PERFORMANCE-BASED FIRE PROTECTION OF NUCLEAR PLANTS

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OUTLINE

- Some important terms
- Operation of nuclear power plants (NPPs)
- Fire protection of NPPs
  - Traditional prescriptive approach
  - Alternative performance-based approach
- Fire modeling in support of performance approach
- Recent testing at SwRI to obtain data for fire modeling in support of performance-based fire protection of NPPs
QUANTIFYING FIRE SIZE
Heat Release Rate

- **Heat release rate**: energy produced by a fire per unit of time, that is, fire power
  - Symbol: \( \dot{Q} \)
  - Units: W, kW, or MW

- Also referred to as **chemical energy release rate**

- \( \dot{Q} \) represents size and damage potential of the fire
  - Flame height for a given diameter is a function of \( \dot{Q} \)
  - Radiant heat flux to the surroundings is determined by \( \dot{Q} \)
  - Fire growth and flashover potential are related to \( \dot{Q} \)
QUANTIFYING FIRE SIZE
How Much Is a Watt?

30 W

300 kW
MEASURING FIRE SIZE
Oxygen Consumption Calorimetry

- Thornton’s rule (1917): $\Delta h_{c,\text{net}}/r_0 = E = 13.1 \text{ kJ/g } O_2 \pm 5\%$

- First reported application to fire testing: Parker (1977)

- In theory implementation of the technique is simple
  \[ \dot{Q} = E \left( \dot{m}_a Y_a^{O_2} - \dot{m}_e Y_e^{O_2} \right) \]

- In practice equations are complex (Parker, Janssens)
  \[
  \dot{Q} = \left[ E\phi - (E_{CO} - E) \frac{1 - \phi}{2} \right] \frac{\dot{m}_e}{1 + \phi (\alpha - 1)} \frac{M_{O_2}}{M_a} \left(1 - X_{H_2O}^{a}\right) X_{O_2}^{A^{a}}
  \]

  with \( \phi = \frac{X_{O_2}^{A^{a}} \left(1 - X_{CO_2}^{A^{e}} - X_{CO}^{A^{e}}\right) - X_{O_2}^{A^{e}} \left(1 - X_{CO}^{A^{a}}\right)}{\left(1 - X_{O_2}^{A^{e}} - X_{CO_2}^{A^{e}} - X_{CO}^{A^{e}}\right) X_{O_2}^{A^{a}}} \)
OXYGEN CONSUMPTION CALORIMETER
General Setup

- Plenum
- Hood
- Specimen
- Weighing platform
- Mixing orifice
- Gas sampling probe
- Exhaust duct
- Bi-directional probe and thermocouple
- Light extinction measurement
QUANTIFYING FIRE DAMAGE POTENTIAL

Heat Flux

- Heat Flux: heat transfer rate per unit area
  - Symbol: \( q \)
  - Units: kW/m\(^2\) or W/cm\(^2\)
- Incident heat flux is a better measure of damage potential
- Threshold values for damage (minutes of exposure)
  - Pain to bare skin: 1 kW/m\(^2\)
  - Burn to bare skin: 4 kW/m\(^2\)
  - Ignition of objects: 10 to 20 kW/m\(^2\)
- Thresholds are higher for shorter exposure times
OPERATION OF NPPs
Boiling Water Reactor Plants

Source: www.nukeworker.com
OPERATION OF NPPs
Pressurized Water Reactor Plants

Source: www.nukeworker.com
OPERATION OF NPPs

Features

- BWR features
  - Older designs
  - Simple (less equipment that can malfunction)
  - Radiation issues more likely

- PWR features
  - Newer designs
  - More complex (more equipment that can malfunction)
  - Radiation issues less likely

- U.S.: 65 PWR (38 plants) and 35 BWR units (24 plants)
FIRE PROTECTION OF NPPs
Purpose and Prescriptive Approach

- Purpose: Ensure safe plant shutdown and minimize likelihood of a catastrophic event in case of fire
  - Core damage (due to loss of cooling)
  - Large early release of radioactive material
- Partly accomplished by use of “redundant trains”
- Fire protection program (FPP) is traditionally based on a prescriptive (or “deterministic”) approach

Example of a deterministic requirement: *Redundant trains must be separated by a 3-hour fire rated barrier*
FIRE PROTECTION OF NPPs
Fire Resistance Testing
FIRE PROTECTION OF NPPs
Performance-Based Approach

- Many nuclear plants in the U.S. and elsewhere are transitioning to a performance-based FPP

