General Training On Methodologies For
Geological Disposal in North America
IAEA Network of Centers of Excellence

Engineered Barriers:
Buffer, Backfill and Sealing Materials

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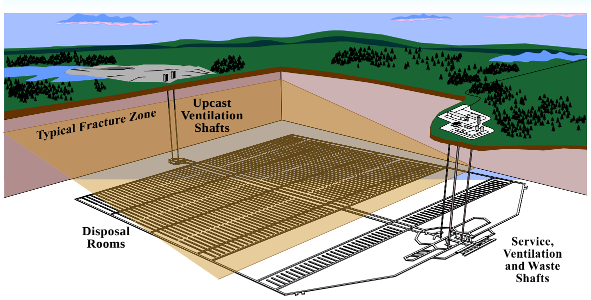
What Are Engineered Barriers?

- Beyond the emplaced waste container, the engineered barriers system consists of a series of compatible and effective engineered seals
- Each seal type has specific requirements that depend, somewhat, on the host-rock environment
- Their function is to isolate and protect the waste container and retard any movement of <u>deleterious</u> materials between the container and the host rock
- Isolation must be effective over the long term

Nuclear Fuel Waste Repository Concept



Generic Geologic Repository Concept

Features common to most concepts:

- Identify practicable site characterization and long-term monitoring methods
- Determine the performance of hard, brittle rock under repository conditions
- Evaluation of the properties and performance of engineered materials (i.e. copper, bentonite-clay and cement-based materials)
- Develop fabrication and inspection concepts for container and engineered barriers

What May A Sealing System Include?

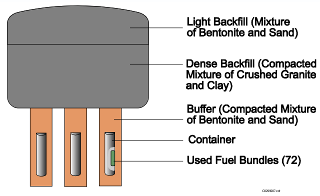
- The near-field rock: disturbed or damaged by excavation
- An engineered barrier material to fill any voids (e.g., clay- and cementitious-based materials)
- Sealing interfaces within the engineered barrier components (e.g., container-seal, concrete-clay or any other interfaces between components)
- Sealing interface between the rock and the sealing system
- Grout injection into interfaces or near-field damaged rock

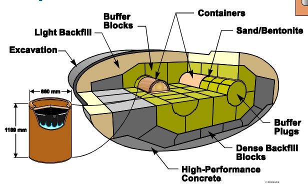
Location of Engineered Barriers

- Around containers within the emplacement rooms
- At emplacement room entrances
- Strategically located in access tunnels
- At hydraulically active discontinuities
- In access shafts, ramps or adits
- In boreholes

AECL's Previous Emplacement Geometries

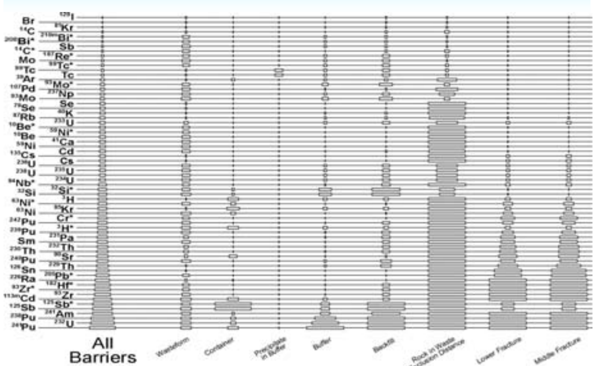
Base Case: In-floor method with 3 rows of relatively small containers along the length of the emplacement room





Second Case Study: In-room method with 2 rows of containers along the length of the room

Barrier Performance Analysis – 100,000 years



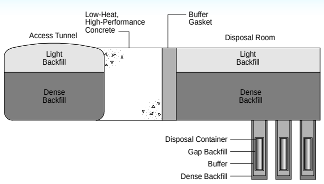
Sealing Material Functions

- Protect waste package
- Fill excavated void volume
- Stabilize local environment
- Limit groundwater flow (to and fro)
- Limit contaminant transport (to and fro)
- Protect workers (preclosure & retrieval)

