Strategy for Glass Waste Form Acceptance for Geologic Disposal

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Summary of Talking Points

1. What are the technical bases, including standards, test methods, and use of databases and models, for DOE’s criteria for qualifying borosilicate glass waste forms as acceptable for disposal in a geologic repository?

2. What is DOE’s technical basis for applying the results of short-term tests on reference glasses or glasses with simplified compositions to assessments of the long-term performance of more chemically complex HLW glasses in repository environments?

3. What is known about the influence of glass chemistry on crystallite precipitation during glass production and on glass corrosion, and how are crystallites taken into account in DOE’s approach to designing glass for disposal in a repository?

4. Are data on natural and archeological glasses used to support DOE assessments of the long-term performance of HLW glass in a repository and, if so, how?
Development of Technical and Performance Standards for HLW Glass

- 1957 - National Academy of Sciences (NAS) recommended deep geologic disposal of HLW once made into a solid form (Disposal of Radioactive Waste on Land)

- Late 1970’s DOE began evaluation of waste forms

- Dec 1982, Record of Decision (ROD) issued selecting borosilicate glass
  - Endorsed by EPA and several independent review groups
  - NRC had no objection

- 1982 Nuclear Waste Policy Act (NWPA) mandated that HLW be sent to a federal repository (based on 1957 recommendation)

- 1985 President ratified the DOE decision to send defense HLW to a civilian repository (Office of Civilian Radioactive Waste Management, OCRWM)

- Early 1990’s Waste Acceptance System Requirements Document (WASRD) generated requiring DOE-EM to develop Waste Acceptance Product Specifications (WAPS)
Waste Form Producer – Repository/Regulatory Interface

Nuclear Regulatory Commission (NRC) (10CFR60)

Environmental Protection Agency (EPA) (40CFR191)

DOE Office of Civilian Radioactive Waste Management (OCRWM)

Licensor/Regulator

Set Standards/Regulatory

Producer

Different Types of Models

DOE Office of Environmental Management (EM)

DWPF-WVDP-WTP
ISSUE: Waste forms being made now must be acceptable to a repository yet to be defined, sited, and/or built.
How Can The Waste Form Producers Comply?

OPTIONS

A. Relate glass dominated short term test results to a “repository relevant” test when a repository is chosen

B. Develop a glass durability standard that meets repository requirements defined by geochemical and HLW performance modeling: All production HLW glasses must be more durable than this standard glass

TECHNICAL JUSTIFICATION

- Perform Long Term (LT) tests (HLW burial glasses and natural analogs)
- Perform repository relevant tests (rock cup tests in tuff, basalt, salt, granite with various groundwaters, at low Eh, etc.)
- Perform in situ tests in repositories (WIPP, STRIPA granite, Ballidon clay UK)
- Perform materials interactions tests (glass & metal, with/without rock present)
- Perform accelerated Short Term (ST) tests (without changing the durability mechanism) with HLW glass and analogs
- Relate LT and ST testing (radioactive and non-radioactive glass testing)
Details of Waste Form Qualification Strategy Used in US (1982-Present)

<table>
<thead>
<tr>
<th>Time Frame</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1982-1983</strong></td>
<td>✓ develop “acceptable waste form durability” from geochemical modeling based on HLW performance modeling</td>
</tr>
<tr>
<td></td>
<td>✓ fractional dissolution rates between $10^{-4}$ to $10^{-6}$ parts per year (ppy)</td>
</tr>
<tr>
<td></td>
<td>✓ a glass waste form would take 10,000 to 1,000,000 years to totally dissolve</td>
</tr>
<tr>
<td></td>
<td>✓ early versions of 10 CFR Part 60.113 specified fractional release rates of $10^{-5}$ ppy</td>
</tr>
<tr>
<td></td>
<td>✓ which was in the middle of the range determined by HLW performance modeling</td>
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<tr>
<td></td>
<td>✓ $10^{-5}$ parts per year was adopted as the waste form specification (ONWI).</td>
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<tr>
<td></td>
<td>✓ if the long-term fractional dissolution rate of a waste form was $\leq 10^{-5}$ parts per year for the most soluble and long-lived radionuclides then borosilicate glass would provide acceptable performance for any repository system</td>
</tr>
<tr>
<td><strong>1987-Present</strong></td>
<td>✓ develop tests (MCC and ASTM) that would provide an understanding of the glass durability mechanisms from a combination of the test protocols</td>
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</table>

