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Recommended Practices for the Safe Design and Operation of Flywheels

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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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

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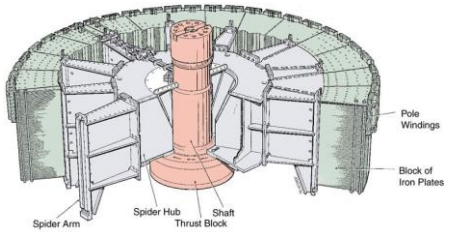
Flywheel Applications

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

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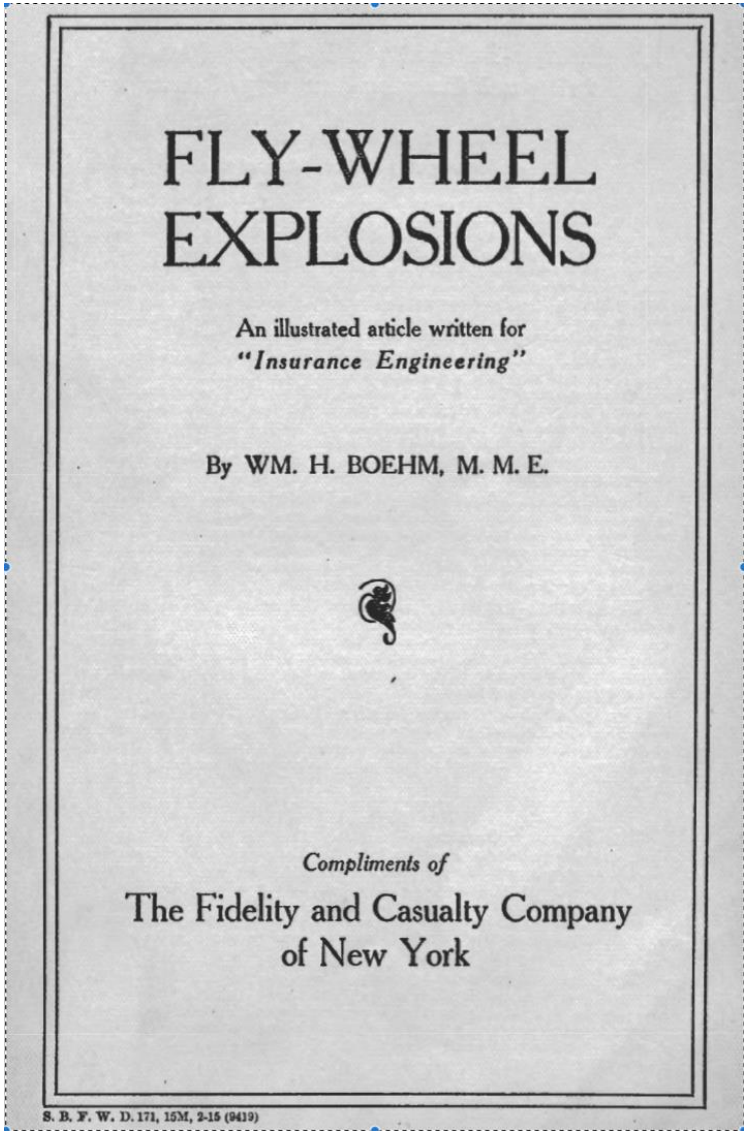
Flywheel Hazards

Hazards

- Rotor failure
  - Rotor stress exceeds it 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



FLY-WHEEL EXPLOSIONS

An illustrated article written for
"Insurance Engineering"

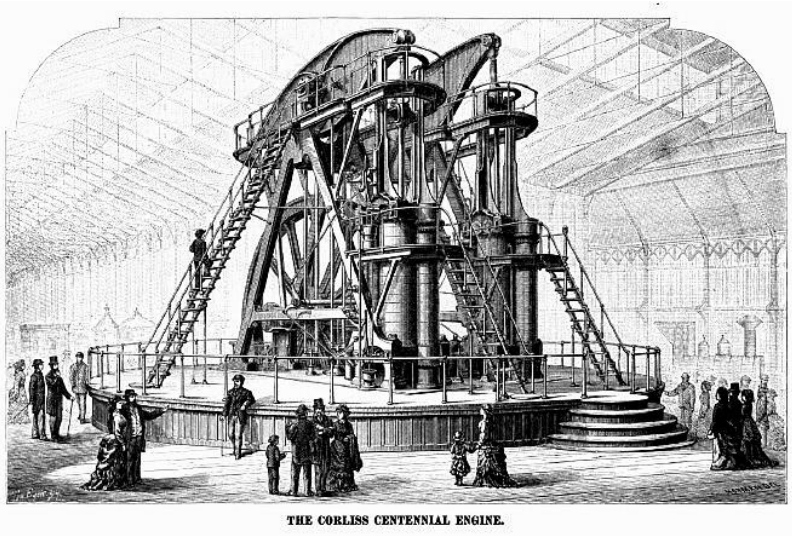
By WM. H. BOEHM, M. M. E.

Compliments of
The Fidelity and Casualty Company
of New York

S. B. F. W. D. 171, 15M, 2-15 (9419)

- 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 CENTRIFUGAL 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

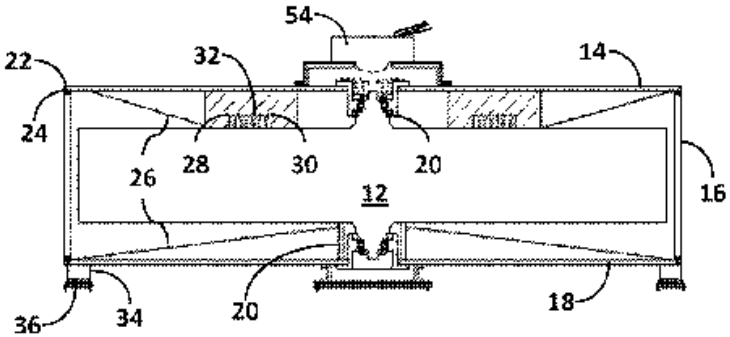


FIG. 2

- 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

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Thank you