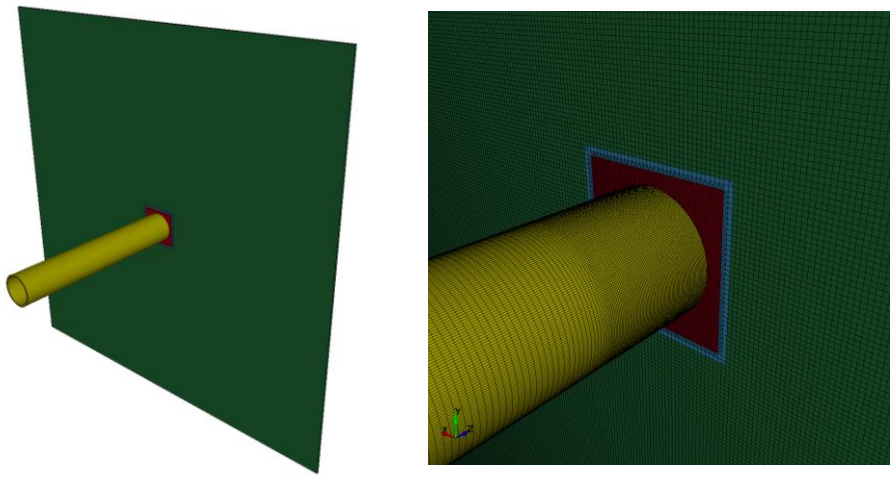


Case 2: high-speed image

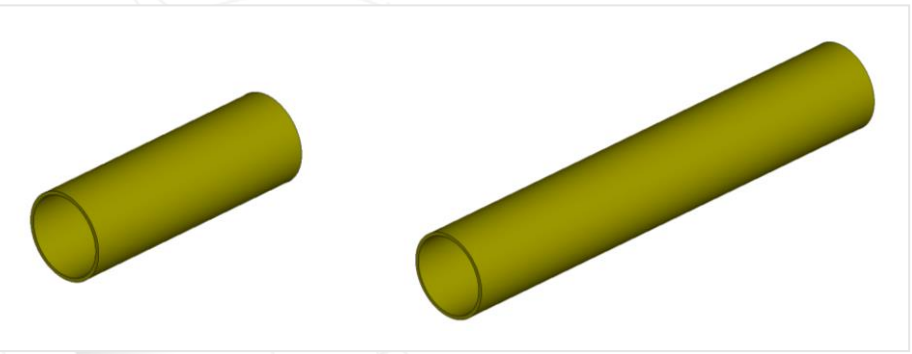


Case 3: high-speed image

Impact Test: Numerical Model vs. Test

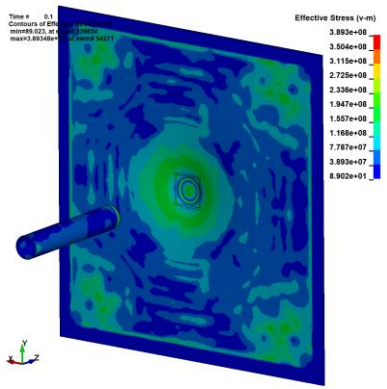


Missile impact model and impact-region detail

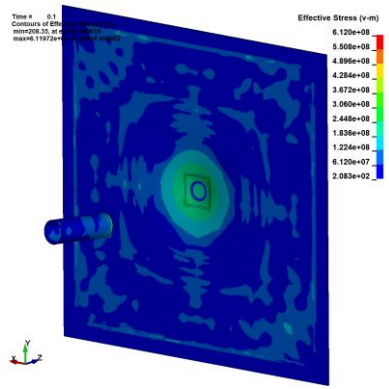


Missile models: 0.5 m and 1.0 m

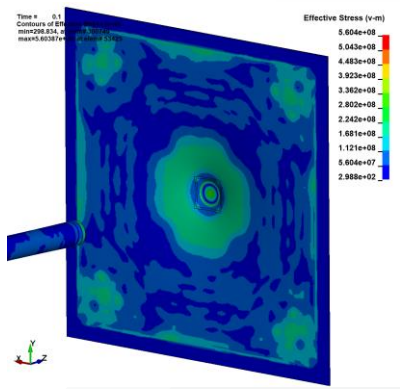
Case	Length (m)	Velocity (m/s)	Penetration – test (cm)	Penetration – analysis (cm)	Error (%)
Case 1	1.00	100.5	6.7	8.5	+26.9
Case 2	0.50	131.0	7.0	6.7	−4.2
Case 3	1.00	155.5	12.2	14.0	+14.8



Case 1: effective stress



Case 2: effective stress



Case 3: effective stress

Finding LS-DYNA penetration depth within −4 % to +27 % of the test

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06

Conclusion

Conclusions and Next Steps

1

Procedure applied to a Korean NPP

- High wind / wind-borne missile fragility procedures (EPRI) reviewed and applied
- Site missile survey in 10 zones; CST selected as the target component

2

Site-specific demand

- Local wind amplification up to 2× (40.0 → 81.6 m/s) by site CFD
- Test-validated CFD-FSI impact velocity 7.9 m/s vs. 30.5 m/s (FSAR)

3

CST missile fragility

- Fs = 1.24 (angle), 1.31 (location)
- βr = 0.15, βu = 0.09
- $V_{1\%}$ = 31.0 → 59.1 m/s (≈ 2×)

4

Experimental validation

- Gas-gun impact tests (100–155 m/s) on a T12 steel plate
- Penetration depth from impact simulation within −4 to +15 % of test

Next steps Follow-up gas gun impact tests on higher impact velocity · experimental check of site wind amplification · extension to other missile-vulnerable SSCs

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Thank you

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