Nondestructive Measurement of Cryogenic Fuel Tank Insulation at Kennedy Space Center using Neutron Methods

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12th Int. Symposium on Nondestructive Characterization of Materials
Blacksburg, VA June 23, 2011
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  – Mike Csonka
Outline

• Introduction
• Fast/Thermal neutron analysis
• MCNP Simulations
• Mockup tests at Goddard SFC
• Conclusions
Diagram of Space Shuttle External Tank

Liquid Hydrogen (20.4 K, -423 °F)

Liquid Oxygen (90.2 K, -297°F)
KSC Cryogenic Storage Tank
ISSUES

• History of Perlite settling
• Discoloration in localized areas on tanks
• Increase in boil-off
• **Advantages:**
  - Provides efficient mechanism for analysis of large structures
  - Solar heating allows for visualization of internal structure due to the slower heating of components with larger thermal mass
  - Allows for visualization of areas of heat penetration (insulation voids)

• **Disadvantages:**
  - Results are based on discernable temperature differences and material emissivity
  - Results are dependent on environmental conditions

**IR Thermal Imaging**
Typical Perlite Composition

- Silicon dioxide: $\text{SiO}_2$ 70-75%
- Aluminum oxide: $\text{Al}_2\text{O}_3$ 12-15%
- Sodium oxide: $\text{Na}_2\text{O}$ 3-4%
- Potassium oxide: $\text{K}_2\text{O}$ 3-5%
- Iron oxide: $\text{Fe}_2\text{O}_3$ 0.5-2%
- Magnesium oxide: $\text{MgO}$ 0.2-0.7%
- Calcium oxide: $\text{CaO}$ 0.5-1.5%
- Loss on ignition 3-5%
- Density
  - Expanded 6 lb/ft$^3$
  - Compacted 16.5 lb/ft$^3$
Prompt Gamma Neutron Activation (PGNA)

Capture  \( {\text{Neutron}} \rightarrow {\text{\(^{35}\text{Cl}}\)} \)

Excited State  \(~10^{-14}\) seconds

Gamma–ray Emission  \( {\text{\(^{36}\text{Cl}}\)} \rightarrow 3\gamma \)
Point Source Gamma-ray Production

\[ \gamma_i = n \sigma^i_a f^i y^i_k \phi_{th} \]

where:
- \( \gamma_i \) = gamma ray production rate, photons per second
- \( n \) = number density of atoms of element
- \( \sigma^i_a \) = neutron capture cross-section of \( i^{th} \) isotope
- \( f^i \) = abundance of \( i^{th} \) isotope
- \( y^i_k \) = yield of \( k^{th} \) gamma ray for \( i^{th} \) isotope
- \( \phi_{th} \) = thermal neutron flux, neutrons/cm\(^2\)· second
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Fe, C, Ni, Cr
Stainless Steel
Perlite
Fe, C Carbon Steel
Moderator
Neutron Generator Tube
Liquid
Gamma-ray Detector
Digital Signal Processor
100110110101
Neutron Generator

\[ D + T \rightarrow {}^4\text{He} + n \]

- Magnet
- Source cathode
- Source anode
- Gas reservoir
- Gas pressure control
- Ion source pulser
- Focus lens
- Accelerator lens
- Target
- High-voltage power supply
- High-voltage insulator
MP -320
Neutron Energies

- Neutron Generator \((D + T \rightarrow ^4\text{He} + \text{n})\) 14 MeV
- Thermal 0.025 eV
- Fast > 1 MeV
Fast/Thermal Neutron Interactions

- Prompt Gamma Neutron Activation
- Inelastic Fast Neutron Scattering
- Delayed Activation (radioactive decay)
Inelastic Fast Neutron Scattering

Incident Neutron

$^{35m}\text{Cl}$

Scattered Neutron

$^{35}\text{Cl}$

Gamma–ray Emission

$\gamma$

$\gamma$

$\gamma$
## Elements Typically Detected

<table>
<thead>
<tr>
<th>PGNA</th>
<th>Inelastic</th>
<th>Delayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Al</td>
<td>Fe</td>
<td>Al</td>
</tr>
<tr>
<td>K</td>
<td>Si</td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td>Al</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
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<td></td>
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<td>H</td>
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<tr>
<td>Fe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
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</tbody>
</table>
Project Work Plan