Performance

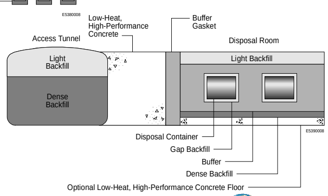
- Swelling capability
- Cation exchange capacity
- Permeability (hydraulic and gas)
- Waste package support strength
- Heat transfer
- Functional life
- Compatibility with abutting materials and groundwater
- Microbe viability
- Ground support pressure
- Resistance to erosion, extrusion, expansion

OPG's Current Emplacement Geometries

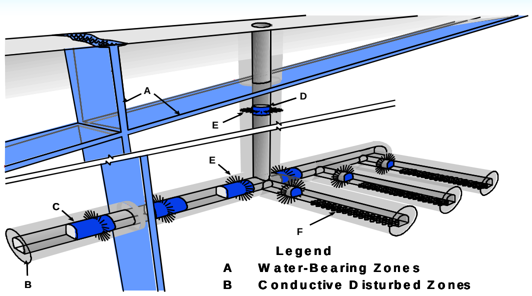


In-Floor Geometry
A single row of boreholes with large containers

In-Room Geometry
Two rows of large containers along the length of a room

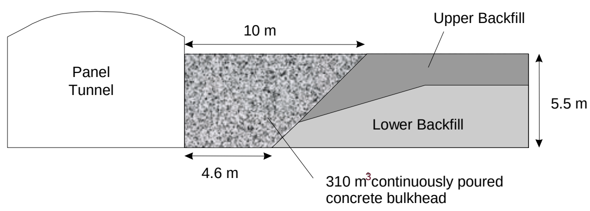


Engineered Barriers Beyond Rooms



Legend
A Water-Bearing Zones
B Conductive Disturbed Zones
C Tunnel Plug
D Shaft Plug
E Grouted Cut-Offs
F Waste-Emplacement Holes

Emplacement Room Seals



Location & Functions of Room Seals

- Located at entrance to emplacement rooms
- Concrete provides restraint of swelling buffer and backfill
- Hydraulically isolates the emplacement room from access tunnel
- Allows buffer and backfill to take on water to generate swelling pressures and isolate these materials from possible drying effects by tunnel ventilation
- Part of nuclear materials safeguards system for the spent fuel in the containers (if required)

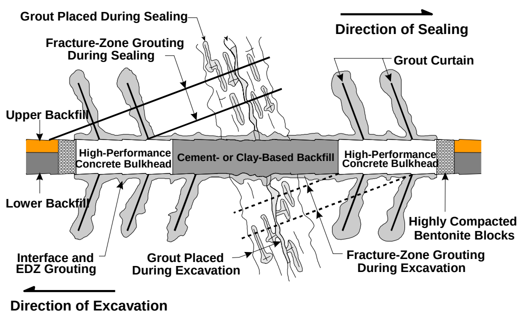
Fracture Zone and Shaft Seals

Fracture Zone and Shaft Seals are similar in purpose and composition

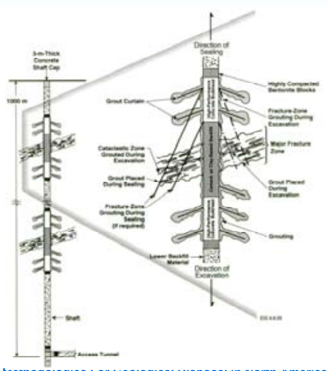
Purpose: To isolate the tunnel or shaft from the regional groundwater flow system and prevent contaminants from entering potential transport pathways that intersect with the surface.

Composition: Composites of compacted bentonite and concrete seals, with damage zone/fracture zone grouting, on either side of the fracture zones that are intersected by the tunnels or shafts.

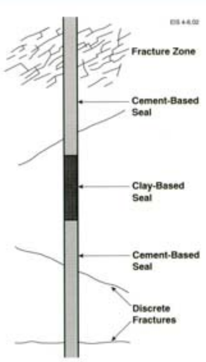
Fracture Zone Sealing



Shaft Seals



Borehole Sealing Concept



- Composite seal including cement-based and clay-based materials
- Cement-based materials, having low hydraulic conductivity and resist erosion by moving groundwater
- Clay-based materials provide a self-sealing capacity to the concrete sections

Sealing System Specification Development

AECL developed two case studies based on in-floor borehole and in-room emplacement methods for small titanium-shell containers