## Details of Waste Form Qualification Strategy Used in the US (Cont’d)

<table>
<thead>
<tr>
<th>Time Frame</th>
<th>Strategy</th>
</tr>
</thead>
</table>
| 1987-present   | ✓ generate data for modeling the maximum radioactive release rate(s) in borosilicate glass by relating the release of soluble $^{99}$Tc, $^{129}$I, and $^{135}$Cs to the release of soluble species such as Na, Li, and B soluble species leach at the same rate (congruently)  
✓ this approach (with references) are part of the ASTM C1285 (PCT) protocol |
| 1987- present  | ✓ develop a short term test and process control strategy for ensuring that every glass produced had a dissolution rate <EA glass at the L95% confidence level based on Na, Li, B  
✓ this ensures acceptable performance control (part of the WAPS compliance strategy) |
| 1994-present   | ✓ Continue to test (qualify) the radionuclide response of production glasses to verify that radionuclide release consistent with the releases predicted by Na, Li, B                                                                                                                                 |
| 1996-present   | ✓ develop a borosilicate glass standard  
✓ Environmental Assessment (EA) glass (1981 DWPF EA; Jantzen, et.al. 1992) bounded the upper release rate found to be acceptable from HLW performance modeling and 10 CFR Part 60.113 |
Accelerated Testing: Must Simulate Correct Long Term Mechanism

* As defined at the August, 1998 NAS/NRC Workshop on Test Methods and Models to Simulate Accelerated Aging of Infrastructure Materials
Accelerated Testing: Must Simulate Correct Long Term Mechanism

- Different times, temperatures, and pH regimes simulate different mechanisms.
- Glass corrosion is complex and involves a variety of mechanisms.
- Different tests are needed to study the different mechanistic regimes.
Tests Developed Since 1980

<table>
<thead>
<tr>
<th>Waste Form (Since 1980-Present)</th>
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</thead>
<tbody>
<tr>
<td>Chemical Durability</td>
</tr>
<tr>
<td>MCC-1, 2, 3, 4, 5 (Soxhlet)</td>
</tr>
<tr>
<td>Aging Effects (thermal and radiation)</td>
</tr>
<tr>
<td>MCC-6, 7, 12, 13</td>
</tr>
<tr>
<td>Volatility</td>
</tr>
<tr>
<td>MCC-8, 9, 16</td>
</tr>
<tr>
<td>Physical Strength</td>
</tr>
<tr>
<td>MCC-10, 11, 15</td>
</tr>
<tr>
<td>Canister Container</td>
</tr>
<tr>
<td>Corrosion Resistance</td>
</tr>
<tr>
<td>MCC-101, 102, 103, 104</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Repository Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canister/container corrosion</td>
</tr>
<tr>
<td>MCC-105\textsuperscript{a}</td>
</tr>
<tr>
<td>Waste Form Durability</td>
</tr>
<tr>
<td>MCC-14\textsuperscript{a}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} The repository interactions tests are divided into site-specific subcategories, e.g., MCC-105.1 (basalt).

ASTM C1220 (MCC-1 & 2) (Test Oven)

ASTM C1285 Product Consistency Test (PCT A and B) (MCC-3)

ASTM C1663 Vapor Hydration Test (VHT)

ASTM C1662 Single Pass Flow Through (SPFT) (MCC-4)

ASTM C1220

Test Oven
What Were the Criteria for PCT (ASTM C1285) Test Development in 1986?

- Waste Form Producers needed to ensure the acceptability of High Level Waste (HLW) glass made in DWPF to the geologic repository (testing and modeling)
- Producers needed to define the durability of DWPF HLW glasses before and during production (Waste Acceptance Product Specifications 1.3 and 1.4)
  - WAPS 1.3 - DWPF must demonstrate (during production) control of the radionuclide release properties of the final waste form
  - WAPS 1.4 – determine the release properties of crystallized glass
- Producers needed a test sensitive to glass composition and glass homogeneity
  - Test factors rigorously controlled so that glass composition and homogeneity dominate the test response
  - standardize particle surface area (S)
  - standardize amount of glass to volume of solution
  - standardize test duration
    » short enough for use during production
    » long enough to get good precision/reproducibility
  - standardize test temperature
- Simple sample preparation/procedure for remote operation
- Acceptance by waste form developers and the repository
PCT was shown to be more sensitive to glass composition and homogeneity than other glass durability tests.

