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Recommended Practices for the Safe Design and Operation of Flywheels

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Overview

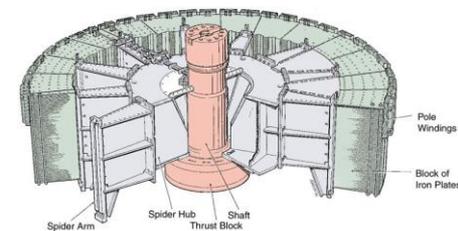
- Heretofore no standard for flywheel safety existed
- In 2015:
 - Sandia published a SAND2015-10759 “*Recommended Practices for the Safe Design and Operation of Flywheels*”
<http://www.sandia.gov/ess/publications/SAND2015-10759.pdf>
 - UL9540 *Standard for Energy Storage Systems and Equipment* was open for comment
- A sub-group for flywheels was created within the Energy Storage Safety Working Group
 - Mentored by Dave Conover
 - Team comprised Sandia, UL, Beacon, Calnetix, Test Devices
 - Best in class composite rotor, steel rotor and spin testing
- Consensus approach to safety published in UL9540
 - Already influencing industry behavior

Flywheel Applications

Pulsed Power



- Powering the Joint European Torus
 - 400 MW, 700 kWh, about 10 pulses daily since 1981
 - 775 tons, 100 m/s tip speed



Rotary UPS



- Commercial and industrial installations world-wide
 - 5% of UPS market (35% of market >2MW) – Source: Hitec

Mobility



- RTG's (Rubber Tire Gantry)
 - Diesel-electric power
 - Flywheel energy recovery
 - Reduces port emissions



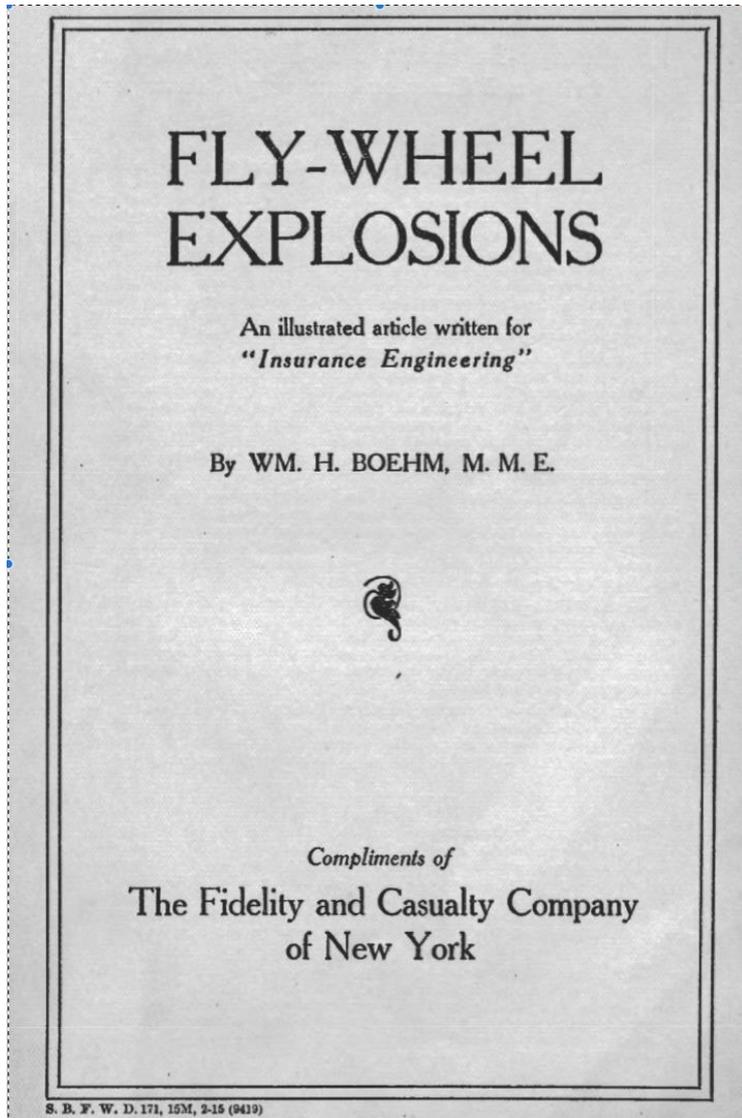
- Roller coaster launch
 - 8 MW for 2s repeated every 90s
 - Continuous charge at 200 kW
 - Avoids disruptive load to grid