  Example of a performance-based requirement: *In case of fire the continued operation of at least one safety-related cable in a redundant set must be ensured*

- In 2004, NRC amended its fire protection requirements in 10 CFR 50.48 by incorporating by reference, with certain exceptions, the 2001 edition of NFPA 805

- 28 of the 62 NPPs in the U.S. are currently transitioning to an NFPA 805 risk-informed performance-based FPP
FIRE PROTECTION OF NPPs
NFPA 805 and Fire Modeling

- NFPA 805 as endorsed by NRC allows for a mix of
  - Compliance with “deterministic” requirements
  - Compliance with alternative performance-based requirements
    - Fire modeling to justify specific VFDRs
    - Fire modeling to support probabilistic risk assessment (FPRA)
- Three types of fire models are used in PB analyses
  - Algebraic models to determine Zone of Influence: FDTs
  - More detailed numerical compartment fire models
    - Zone models: CFAST
    - CFD models: Fire Dynamics Simulator (FDS)
PERFORMANCE-BASED FIRE MODELING
Algebraic Models: Fire Dynamics Tools (FDTS)

Source: NUREG 1934
PERFORMANCE-BASED FIRE MODELING
Zone Models: CFAST

Source: NUREG 1934
PERFORMANCE-BASED FIRE MODELING
Field Models: Fire Dynamics Simulator (FDS)

Source: NUREG 1934
PERFORMANCE-BASED FIRE MODELING
Input Data for Fire Models

- Fire models do not model the fire but estimate the consequences of a user-specified fire (heat release rate, radiative fraction, soot generation rate, etc.)
- Statistical HRR distributions for a wide range of combustibles found in NPPs are compiled in NUREG/CR-6850 (NRC Fire PRA methodology)
- Other input parameters are obtained from handbooks, NUREGs, test reports and peer-reviewed publications
- Licensees can also perform experiments at a recognized independent testing laboratory
PERFORMANCE-BASED FIRE MODELING
Verification and Validation of Fire Models

- Only fire models that have been properly verified and validated are acceptable to the NRC
  - Verification: Are the model equations solved correctly?
  - Validation: Are the results of the model calculations in agreement with experiments?

- V&V process is described in ASTM E1355

- NUREG 1824 describes V&V of FDTs, CFAST and FDS
  - Is also used to account for model bias and uncertainty
  - Supplement that expands database from 36 to over 1000 experiments is currently under review
JNES PROJECT
Overview

- Five-year project was initiated in April 2011 to obtain fire test data for cables, oils and HVAC filters used in nuclear power and fuel processing plants in Japan
- Funded by JNES (now NRA)
- To-date tests have been performed on
  - Eleven types of electrical cables
  - Four types of oils (turbine and lubricating)
  - Two types of filters (carbon and HEPA)
- Tests have also been performed to quantify the effect of high-energy arcing faults (HEAFs)
Electrical cables account for a large fraction of the combustible loading in NPPs

- An electrical cabinet is the ignition source in most scenarios
- Cables account for most of the combustible loading in cabinets
- Cable trays can act as “secondary” combustibles (FLASH-CAT)

Cables essential for safe plant shutdown are “targets” in a performance-based fire safety analysis

- Electrical failure is assumed to occur when temperature under the jacket reaches a critical value
- THIEF model can be used to estimate time to failure
JNES PROJECT
Dual Role of Electrical Cables (2)
# JNES PROJECT
## Cables Tested

