Water Mist Protection of Wind Turbine Nacelles

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- $2 million replacement cost per MW capacity

Wind Turbine Nacelle Fires

Main causes:

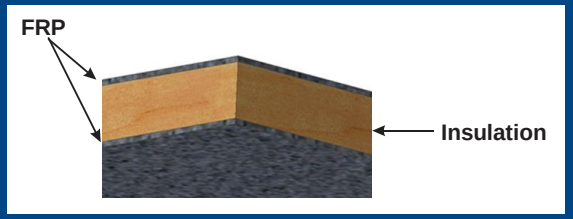
- **Lighting strike**
- **Electric/Mechanical Malfunction**

Current Status

- A dedicated certification standard is unavailable for fire protection of wind turbine nacelles
- Fire prevention measures:
  - Control ignition source
    - ✓ Avoid hot work
    - ✓ Provide braking shield
    - ✓ Prevent electrical faults
    - ✓ Isolate electrical cables from other combustibles
    - ✓ Confine combustible fluids and provide drainage
  - Provide passive fire mitigation measures
    - ✓ Use approved hydraulic, lubrication and heat transfer fluids
    - ✓ Use fire-resistant cables
    - ✓ Construct nacelles with noncombustible materials
    - ✓ Provide good housekeeping, regular inspection, monitoring and maintenance

Nacelle Combustibles and Fire Hazards

- Major nacelle combustibles
  - Electrical cables
  - Ignitable liquids
    - Lubricants
      - Bearing (1.4 – 2.1 bar)
      - Gearbox (7.6 – 9.0 bar)
    - Hydraulic fluid (up to 276 bar)
    - Transformer oil (0 – 0.4 bar)
  - Nacelle enclosure construction



- Potential fire hazards
  - Pool fire
  - Spray fire
  - Spill fire
  - Oil-soaked insulation fire

Wind Turbine Design Wind Speeds

- IEC (International Electrotechnical Commission) wind classes:
  - ✓ Class 1 (high wind)
  - ✓ Class 2 (medium wind)
  - ✓ Class 3 (low wind)
  - ✓ Class 4 (very low wind speed)
- Class 1 wind turbines
  - Typical average design wind speed for power generation: 10 m/s
  - Design wind speed for wind turbine structure:
    - 10-min average: 50 m/s
    - 3-s average: ~72 m/s

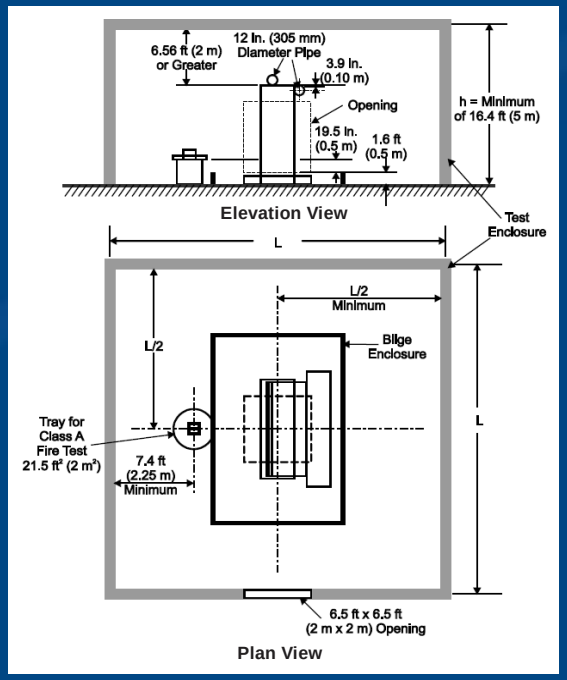
Wind- and Temperature-driven Air Exchanges for a 4-MW Nacelle

- 4-MW wind turbines
  - Nacelle size: ~220 m^3
  - Nacelle height: ~ 4 m
  - Vent openings and crevices: ~ 0.5 m^2
- Wind-driven air exchange: ~69 m^3/min
  - Operation wind speed: 10 m/s
  - Windward opening: 0.25 m^2
  - Leeward opening: 0.25 m^2
- Temperature-driven air exchange: ~30 m^3/min
  - Nacelle height: 4 m
  - Temperature inside the nacelle: 100°C

Combined air exchange: ~99 m^3/min

Existing Water Mist Protection of Enclosure Fires

FM Approvals Standard 5560 (Parts 8 and 14 of EN 14972)