PCT can be routinely performed remotely on DWPF glass during production.

Test durations of $\geq 7$ days were shown to be adequate to distinguish between different glass durabilities.

PCT test response has been related to other ASTM HLW glass test responses.

ASTM Committee C26.13 (composed of waste form developers, repository representatives, and the Nuclear Regulatory Commission) peer reviewed the test from 1987 to present.

Independent Confirmation of Test Discrimination Testing at PNNL (Shade & Piepels, 1990-1991; PNL-7530)
These test methods (PCT-A and PCT-B) provide data useful for evaluating the chemical durability of glass waste forms as measured by elemental release. Accordingly, it may be applicable throughout manufacturing, research, and development.

Test Method A (short term) can specifically be used to obtain data to evaluate whether the chemical durability of glass waste forms have been consistently controlled during production.

Test Method B (long term) can specifically be used to measure the chemical durability of glass waste forms under various test conditions, for example, varying test durations, test temperatures, ratio of sample-surface area (\(S\)) to leachant volume (\(V\)), and leachant types. Data from this test may form part of the larger body of data that are necessary in the logical approach to long-term prediction of waste form behavior (see Practice C1174).

CONTROL IS ON GLASS COMPOSITION DEFINED BY GLASS PROPERTIES

- To be a compliant glass, the glass composition must have properties that fall within the solid quadrilateral shown
  - Multivariate theory used to control within multidimensional composition space
- Each process model is based on geochemical principles and/or glass structure models + data
  - Homogeneity: Nolan’s (1966) basalt system (Al₂O₃-[Fe₂O₃-FeO]-Na₂O-SiO₂)
  - Liquidus: Nolan, Bailey & Schairer (1966) crystallization in same basalt system and Burnham’s quasicrystalline theory
  - Viscosity: glass polymerization
  - Durability: PCT-A versus glass polymerization (short range order) and thermodynamics
- SPC accounts for “model error”, analytic error, tank transfer error, and heels
  - 95% confidence is obtained at max WL
DWPF SPC Defines A Qualified Composition Range for Waste Acceptance

MINIMIZES CONFIRMATORY SAMPLES TO BE TAKEN DURING PRODUCTION

- Qualified glass range is processable
  - proven for the last 21 years of DWPF operation
- Process control is used to demonstrate acceptable performance by linking relationships

SPC Durability Model is known as THERMO™ (Thermodynamic Hydration Energy Reaction MOdel)

Compares the durability response of every melter feed batch (once made into glass) to the EA glass at 95% confidence; 2 standard deviations below EA glass

Production control using THERMO™ is based on PCT-A testing

Repository modeling uses a variety of test methods, including PCT-A and PCT-B

The Environmental Assessment (EA) HLW Borosilicate Glass Standard

Table 1-1

<table>
<thead>
<tr>
<th>Property or Characteristic</th>
<th>Borosilicate Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cm³</td>
<td>2.75</td>
</tr>
<tr>
<td>Waste Loading, wt %</td>
<td>28</td>
</tr>
<tr>
<td>Tolerance of Waste Variability</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Long-Term Leachability,* g/m²•d</td>
<td>10⁻³ to 10⁻⁴</td>
</tr>
<tr>
<td>Fractional Release Rate, from Full-Size Form,** yr⁻¹</td>
<td>10⁻⁵ to 10⁻⁶</td>
</tr>
<tr>
<td>Radiation Stability</td>
<td>Very good</td>
</tr>
<tr>
<td>Impact Response,† wt % fines</td>
<td>0.14 to 0.18</td>
</tr>
<tr>
<td>Processability††</td>
<td>Relatively simple</td>
</tr>
</tbody>
</table>

* Based on plutonium leach rates in long-term tests at room temperature.

** Estimated from plutonium leaching data (conservatively assumes that release of radionuclides is not reduced by solubility limitations).

† Generation of particles less than 10 micrometers in size from single impact of 10 J/cm³ energy density.

†† Relative ease of producing the waste form.