<table>
<thead>
<tr>
<th>Cable ID</th>
<th>Jacket/Insulation</th>
<th>Number of Conductors</th>
<th>Diameter (mm)</th>
<th>Linear Mass (kg/m)</th>
<th>Insulation (% mass)</th>
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<tbody>
<tr>
<td><strong>Nuclear Power Plant Cables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6kV-CSHVT</td>
<td>PVC/XLPE</td>
<td>1</td>
<td>27.0</td>
<td>1.45</td>
<td>37</td>
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<tr>
<td>SHCVV</td>
<td>PVC/PVC</td>
<td>8</td>
<td>14.0</td>
<td>0.30</td>
<td>54</td>
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<tr>
<td>SPVV(SB)</td>
<td>PVC/PVC</td>
<td>2</td>
<td>9.0</td>
<td>0.11</td>
<td>64</td>
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<tr>
<td>FR-STP*</td>
<td>EPR/PVC</td>
<td>2</td>
<td>10.5</td>
<td>0.15</td>
<td>71</td>
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<tr>
<td>FR-CSSHV-SLA*</td>
<td>PVC/XLPE</td>
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<td>10.0</td>
<td>0.12</td>
<td>79</td>
</tr>
<tr>
<td>CCV</td>
<td>PVC/XLPE</td>
<td>8</td>
<td>14.0</td>
<td>0.29</td>
<td>50</td>
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<tr>
<td>FR-PSHV*</td>
<td>PVC/EPR</td>
<td>8</td>
<td>16.0</td>
<td>0.40</td>
<td>56</td>
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<tr>
<td><strong>Nuclear Fuel Cycle Facility Cables</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR-PV(-T)</td>
<td>PVC/EPR</td>
<td>3</td>
<td>18.4</td>
<td>0.62</td>
<td>42</td>
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<tr>
<td>ECO (CE/F)</td>
<td>PE/XLPE</td>
<td>2</td>
<td>10.5</td>
<td>0.11</td>
<td>69</td>
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<tr>
<td>FR-CPSHV*</td>
<td>PVC/EPR</td>
<td>8</td>
<td>15.2</td>
<td>0.33</td>
<td>58</td>
</tr>
<tr>
<td>CV-2</td>
<td>PVC/EPR</td>
<td>2</td>
<td>10.0</td>
<td>0.10</td>
<td>69</td>
</tr>
</tbody>
</table>
JNES PROJECT
Cable Tests Performed

- Cone Calorimeter (ASTM D6113): Ignition & HRRPUA
- LIFT (ASTM E1321): Opposed-flow flame spread
- Penlight: Electrical failure temperature
  - Similar to CAROLFIRE tests (NUREG-6931, Vols. 1-2)
- Modified ICAL (ASTM E1623): HRR & failure temperature
  - Cable length instrumented with thermocouples
  - Cable length connected to IRMS
- Full-scale open calorimeter cable tray tests
  - Similar to 1- and 3-tray CHRISTIFIRE tests (NUREG/CR-7010)
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ASTM D6113 Specimen Preparation
JNES PROJECT
ASTM D6113 Test of Thermoplastic Cable
### JNES PROJECT
ASTM D6113: Ignition Data

<table>
<thead>
<tr>
<th>Heat Flux (kW/m²)</th>
<th>( t_{ig} ) (s)</th>
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</thead>
<tbody>
<tr>
<td>14</td>
<td>NI</td>
</tr>
<tr>
<td>15</td>
<td>392</td>
</tr>
<tr>
<td>20</td>
<td>99</td>
</tr>
<tr>
<td>25</td>
<td>47</td>
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<td>25</td>
<td>53</td>
</tr>
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<td>25</td>
<td>48</td>
</tr>
<tr>
<td>50</td>
<td>14</td>
</tr>
<tr>
<td>50</td>
<td>13</td>
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<td>50</td>
<td>13</td>
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<td>75</td>
<td>5</td>
</tr>
<tr>
<td>75</td>
<td>5</td>
</tr>
<tr>
<td>75</td>
<td>5</td>
</tr>
</tbody>
</table>

![Graph showing CHF/HF vs. \( t_{ig} \) with data points and equations](image)

- CHF : 14.5 kW/m²
- \( T_{ig} \) : 377 °C
- \( h_{ig} \) : 36.5 W/m²-K
- \( b \) : 0.0792 s\(^{-0.5}\)
- \( t^* \) : 160 s
- \( k_{pc} \) : 0.2710 kW²-s/m⁴-K²

\( t^* = 160 \text{ s} \)
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ASTM D6113: Heat Release Rate Data
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ASTM E1321: Flame Spread Properties (1)
JNES PROJECT
ASTM E1321: Flame Spread Properties (2)
JNES PROJECT
ASTM E1321: Flame Spread Properties (3)
# JNES PROJECT
## Ignition and Flame Spread Data