- Enclosures exceeding 260 m^3
  - Minimum ceiling height: 5 m
  - Opening: 2 x 2 m

Heptane spill fire (10th IWMC)

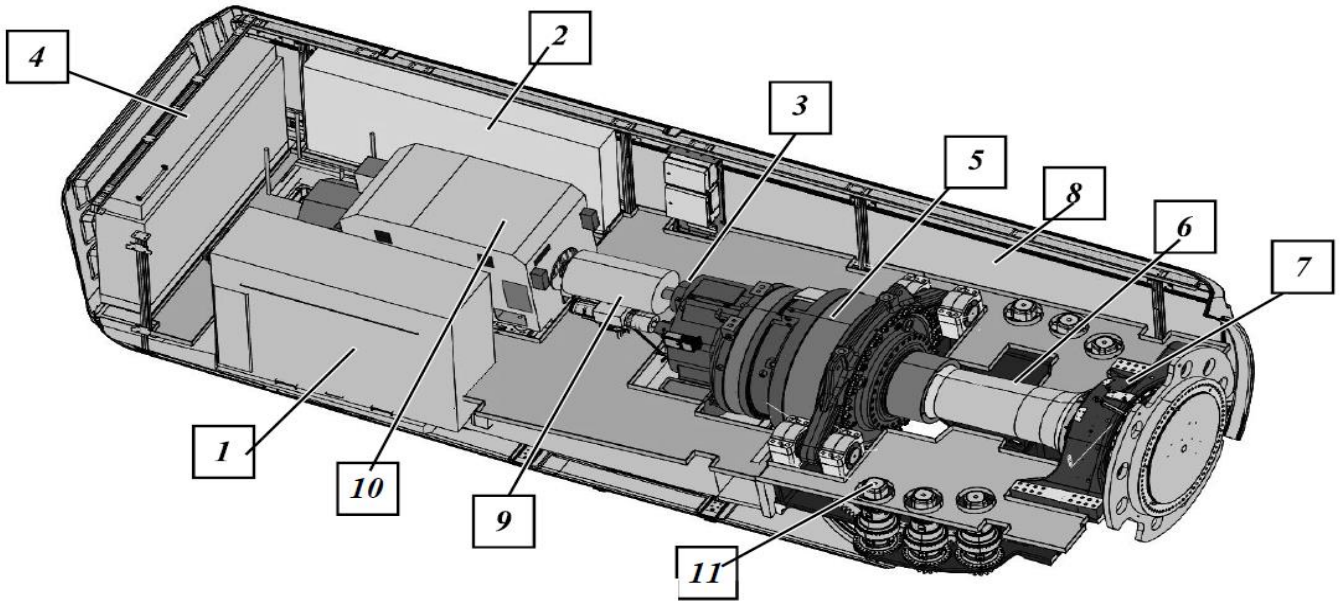
- 442-m^3 enclosure
  - Ceiling height: 7.6 m
  - Opening: 3.7 x 3.7 m

Air Exchanges Induced by Enclosure Fires

- Machinery/turbine enclosures exceeding 260 m^3: 144 m^3/min
- Heptane spill fire in 442-m^3 enclosure: 427 m^3/min

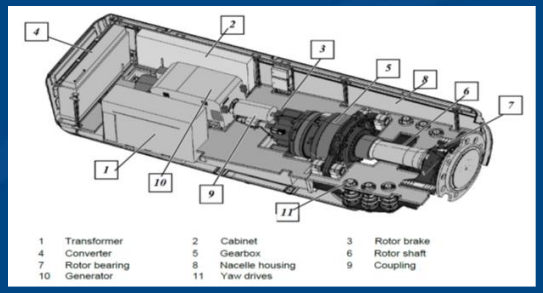
Both are greater than 99 m^3/min!