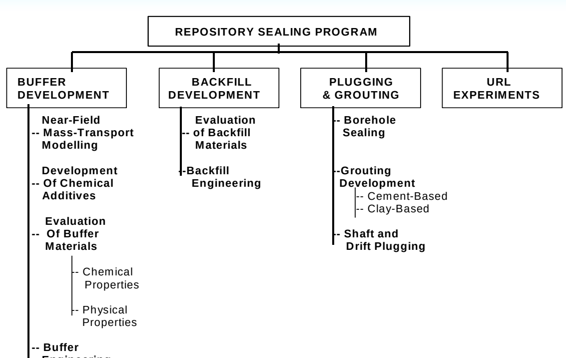
Ontario Power Generation (OPG) developed a third case study based on modified emplacement methods with large copper-shell containers

The case studies did not specify a set of sealing materials but presented “reference” sealing materials and geometries that appeared to be suitable for use and that could be further developed into an “optimized” sealing system

Identifying Potential Sealing Components

- Screen a wide variety of potential materials
- Identify one or more candidate materials
- Characterization candidate materials
- Develop a set of potentially workable materials for use in performance assessment
- Develop and test a variety of numerical models for use as performance assessment tools for application at an actual repository
- Conduct optimization to develop formal specifications for materials and a toolbox of sealing technologies for use in repository design

Repository Seal Research Program



Selection of Barrier Components

Define the Function and Performance of the Buffer

- Retard the movement of groundwater and contaminants by limiting flow to that of diffusion, by enhancing sorption of contaminants and by modifying the chemistry of the groundwater
- Limit the container corrosion rate by inhibiting the movement and modifying the chemistry of groundwater near each container
- Limit the waste form dissolution rate by inhibiting the movement and modifying the chemistry of groundwater near each container

Possible Choices of Buffer Materials and Their Purposes
(after Bird (1979) and Bird and Cameron (1982))

Physical and Chemical Properties Required	Possible Buffer Materials
• Adequate bearing capacity to support waste container and sufficiently plastic to dissipate high localized stresses. • Low permeability & porosity to limit groundwater flow & ionic diffusion. • Thermal Conductivity equal to or greater than surrounding rocks • Long-term thermal stability/ predictability under conditions of: • Temperature < 150°C at the buffer-container surface. • Temperature ~ 100°C in repository. • Pressures of 5 to 45 MPa. • Good sorption characteristics for radionuclides • No unfavourable chemical interactions with waste container or waste form. • Very low solubility in groundwater. • Availability in sufficient quantities • Ability to be handled / emplaced (engineering technology)	• Bentonite clay • Bentonite clays mixed with crushed roc • Kaolinitic clays • Illitic clays • Synthetic swelling materials such as MgO and silica gel • Zeolite minerals • Anhydrite • Crushed rock that will hydrate readily and increase in volume (olivine, gabbrc peridotite, dunite) • Inorganic metals, oxides, sulphides, carbonates and phosphates. • Graphite • Other materials

Selection of Barrier Components: Buffer

Buffer development for the Canadian repository concept influenced by work initially performed by SKB prior to 1980 where highly compacted bentonite (HCB) was proposed

The SKB HCB buffer had:

- High swelling pressure (>5 MPa)
- Low hydraulic conductivity (<<10^{-10} m/s)
- Adequate thermal and mechanical properties
- Essentially insensitive to changes in groundwater salinity

Selection of Barrier Components: Buffer

Concerns with HCB in early 1980's:

- High-swelling pressures, especially if a thin-walled container is selected. Is 5-10 MPa necessary to accomplish the sealing requirements?
- Practicability of manufacturing and assembling large numbers of HCB buffer segments in the borehole geometry
- Material cost (bentonite is expensive)
- Cost of manufacturing HCB blocks

AECL surveyed potential clay and non-clay buffer materials and focused research on bentonite-based materials since they provided a self-sealing capability

Development of Buffer

- Identified bentonite as a suitable sealing material
- Defined the Effective Clay Dry Density (ECDD) and Effective Montmorillonite Dry Density (EMDD) to accurately describe the swelling pressure, hydraulic conductivity and diffusion behaviours solely by the dry density of the smectite component of the system
- Aggregate materials and non-swelling clays act as inert fillers in bentonite–aggregate mixtures, the presence of >50 wt% of bentonite does not result in any improvement in swelling pressure, hydraulic conductivity or diffusion characteristics for a given compactive effort