- EA glass is the glass that was qualified in the SRP HLW Environmental Assessment (DOE/E-0179)
- Typical Properties and characteristics of borosilicate waste forms provided fractional releases based on Pu leaching of 10⁻⁵-10⁻⁶ assuming no solubility limitations (MCC-1 testing)
For EA - Eliminated U₃O₈ and renormalized the composition

For EA glass manufacture MnO₂ converted to MnO and part of the iron converted to FeO to give an Fe²⁺/ΣFe ratio of 0.18 which corresponds to the REDuction/OXidation (REDOX) that the DWPF flowsheet targets for each waste glass batch

1000 pounds fabricated by Corning Glass Works for usage in DOE complex

Other “standard” glasses can be used to ensure the PCT-A or PCT-B tests are in control include ARM-1 and ARG-1
— PCT-A has been compared to long-term PCT-B (Mueller et.al. 2004 & 2006)
— PCT-A has been related to long-term burial tests (Jantzen, et.al. 2008)
— PCT-B long term tests have been related to shorter term, higher temperature, Vapor Hydration Test (VHT) responses
  e.g. the HLW Environmental Assessment (EA) glass reaches the same stage of durability within 56 days at 20,000 m⁻¹ or >313 days at 2000 m⁻¹ when tested by PCT at 90 °C or within 6 days when tested by VHT at 200°C (Bates, et. al. 1996)
— the rate of the short term crushed glass test (PCT-A) has been shown to be an upper bound for accelerated durability behavior (the resumption of dissolution or Stage III leaching behavior) (Ebert 2000)
Database: Accelerated Leach Testing of GLASS (ALTGLASS)

ALTGLASS constructed by SRNL (2013-Present) from Literature and SRNL Data
- Contains ASTM C1285; PCT A (7day) and PCT B (up to 20 yrs)
- 490 Glasses (113 HLW and 377 LAW) – some exhibit Stage III and some do not

Database Is Being Used to Understand Many Aspects of the Relationship Between Glass Composition and Leaching Behavior (which impacts gel-leachate behavior)
- Dissolution processes of ion-exchange and diffusion form a “hydrogel layer”
- Hydrogels ripen into clays (causing no acceleration of long term durability) when there is little interaction with leachate species
  - Solution is buffered
- Hydrogels ripen/solution precipitates zeolites from strong interaction with leachate species (solution mediated), especially excess OH⁻ (Strong Base) (causing acceleration of long term durability)
  - Solution not buffered, excess (Na,K,Li)OH in leachate interacts with aluminosilicate gel and Al in solution
  - Mimics industrial processing of zeolites from gel and NaOH

The strong base-weak acid model represents effects of solution chemistry on glass dissolution behavior better than pH alone.

Dissolution of some glass compositions generate leachates enriched in strong base, high alkali containing glasses.

Dissolution of other glass compositions generate leachates enriched in weak acids.


Calculated Evolution of Gel Composition from Database

Hydrogel compositions were calculated from differences between measured solution concentrations and predicted based on dissolution congruent with boron.

WA and SB enriched samples were sorted into resumption and non-resumption populations: gel composition trends with reaction time (progress) were investigated with stepwise regression.

SB-enriched sample gels gave Al/Si ratios consistent with zeolite X (2 Al:3 Si) and analcime (2 Al:4 Si).

WA-enriched sample gels gave Al/Si ratios consistent with allophane (2 Al:1.3 Si) and Fe/Si ratios consistent with hisingerite/smectite/nontronite (2 Fe:2 Si).

Solution-Mediated Reactions That May Trigger Stage III Behavior

If leachate is not enriched in strong base:

\[
3Na_2O \cdot 2Fe_2O_3 \cdot 2Al_2O_3 \cdot 12SiO_2 + 17H_2O \rightarrow \text{hydrogel}
\]

\[
2(Fe^{+3})_2Si_2O_5(OH)_4 \cdot 2H_2O + 2(Al_2O_3 \cdot SiO_2) + 6NaOH + 6H_2SiO_3
\]

If leachate is enriched in strong base:

\[
3Na_2O \cdot 2Fe_2O_3 \cdot 2Al_2O_3 \cdot 12SiO_2 + 2LiOH + 7H_2O \rightarrow \text{hydrogel}
\]

\[
2NaLiAl_2Si_4O_{12} \cdot 2H_2O + 2(Fe_2O_3 \cdot SiO_2) + 4NaOH + 2H_2SiO_3
\]

The incorporation of these process dependencies and strong base-weak acid model into Stage 3 model as triggering mechanism is being evaluated.