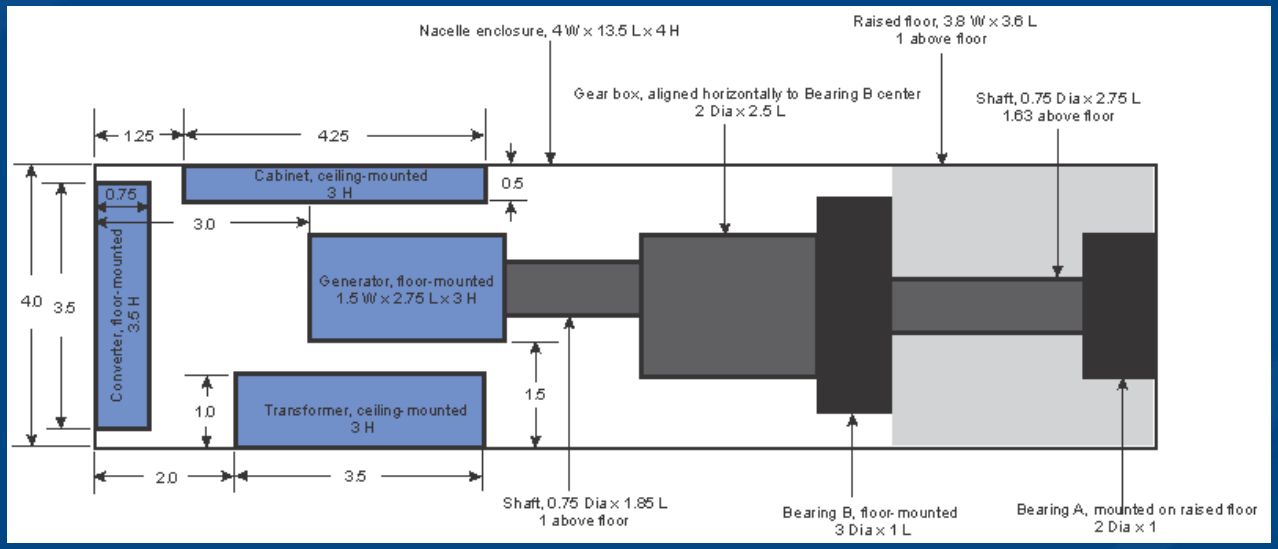
A Typical Nacelle Enclosure



1	Transformer	2	Cabinet	3	Rotor brake
4	Converter	5	Gearbox	6	Rotor shaft
7	Rotor bearing	8	Nacelle housing	9	Coupling
10	Generator	11	Yaw drives		

4-MW Nacelle Enclosure Mockup



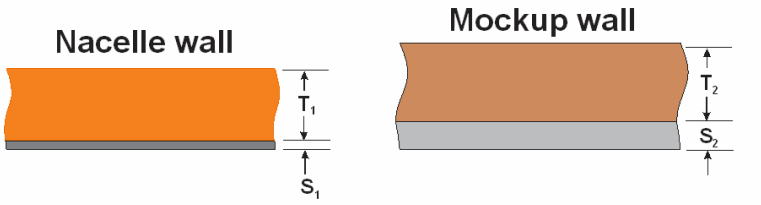


- Metal frame construction, with gypsum board sheathing and external insulation
- One same-size opening on each long side wall of the mockup
- Protections for different nacelle sizes to be tested in 4-MW increments

Protection Objectives

- Extinguish all test fires
- Maintain nacelle enclosure structure integrity
  - The outer surface temperature of gypsum boards does not exceed the failing temperature of RFP.

Scaling of Mockup Wall Thickness



$S_1 (Density)_{S1} (Specific\ Heat)_{S1} = S_2 (Density)_{S2} (Specific\ Heat)_{S2}$

$T_1 (Density)_{T1} (Specific\ Heat)_{T1} = T_2 (Density)_{T2} (Specific\ Heat)_{T2}$

Wall Type	Material	Density	Specific Heat
Nacelle	RFP	1550 kg/m^3	1620 J/kg/°C
	Polyurethane Foam	19 – 50 kg/m^3	2440 J/kg/°C
Mockup	Gypsum Board	800 kg/m^3	890 – 1017 J/kg/°C
	Fiberglass Insulation	150 kg/m^3	700 J/kg/°C

To correspond to 2.5-mm thick RFP and 25-mm polyurethane foam:

- Gypsum board thickness: ~10 mm
- Fiberglass insulation thickness: 9 – 24 mm

Ignitable Liquid for Fire Tests

Nacelles:

Nacelle Liquids	Boiling Point (°C)	Flash Point (°C)	Operating Temperature (°C)	Operating Temperature to Flash Point (°C)
Lube oil	~300	170 – 225	~95	75 – 130
Hydraulic fluid	-	148 – 315	~100	48 – 215
Transformer oil	300 – 400	> 140	~105	> 35

Mockup:

Mockup Liquid	Boiling Point (°C)	Flash Point (°C)	Initial Temperature (°C)	Initial Temperature To Flash Point (°C)
Diesel	160 – 366	52 – 96	20	32 – 76

Test Fires

- Diesel spray fires (FM Approvals 5560)