Definitions of ECDD, EMDD & EMWC

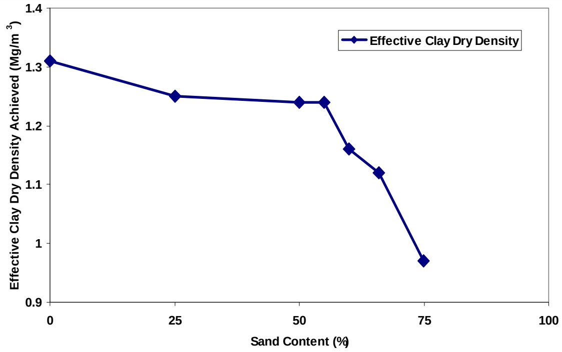
Principle – Clay, particularly montmorillonite, is the sole or active component affecting sealing material behaviour – other materials effectively inert

ECDD (effective clay dry density) =
mass of clay/(volume of clay + void)

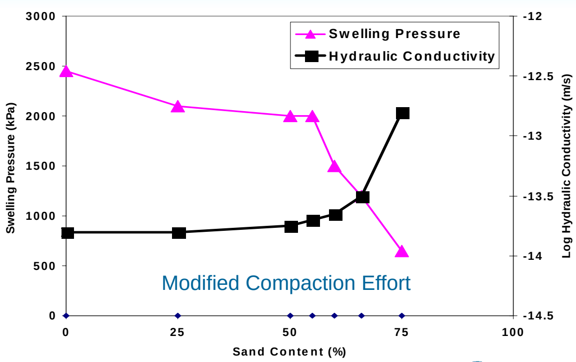
EMDD (effective clay dry density) =
mass of montmorillonite/(volume of montmorillonite + void)

EMWC (effective montmorillonite water content) =
mass of water/mass of dry montmorillonite

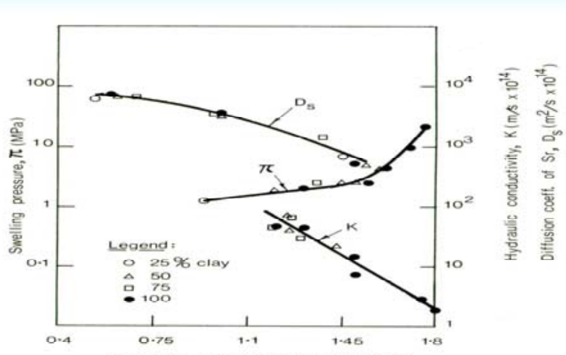
Effect of Sand Content on ECDD



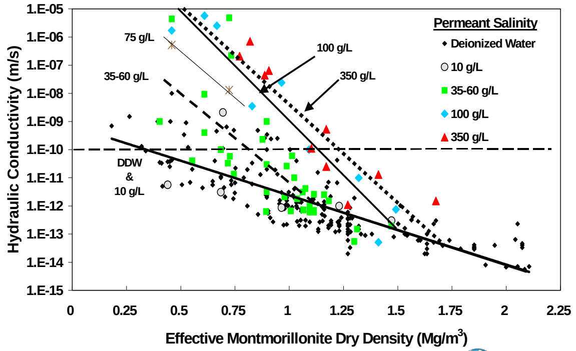
Sand Effect on Behaviours



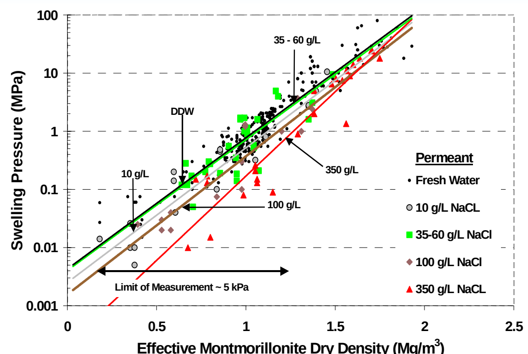
Effect of ECDD on Behaviours



Effect of Salinity on Hydraulic Conductivity



Effect of Salinity on Swelling Pressure



Results of Research on Bentonite

- Means developed to predict the swelling, hydraulic and diffusive characteristics of bentonite-based materials under a range of potential density and groundwater conditions
- A barrier material can be “tailored” to suit a wide range of field conditions (e.g., salinity)
- A general “tool box” developed to be used in design, providing for a robust sealing system
- The tool box can be used to describe non-buffer materials (backfill)