Summary of Talking Points

1. What are the technical bases, including standards, test methods, and use of databases and models, for DOE’s criteria for qualifying borosilicate glass waste forms as acceptable for disposal in a geologic repository?

2. What is DOE’s technical basis for applying the results of short-term tests on reference glasses or glasses with simplified compositions to assessments of the long-term performance of more chemically complex HLW glasses in repository environments?

3. What is known about the influence of glass chemistry on crystallite precipitation during glass production and on glass corrosion, and how are crystallites taken into account in DOE’s approach to designing glass for disposal in a repository?

4. Are data on natural and archeological glasses used to support DOE assessments of the long-term performance of HLW glass in a repository and, if so, how?
Durability of Homogeneous vs. Inhomogeneous Glasses

Homogeneous Glass

\[
\sum \text{Durability} = \underbrace{\text{durability}_{\text{homogeneous}}}_{\text{1st term}} + \underbrace{\text{durability}_{\text{amorphous phase separation}}}_{\text{2nd term}} + \underbrace{\text{durability}_{\text{crystallization}}}_{\text{3rd term}} + \underbrace{\text{durability}_{\text{accelerated grain boundary}}}_{\text{4th term}}
\]

Phase Separated Glass and/or crystallized glass (requires that distribution of radionuclides amongst the phases be known)

Crystallization of spinel (isometric) produces no impact on glass durability, i.e. does not deplete surrounding glass of glass forming species that can degrade durability

Also done for a variety of other glasses including the Waste Compliance Plan (WCP) glasses that span the range of compositions to be produced at SRS

Effect of Crystallization on Durability -131 Glass

- Crystallization of nepheline (NaAlSiO$_4$; not isometric) does impact glass durability-depletes surrounding glass of glass formers (Si and Al)
- “nepheline discriminator” used as part of process control to avoid HLW glass compositions that could precipitate nepheline during canister cooling


A roadmap for the steps involved in predicting long-term behavior:
(1) problem definition
(2) Testing (includes natural analogs and how to accelerate testing)
(3) modeling
(4) prediction
(5) model confirmation.

Many iterations between testing and modeling
ASTM C-1174 (Testing Module)

III - MODELING

- Conduct Literature Survey
- Conceptualize Model
- Perform Modeling
- Develop Predictions
- Identify Materials Alteration Modes
- Plan Tests
- Conduct Tests for Model Development and Validation
- Analyze & Qualify Data
- Model Validated?
- Yes: Identify Options
- No: Iterate?
- Identify Options
- Yes: Iterate
- No: Select Other Options
- Adopt Model for License Application

II - TESTING

- Examine Analogs
- Identify Analog
- Initiate Confirmation Tests
- Conduct Tests for Model Development and Validation
- Predictions Confirmed?
- Yes: Conduct Tests for Model Development and Validation
- No: Assemble Data

Identify Options

No

Yes

Adopt Model for License Application
Use of Natural and Ancient Glass Analogs

- **Natural Glasses**
  - Obsidians
  - Basalt
  - Tektites

- **Ancient Glasses**
  - Libyan Desert Glass
  - Ancient and Medieval Glasses

- **Other Glasses (Window, Pyrex)**

Helps determine leaching mechanisms, gel formation, gel conversion to clays and zeolites and relations to natural and ancient glasses.

Historical Context for Waste Glass Durability

Glass Composition (mole fraction)

0.14 Na₂O
0.06 MgO
0.05 CaO
0.75 SiO₂

Silicon release from durability testing

Medieval Window Glass ~ 10³ years

R²=0.86

Waste Glasses

Natural Basalts, Obsidian, Tektites of ~10⁶ years

0.14 ΔGₜₜ (kcal/mole)

More Durable

2Na⁺ + 2 OH⁻ + H₂SiO₃

= 0.14 (-28.815)

Mg⁺ + 2 OH⁻ + H₂SiO₃

= 0.06 (-13.888)

Ca⁺ + 2 OH⁻ + H₂SiO₃

= 0.05 (-16.116)

H₂SiO₃

= 0.50 (+5.59)

Sum ΔG° = -2.878 Kcal/mole

Responses to Talking Points

1. What are the technical bases, including standards, test methods, and use of databases and models, for DOE's criteria for qualifying borosilicate glass waste forms as acceptable for disposal in a geologic repository? A variety of ASTM tests are used to determine glass durability mechanisms including PCT-B while PCT-A is used for production quality assurance. The main HLW glass durability standard is the EA glass, the main database of short term PCT-A and long term PCT-B is ALTGLASS, waste form producers use different models (i.e. THERMO™) from the repository modelers.