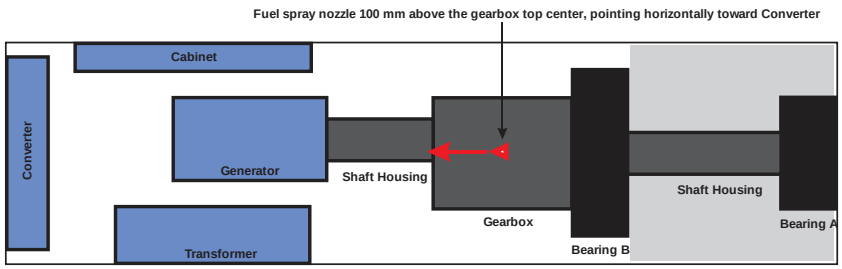
Spray Fire Type	Low-Pressure Spray Fire	High-Pressure Spray Fire
Nominal Oil Pressure	8.6 bar	150 bar
Nominal Fuel Flow Rate	1.91 kg/min	3.00 kg/min
Nominal Heat Release Rate	1.1 MW	1.8 MW

- Diesel pool fire (FM Approvals 5560): 1 x 1 m
- Diesel spill fire: 20 lpm spill from the top of the transformer mockup
- Diesel-soaked insulation fire
  - 1 m in Width x Nacelle height x Insulation Thickness

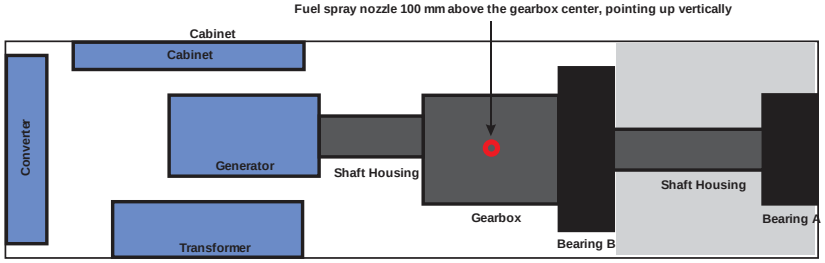
Fire Tests – 1

- Both the long side walls of the nacelle mockup are equipped with one same size opening
- One of the two openings is subjected to the intended wind speed

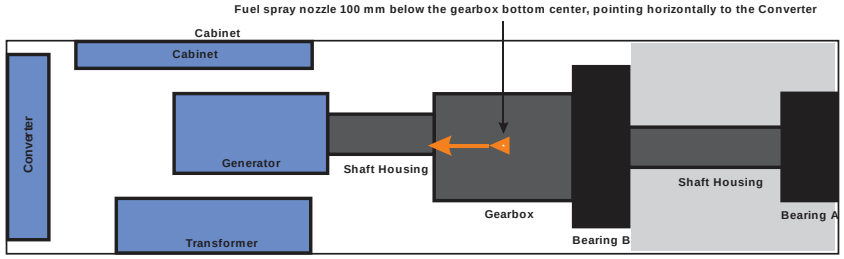
Low Pressure, Exposed, Horizontal Spray Fire



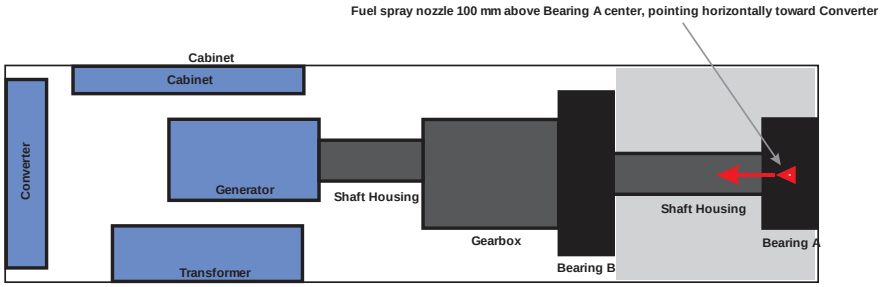
Low Pressure, Exposed, Verticall Spray Fire