Backfill Development

Backfill requirement:

- Fill the remaining void in emplacement rooms to maintain the buffer and containers securely in place
- Fill the tunnel and shaft voids to prevent future access and any excavation flow paths
- To retard the movement of contaminants by slowing any movement of groundwater, by enhancing sorption of contaminants and by chemically conditioning the groundwater

Backfill Development

Practical needs for backfilling rooms and tunnels led to defining two different backfills

Dense Backfill

To fill the lower portions of the tunnels and rooms

Light Backfill

To fill the uppermost and perimeter regions of tunnels and rooms

Required Backfill Characteristics

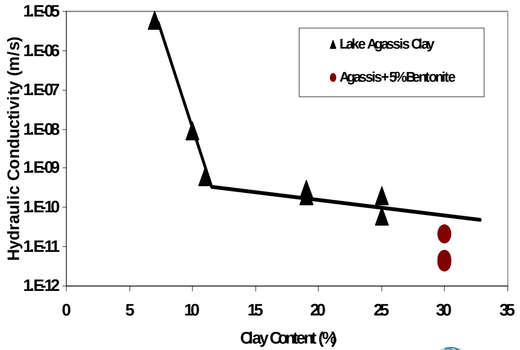
Dense Backfill

- *In-situ* compacted or precompacted-block placement
- High mechanical strength and low compressibility
- High volumetric stability
- Self-sealing capacity
- Relatively insensitive to groundwater chemistry
- Adequate thermal conductivity

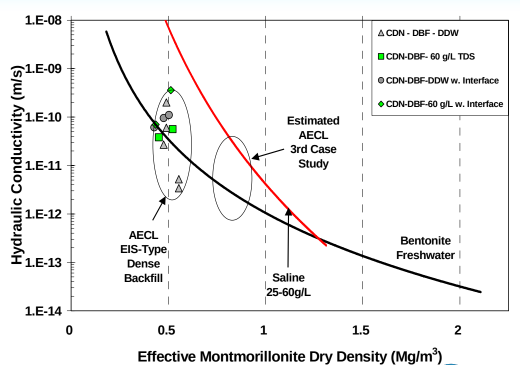
Light Backfill

- Self-sealing capacity at the room perimeter
- Maintain low hydraulic conductivity

Dense Backfill Of Various Clay Contents



Characterization of Dense Backfill



Light Backfill

- Light backfill formulation and placement continues to prove problematic
- Materials can be placed with pneumatic or *in-situ* compaction technologies, depending on access
- High bentonite content (>30%) proposed
- Achieving material placement with consistent and sufficient density for performance under saline conditions not yet demonstrated
- EMDD and salinity relationships are directly applicable to the proposed LBF formulations, enabling the buffer design tool box for use in predicting LBF performance

Concrete and Grouting Materials

- U/G excavation needs some water-ingress control
- Concrete needed for construction of rigid walls and restraint systems
- In-room emplacement method requires a smooth and durable floor for placement of pre-compacted buffer and backfill blocks where concrete is a candidate
- Durability of cementitious materials in a repository environment was an early unknown and could adversely affect the groundwater chemistry (e.g., high pH of conventional cement) and alteration of smectite minerals

Concrete and Grouting Materials

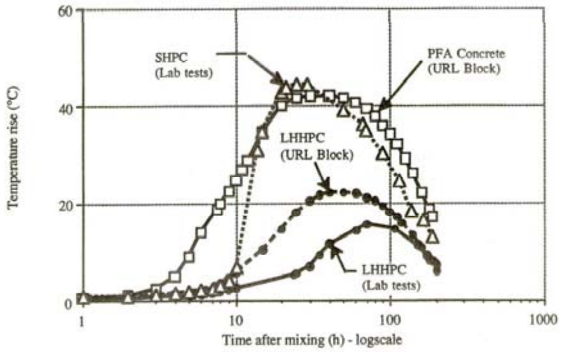
- Conventional concrete and cement grouts generate high pH, based on large quantities of unreacted lime ($Ca(OH)_2$), and generate heat during the curing
- Conventional concrete and grouting materials are unstable over the long-term and their performance are uncertain
- Investigations examined:
  - high strength
  - low pH (low lime content)
  - low heat generation during curing
  - low permeability
  - high chemical stability