<table>
<thead>
<tr>
<th>Cable ID</th>
<th>CHF ($\text{kW/m}^2$)</th>
<th>$T_{ig}$ (°C)</th>
<th>kpc ($\text{kW}^2 \cdot \text{s/m}^4 \cdot \text{K}^2$)</th>
<th>$T_{s,min}$ (°C)</th>
<th>Velocity (mm/s)</th>
</tr>
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<tbody>
<tr>
<td>6kV-CSHVT</td>
<td>29.1</td>
<td>510</td>
<td>0.223</td>
<td>307</td>
<td>1.4</td>
</tr>
<tr>
<td>SHCVV</td>
<td>11.5</td>
<td>318</td>
<td>0.335</td>
<td>205</td>
<td>2.9</td>
</tr>
<tr>
<td>SPVV(SB)</td>
<td>12.5</td>
<td>334</td>
<td>0.401</td>
<td>181</td>
<td>1.3</td>
</tr>
<tr>
<td>FR-STP</td>
<td>13.6</td>
<td>350</td>
<td>0.677</td>
<td>350</td>
<td>∞</td>
</tr>
<tr>
<td>FR-CCSHV-SLA</td>
<td>12.5</td>
<td>334</td>
<td>0.609</td>
<td>334</td>
<td>∞</td>
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<tr>
<td>CCV</td>
<td>15.7</td>
<td>377</td>
<td>0.271</td>
<td>149</td>
<td>0.9</td>
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<tr>
<td>FR-PSHV</td>
<td>18.8</td>
<td>414</td>
<td>0.601</td>
<td>414</td>
<td>∞</td>
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<tr>
<td>ECO (CE/F)</td>
<td>21.9</td>
<td>447</td>
<td>0.408</td>
<td>52</td>
<td>0.2</td>
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<tr>
<td>FR-CPSHV</td>
<td>18.8</td>
<td>414</td>
<td>0.389</td>
<td>338</td>
<td>5.6</td>
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<tr>
<td>CV-2</td>
<td>9.4</td>
<td>283</td>
<td>0.427</td>
<td>165</td>
<td>2.1</td>
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</table>
JNES PROJECT
Penlight Test of Thermoplastic Cable
JNES PROJECT
Cable Insulation Resistance Measurements
JNES PROJECT
Cable Temperature Measurements
JNES PROJECT

Penlight Test of Thermoset Cable

Failure ~ 952-956 s
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ASTM E1623 Radiant Panel
JNES PROJECT
Radiant Heating Test of Thermoplastic Cable
JNES PROJECT
Typical Radiant Heating Test Results

Net HRR net is based on subtracting the nominal 300 kW panel HRR.
# JNES PROJECT

## HRRPUA: Cone Calorimeter vs. ICAL

<table>
<thead>
<tr>
<th>Cable ID</th>
<th>Cone Calorimeter</th>
<th>ICAL</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>HRRPUA (kW/m²)</td>
<td>HRRPUA (kW/m²)</td>
</tr>
<tr>
<td></td>
<td>Δt (s)</td>
<td>Δt (s)</td>
</tr>
<tr>
<td>6kV-CSHVT</td>
<td>118 ± 7</td>
<td>253 ± 65</td>
</tr>
<tr>
<td></td>
<td>235 ± 14</td>
<td>759 ± 248</td>
</tr>
<tr>
<td>SHCVV</td>
<td>146 ± 2</td>
<td>169 ± 60</td>
</tr>
<tr>
<td></td>
<td>1207 ± 34</td>
<td>332 ± 161</td>
</tr>
<tr>
<td>SPVV(SB)</td>
<td>183 ± 3</td>
<td>244 ± 57</td>
</tr>
<tr>
<td></td>
<td>753 ± 22</td>
<td>163 ± 54</td>
</tr>
<tr>
<td>FR-STP</td>
<td>149 ± 0</td>
<td>148 ± 27</td>
</tr>
<tr>
<td></td>
<td>771 ± 4</td>
<td>199 ± 51</td>
</tr>
<tr>
<td>FR-CCSHV-SLA</td>
<td>148 ± 3</td>
<td>131 ± 29</td>
</tr>
<tr>
<td></td>
<td>93 ± 14</td>
<td>231 ± 121</td>
</tr>
<tr>
<td>CCV</td>
<td>262 ± 28</td>
<td>192 ± 12</td>
</tr>
<tr>
<td></td>
<td>1171 ± 110</td>
<td>363 ± 126</td>
</tr>
<tr>
<td>FR-PSHV</td>
<td>159 ± 10</td>
<td>162 ± 28</td>
</tr>
<tr>
<td></td>
<td>1098 ± 46</td>
<td>387 ± 119</td>
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<tr>
<td>FR-PV(-T)</td>
<td>123 ± 4</td>
<td>96 ± 17</td>
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<tr>
<td></td>
<td>1653 ± 51</td>
<td>714 ± 53</td>
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<tr>
<td>ECO (CE/F)</td>
<td>341 ± 23</td>
<td>266 ± 65</td>
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<tr>
<td></td>
<td>868 ± 56</td>
<td>378 ± 130</td>
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<tr>
<td>FR-CPSHV</td>
<td>124 ± 2</td>
<td>82 ± 5</td>
</tr>
<tr>
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<td>1604 ± 21</td>
<td>574 ± 48</td>
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<tr>
<td>CV-2</td>
<td>221 ± 12</td>
<td>209 ± 58</td>
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<tr>
<td></td>
<td>868 ± 56</td>
<td>332 ± 81</td>
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</tbody>
</table>
### JNES PROJECT