Flywheel Hazards

Hazards

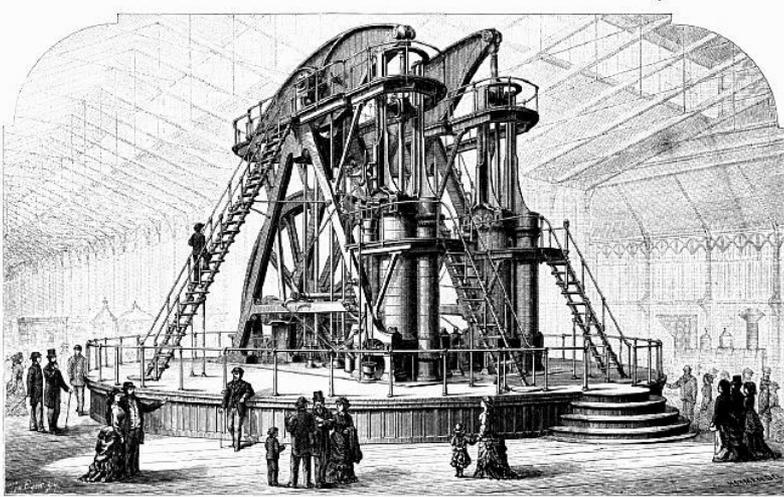
- Rotor failure
 - Rotor stress exceeds its strength.
 - Rotor fails creating energetic, destructive projectiles
 - Mitigation: Prevent rotor failure over the life of the system
 - Use adequate margin in design: 2x required by UL9540.
 - Qualify margin with appropriate material certification, testing
 - Containment is never a cost-effective solution
 - Energy goes in all directions, 10x rotor mass required to contain
- Loose rotor
 - Failure of bearing, shaft, or hub
 - Energy in rotor couples to the surroundings
 - Mitigation: Assure that energy coupling is managed and benign
 - Prevent contact between the rotor exterior and housing
 - Verify with full-scale drop tests

Unregulated for >100 years



- 1915 insurance co. study
 - Accident rate: 60 per yr
 - Fatalities common
 - Policies available for flywheels
- Rotor material: cast iron
 - Top allowable speed: 60 mph
 - Safety factor >10x on stress, > 3x on speed
- Recurring themes
 - Often due to governor failure
 - Large wheels with low energy: 30 ft. diameter, 10s of tons but only 5 kWh stored due to low speed.

Fatalities



THE CORLISS CENTENNIAL ENGINE.



FLY-WHEEL EXPLOSION UNION BREWING CO., ST. LOUIS, MO., 40,000-
POUND WHEEL ON ICE MACHINE RUNNING NORMALLY AT ONLY
50 R.P.M. MACHINE RACED AND BURST WHEEL BY CEN-
TRIFUGAL FORCE, HURLING 8,000-POUND CHUNKS
GREAT DISTANCES. RIM SECTION WAS 13"x16",
TO BREAK WHICH REQUIRED 4,000,000
POUNDS. LOSS \$13,423. WHEEL INSURED.

- Last flywheel fatality in 1995
 - Spin test carbon composite rotor, < 1kWh stored energy
 - Disk-plane burst redirected axially, forced lid off

Fast Forward to 2015

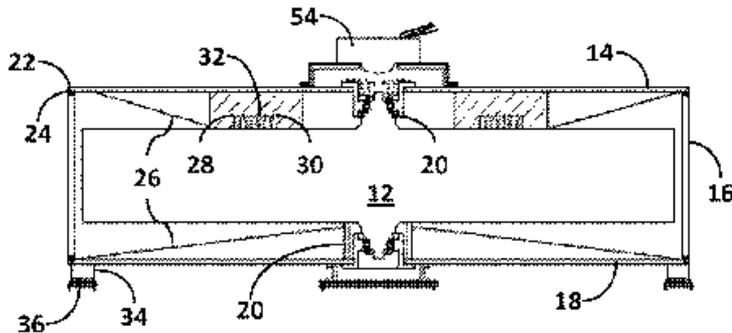


FIG. 2

- Burn-in at developer site
 - Intended for customer delivery
 - Less than 24 hours operation
 - Solid steel disk, 11,700 lb
 - 570 m/s surface speed
 - 120 kWh stored energy
 - Thin-wall vacuum enclosure
 - Below grade cell, uncovered

- Failure
 - Essentially no design margin
 - Prompt failure, no warning
 - Earth surrounding the cell redirected part of blast axially
 - Ejecta travelled up to ¼ mile
 - No fatalities, 5 injured

Loose rotor event



- Grid connected site
 - Normal operation
 - Composite rotor, 2000 lb
 - 33 kWh stored energy
 - Thin-wall vacuum vessel
 - Below grade, concrete “vault”
- Component failure
 - Dropped composite rim
 - Destroyed vac. vessel and vault
 - Ejected carbon composite dust
 - No projectiles escaped vault
 - Rotor intact
 - Root cause: Manufacturing defect. Two components from the same lot failed same way.

Summary

- Flywheel hazards have existed for a long time
- Straightforward to design a safe system
 - Design margin into the rotor
 - Assure safe management of loose rotor
- UL9540 is the first standard to promote this approach
 - Already impacting industry behavior
 - Flywheel developers seeking a UL mark are using SAND2015-10759 *“Recommended Practices for the Safe Design and Operation of Flywheels”* for guidance

Thank you