Low Pressure, Shielded, Horizontal Spray Fire

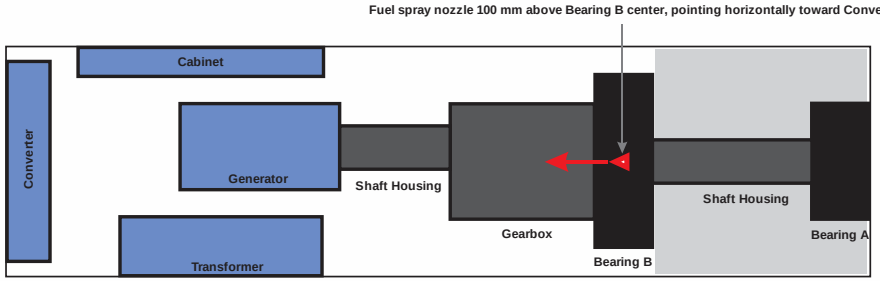


High Pressure, Exposed, Horizontal Spray Fire

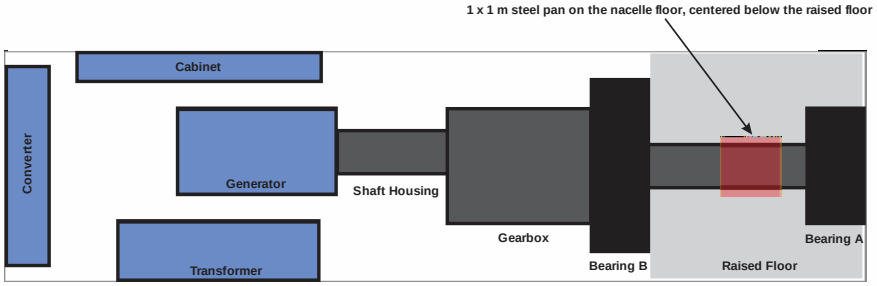


Fire Tests – 2

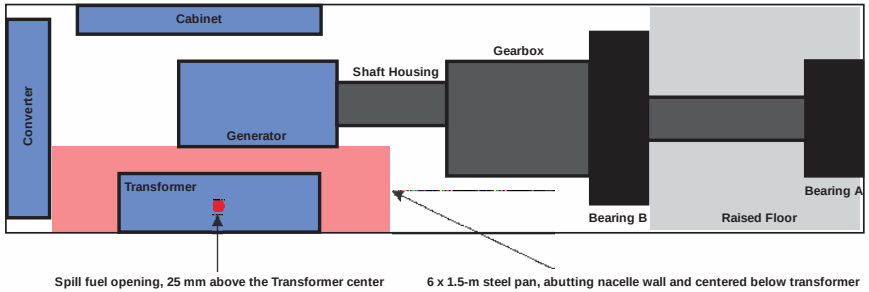
High Pressure, Exposed, Horizontal Spray Fire



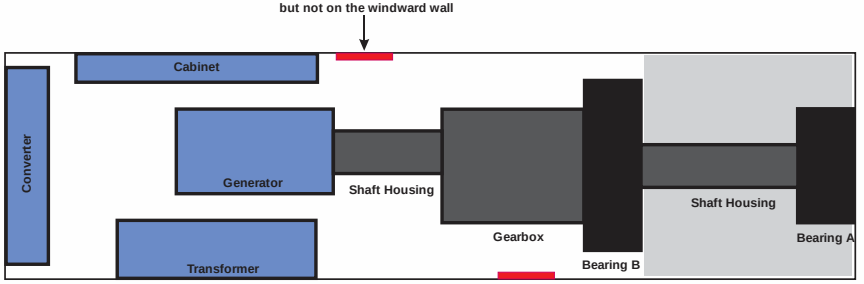
Shielded Pool Fire



Spill Fire



Oil-Soaked Insulation Fire



System Component Reliability Evaluation

- Reliability evaluation of system components (FM Approvals 5560)
  - ✓ Hydrostatic strength
  - ✓ Cycling durability
  - ✓ Extreme temperature (to expand from 40 – 130°F)
  - ✓ Corrosion/humidity/dust resistance
  - ✓ Vibration damage resistance (may need to expand from 0.15” vibration displacement)
  - ✓ Gaskets, seals and O-rings
  - ✓ Nozzle operation
  - ✓ Valve and actuator operation
  - ✓ Pump operation
  - ✓ Cylinder/tank for gas or water supply
  - ✓ Fire detection devices
  - ✓ System monitoring devices
  - ✓ Anti-freezing: lowest temperature and corrosion

Summary

This talk has:

- Assessed the efficacy of water mist extinguishment of wind turbine nacelle fires.
- Presented an evaluation protocol for water mist protection of wind turbine nacelles, consisting of a fire test protocol and reliability evaluation of protection system components.

Thank you!