**Failure Temperature: Penlight vs. ICAL**

<table>
<thead>
<tr>
<th>Cable ID</th>
<th>Penlight $T_{\text{fail}}$ Range (°C)</th>
<th>ICAL $T_{\text{fail}}$ Range (°C)</th>
</tr>
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<tbody>
<tr>
<td>CCV</td>
<td>442</td>
<td>440-573</td>
</tr>
<tr>
<td>FR-PSHV</td>
<td>358-386</td>
<td>377-467</td>
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<tr>
<td>FR-PV(-T)</td>
<td>374-436</td>
<td>378-485</td>
</tr>
<tr>
<td>FR-CPSHV</td>
<td>327-395</td>
<td>335-373</td>
</tr>
<tr>
<td>CV-2</td>
<td>369-419</td>
<td>452-491</td>
</tr>
</tbody>
</table>
JNES PROJECT
Open Calorimeter Cable Tray Tests
JNES PROJECT
Open Calorimeter Cable Tray Tests
JNES Project
Effect of FR Coating

At 4:00 min flame for uncoated cables has reached the top of the tray, flames for coated are half-way.

At 7:30 min uncoated cables are consumed, coated cables are still burning.
JNES PROJECT
Cable Tray Configurations Tested

- Single Horizontal Open Ladder Tray
- Single Horizontal Open Ladder Tray with Coated Cables
- Stack of Three Horizontal Open Ladder Trays
- Vertical Open Ladder Tray
- Vertical Open Ladder Tray with Coated Cables
- Single Closed Horizontal Tray
APPLICATION EXAMPLE

Fire Scenario

- Switchgear room fire example in Appendix B of NUREG-1934 (NPP Fire MAG)
- Three banks of electrical cabinets (A, B and C)
- Stack of three horizontal cable trays above each bank (A, B and C)
- Fire initiates in electrical cabinet in middle bank
- HRR from NUREG/CR-6850 for cabinet with closed doors and multiple cable bundles
- Cables in trays are CCV
Cabinet Bank A
Cabinet Bank B
Cabinet Bank C
Cabinet Vent (Fire Origin)

Cabinet Width = 1 m
Cable Tray Width = 0.8 m
Cabinet Vent Size = 0.6 x 0.3 m
APPLICATION EXAMPLE
HRR of Electrical Cabinet

![Graph showing Heat Release Rate (kW) vs Time (min)](image-url)
APPLICATION EXAMPLE
Objectives and Results of Analysis

- Use THIEF model in CFAST to determine the time to failure of the CCV cables in the bottom tray above the burning cabinet?
  
  Result: No failure occurs as temperature under the jacket remains below \( T_{\text{fail}} = 400^\circ\text{C} \)

- Use FLASH-CAT model in NUREG/CR-7010 with HRRPUA from ASTM D6113 tests
  
  Result: Shown on the next slide
APPLICATION EXAMPLE
HRR of Stack of CCV Cable Trays

[Graph showing Heat Release Rate (HRR) over time]
JNES PROJECT
HEAF Tests

- Understand HEAF fire at Onagawa on 3/11 that resulted in destruction of 7 electrical cabinets in bank of 10
  - Determine whether one or two HEAFs occurred?
  - Subsequent cable fire
- Energy of main HEAF event is estimated at 280 MJ (7 kV and 20,000 A for 2 seconds)
- Actual HEAF experiments at KEMA
- Simulated HEAF experiments using rocket fuel at SwRI
REFERENCES
NUREGs (1)


REFERENCES
NUREGs (2)


REFERENCES
NUREGs (3)


REFERENCES

NUREGs (4)


REFERENCES

JNES


Hydrogen Garage Study (1)
Hydrogen Garage Study (2)

8% IR Video

Exterior HS Video
Hydrogen Vehicle Study

- Objective: Energy release from explosion of H$_2$ cylinder on a vehicle with non-operative pressure release device
- Methodology: Expose vehicle-mounted type III cylinder at 34 MPa to bonfire
- Results:
  - 13 MJ mechanical and 220 MJ chemical
  - Car untenable in 4 min, cylinder failed at 12 min
  - Vehicle parts up to 100 m from site
  - Ear drum rupture at 15 m, glass breakage at 20 m
If you have any questions or comments feel free to contact me at the following address:

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