• Phase 1: MCNP numerical simulations
• Phase 2: Measurements on test article at Goddard SFC
• Phase 3: Measurements on cryogenic tanks at Kennedy SC

Feasibility criterion: Detection of 120 cm thick void in perlite
MCNP Geometry
Neutron Parameters, Expanded Perlite

- Slowing-down length: 460 cm (15.1 ft).
- Thermal diffusion length: 238 cm (7.81 ft).
MCNP Simulations

- 24 Perlite layers @ 5 cm thick
- 10 μs time bins
- 260 energy bins
- $10^8$ neutron time histories
- Variance reduction techniques
  - implicit capture
  - weight windows
  - Russian Roulette
  - Particle splitting
  - time cut-off
  - geometry cutoff
Inelastic, Expanded Perlite
Inelastic, Compacted Perlite

![Energy Spectrum Graph](image)
Total Inelastic Counts vs. Perlite Density

Line Fit: Counts = a + b * Density
Coefficient values ± one standard deviation
a = 52461 ± 440
b = 871.47 ± 43.4
R^2 = 0.997529
Inelastic Summary

- Acquisition time: 1 second
- Dynamic range: 39%
- Linearity: $R^2 = 0.999$
- Precision: 0.4%
Test Article, Goddard SFC

- Validate MCNP results
- Determine background level
- Optimize operating parameters
  - Counting time
  - Standoff distance
  - Neutron generator/detector separation
- Establish protocol for field measurements
Field Test at Goddard
Experimental Variables

- Perlite density (void, compacted, expanded)
- Standoff distance (35, 45, 55 cm)
- Neutron source / detector spacing (35, 45, 55 cm)
## Perlite Densities

<table>
<thead>
<tr>
<th></th>
<th>Kennedy SC</th>
<th>Goddard SFC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 lb/cf</td>
<td>4 lb/cf</td>
</tr>
<tr>
<td></td>
<td>16 lb/cf</td>
<td>7 lb/cf</td>
</tr>
</tbody>
</table>
Test Article Preliminary Results

• Very weak correlation between total counts and Perlite density
• Si inelastic peak can discriminate between void and Perlite
• Si inelastic peak can be ambiguous between expanded and compacted Perlite
• Not possible to compare with MCNP simulations due to differing Perlite densities
Conclusions

• Compaction of Perlite insulation is affecting the performance of cryogenic fuel tanks at KSC
• Neutron methods are feasible for NDT of density variations because they are based on the number density of atoms
• Fast neutrons are more suited for measuring compaction, i.e. densities > 6 lbs/cf
• Thermal neutrons are suited for measuring voids, i.e. densities < 6 lbs/cf, if a lanthanum halide detector is used.
Thank you for your attention!

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LH2 Tank Construction

- 850 thousand gallon, double-walled, spherical tank
- Constructed in 1965
- Annular region filled with Perlite insulation and under vacuum
- Inner tank supported by 40 tie rods
- Outer tank reinforced with shell stiffeners
- Outer tank diameter is 70 feet, inner tank diameter is 63 feet
LOX Tank Construction

• 900 thousand gallon, double-walled, spherical tank
• Constructed in 1965
• Annular region filled with Perlite insulation and under slight nitrogen purge
• Inner tank supported by 165 tie rods
• Outer tank diameter is 69 feet, inner tank diameter is 63 feet
D-T Tube Moderator Geometry

Side View

End Cap
Tritium Target
Aluminum Tube

End View
Annulus
MCNP Simulations
(Monte Carlo N-Particle)

Thermal Neutron Flux, n/cm^2 s

End Cap Thickness, cm

Wall Thickness
- 0
- 5
- 10
- 15
- 20
# Effect of Moderator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Without</th>
<th>With</th>
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<tbody>
<tr>
<td>Thermal diffusion length</td>
<td>238 cm</td>
<td>2.24 cm</td>
</tr>
<tr>
<td>Thermal neutron decay time</td>
<td>10.84 ms</td>
<td>168.4 µs</td>
</tr>
<tr>
<td>Thermal/total gamma counts</td>
<td>≈ 0</td>
<td>6%</td>
</tr>
</tbody>
</table>
PGNA, Expanded Perlite

![Graph showing pulse height spectrum vs. energy (MeV). Peaks and valleys indicate different elements and thermal effects.](image-url)
PGNA, Compacted Perlite