2. What is DOE's technical basis for applying the results of short-term tests on reference glasses or glasses with simplified compositions to assessments of the long-term performance of more chemically complex HLW glasses in repository environments? Glass standards are complex glasses usually without radionuclides. Glasses with radionuclides were tested and no differences in the leaching characteristics or mechanisms were noted with non-radioactive equivalents which gives confidence that it is acceptable to use these non-radioactive glasses.

3. What is known about the influence of glass chemistry on crystallite precipitation during glass production and on glass corrosion, and how are crystallites taken into account in DOE's approach to designing glass for disposal in a repository? Crystalline phases that are known to impact glass durability are avoided by careful glass formulation. Crystalline phases that do not have an impact on glass durability are allowed.

4. Are data on natural and archeological glasses used to support DOE assessments of the long-term performance of HLW glass in a repository and, if so, how? Natural analog glasses have been a part of DOE assessments of long-term performance since the late 1970’s. Natural analogs help determine leaching mechanisms, gel formation mechanisms, gel conversion to clays and/or zeolites, longevity of waste form (historical context).
Backup Slides
Waste Acceptance Product Specifications (EM-WAPS-Rev. 3)

**WAPS 1.0** Waste Form Specifications (Glass or RW Equivalent and complies with NWPAA)
- **WAPS 1.1** Chemical Composition (projections and during production)
- **WAPS 1.2** Radionuclide Inventory (projections and during production)
- **WAPS 1.3** Product Consistency (more durable than the EA glass by two standard deviations; can project durability and/or meas. production glasses)
- **WAPS 1.4** Phase Stability
- **WAPS 1.5** Hazardous Waste
- **WAPS 1.6** IAEA Safeguards

**WAPS 2.0** Canister Specifications
- **WAPS 2.1** Material
- **WAPS 2.2** Fabrication and Closure
- **WAPS 2.3** Identification and Labeling
- **WAPS 2.4** Canister Dimensions

**WAPS 3.0** Canistered Waste Form
- **WAPS 3.1** Exclusion of free liquid/gases
- **WAPS 3.2** Tamper Indicating Seals
- **WAPS 3.3** Exclusion of explosive, pyrophoric and combustible materials
- **WAPS 3.4** Exclusion of organics
- **WAPS 3.5** Chemical Compatibility
- **WAPS 3.6** Metric Tons of Heavy Metals
- **WAPS 3.7** Surface Decontamination
- **WAPS 3.8** Heat Generation
- **WAPS 3.9** Maximum Dose Rates
- **WAPS 3.10** Subcriticality
- **WAPS 3.11** Weight and Overall Dimensions
- **WAPS 3.12** Drop Test
- **WAPS 3.13** Handling Features
- **WAPS 3.14** Plutonium Concentration

**WAPS 4.0** Quality Assurance
- RW-0333P

SRNL-STI-2017-00377

We put science to work.™
<table>
<thead>
<tr>
<th>Vitrification Plant</th>
<th>Borosilicate Waste Glass Produced (metric tons)</th>
<th>Waste Loading Range (wt%)</th>
<th>Size of Canisters (meters)</th>
<th>Number of Canisters</th>
</tr>
</thead>
<tbody>
<tr>
<td>DWPF Savannah River Site*</td>
<td>7200 (1996-2013)</td>
<td>28-40</td>
<td>0.61 x 3.05</td>
<td>4,242 made</td>
</tr>
<tr>
<td>West Valley Demonstration Project (WVDP)†</td>
<td>~573.8 (1996-2002)</td>
<td>~20.4-23.5</td>
<td>0.61 x 3.05</td>
<td>275 made</td>
</tr>
<tr>
<td>Hanford Waste Treatment Plant HLW**</td>
<td>31,968 (projected)</td>
<td>~35-40</td>
<td>0.61 x 4.57</td>
<td>0</td>
</tr>
</tbody>
</table>

*Chew and Hamm 2016
**Certa et. al. 2011
† T Palmer, et. al 2004