Concrete and Grouting Materials

Investigations focused on reducing lime content of cement (heat generation, pH and chemical stability). Pozzolan (silica fume) replaced most portland cement in Low-heat, High-performance concrete (LHHPC) resulting in:

- Reduced heat during curing (temperature rise from ~40°C down to <20°C)
- Reduced pH (from >11 to ~9)
- Eliminated most lime content
- Produced a finer texture (smaller pore size)
- Greatly reduced its hydraulic conductivity
- Increased concrete long-term durability

Concrete Heat Generation



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Grout Material for Repository Use

Grouting may be needed to inhibit excessive groundwater flow at hydraulically critical points, such as around bulkheads, around plugs and in the EDZ

Cement grouts have similar issues as concrete on the chemical effects on the surrounding groundwater and long-term durability

Also grout must effectively enter into very small openings (e.g., fractures and gaps)

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Grout Material for Repository Use

- High pH of grouts due to high lime content of the portland cement. Much cement was replaced with a pozzolan (silica fume)
- Silica fume reduced lime content of the hardened paste, reduced the average pore size, increased chemical durability and decreased hydraulic conductivity
- Cement component was reground to a much finer than normal size, that resulted in a grout that enters fine cracks (e.g., 10 – 20 μm wide) and produces finer texture

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Demonstration of Grout & Concrete Materials & Technologies

Laboratory development and characterization of specialty concretes and grouts identified candidate materials that appeared to have the desired/ required physical, chemical and hydraulic characteristics

After laboratory characterization, these materials were demonstrated under realistic geologic conditions in a URL

These materials were used in a number of sealing experiments in the well characterized rock mass of the URL and under conditions that facilitated extended monitoring of performance

Summary of Laboratory Developments

Means developed for predicting swelling, hydraulic and diffusion characteristics of buffer and backfills for a wide range of repository conditions

Range of materials characterized, facilitating the use of materials from various sources

Special grouts and concretes developed that should be compatible with the geosphere and clay-based materials

A knowledge-base of materials and a design tool box developed for potential for use in repository sealing

Laboratory Knowledge to Field Applications

The broad knowledge gained of materials properties from laboratory testing must be “validated” via field applications to prove both their performance and engineering viability

All parameters cannot be accurately simulated or predicted in the laboratory and this may affect barrier performance. Field testing provides the opportunity to identify and/or correct them

From the combination of laboratory, bench-scale and field demonstrations, confidence will be developed in the sealing approaches proposed for a variety of geologic environments

Defining the Design and Performance Requirements for Engineered Barriers

- With demonstration of the constructibility and performance of the sealing system components, practicable Preliminary Design Requirements (PDRs) can be developed for repository seals
- PDRs based on actual experience define the functional and performance requirements by which objective repository design can be accomplished
- The PDRs will evolve with experience and must be flexible to accommodate actual encountered field conditions

Canadian *In-Situ* Engineered Barriers Studies

- *In-situ* engineered barrier studies developed from a need to demonstrate, on an engineering scale, the appropriateness of the designs proposed for seals and the field performance of materials selected as the result of laboratory testing.
- *In-situ* engineered barriers demonstrations served to identify processes that were not initially recognized in laboratory-scale investigations or cannot be simulated in the laboratory but have the potential to affect barrier performance.

Canadian Engineered Barrier Experiments

Fracture Zone 2 Grouting
Buffer/Container Experiment
Isothermal Test
Composite Seal Experiment
Tunnel Sealing Experiment (TSX)
Pneumatic Shotclay Placement Trials

Some of which are discussed in Session 16: Underground Exploratory Studies

Processes Examined at the URL

- The full range of thermal, hygroscopic, hydraulic, mechanical, chemical and microbiological processes
- Constructability – the human, equipment and workplace factors that influence the ability to place or install the sealing materials within a confined and harsh underground environment

  (i.e., in the 'as-built' form and scale as opposed to idealized laboratory form and scale)

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