

Architectural Space Requirements and Structural Thermodynamics for Subterranean and Agricultural Food Storage Systems

Introduction

The engineering of passive agricultural storage systems capable of preserving a full year's harvest for a single-family unit represents a highly complex, interdisciplinary endeavor. The architectural design process must rigorously synthesize geotechnical engineering, thermodynamics, psychrometrics, structural mechanics, and biological mass transfer. Unlike modern active refrigeration, passive and low-energy agricultural storage relies entirely on architectural geometry, advanced material science, and the precise manipulation of environmental physics to arrest the senescence and decay of organic matter.

To draft the precise architectural space requirements—specifically calculating the exact cubic footage for earth-sheltered root cellars, dry grain silos, and cold-smoking meat preservation structures—the foundational volumetric demand must first be established based on human nutritional intake models. From this volumetric baseline, the structures must be engineered to withstand the immense gravitational and lateral loads of bulk solids and saturated earth, regulate phase-shifted geothermal waves, and safely manage the metabolic off-gassing and hygroscopic expansion of the stored agricultural products. This report provides an exhaustive analysis of the physical principles, empirical standards, and spatial calculations required to design high-performance food storage architecture.

Nutritional Baseline and Raw Mass Calculations

Architectural space requirements are strictly dictated by the total mass of the annual harvest, which is fundamentally tied to the per capita consumption rates of the target demographic. For the purpose of this structural analysis, a standard single-family unit is defined as four individuals.

Consumption statistics provided by the German Federal Ministry of Food and Agriculture (BMEL) and related dietary studies provide a robust baseline for agricultural demand in a developed context [cite: 44-56, 190-205]. The data indicates that the average annual per capita consumption includes approximately 93 kg of bread and cereal products¹, 71.7 kg of potatoes, 98.6 kg of general vegetables, and 66.5 kg of fruit³. Furthermore, annual meat consumption in the developed world averages 80 kg per capita⁴.

Scaling these per capita metrics to a four-person family unit yields the gross mass requirements necessary to sustain the group for one year. To translate this raw mass into spatial cubic footage, the specific bulk density of the agricultural commodities must be applied. The American Society of Agricultural and Biological Engineers (ASABE) provides

standardized bulk densities under standard D241.4, which dictates the specific gravity and mass-moisture relationships of grains and seeds for storage⁶.

Commodity Classification	Approximate Bulk Density (kg/m ³)	Approximate Bulk Density (lb/ft ³)	Gross Mass Required (4-person family)	Raw Material Volume Required (ft ³)
Wheat / Heavy Grains	772	48.1	372.0 kg	17.0 <i>ft</i> ³
Potatoes / Root Vegetables	721	45.0	286.8 kg	14.0 <i>ft</i> ³
Assorted Vegetables & Fruits	609 - 673	38.0 - 42.0	660.4 kg	36.0 <i>ft</i> ³
Fresh Meat / Carcass	1000	62.4	320.0 kg	11.3 <i>ft</i> ³

While the absolute raw volume of the commodities presented in the table is relatively small, the architectural structures housing them must be exponentially larger. The design must account for void fractions (porosity), aerodynamic spacing for respiration, structural ullage, internal diffusion pathways, and human operational access.

Earth-Sheltered Root Cellar Engineering

Root crops and orchard fruits are living, breathing organisms that continue to undergo aerobic respiration post-harvest. The primary objective of an earth-sheltered root cellar is to maintain a strict, unvarying internal environment of $0 - 4^{\circ}C$ ($32 - 40^{\circ}F$) coupled with high relative humidity (80-95%) to optimize the long-term preservation of agricultural produce⁸. To achieve this, the subterranean structure must function as an active, self-regulating thermodynamic system, balancing geothermal heat flux, convective cooling, and the massive structural loads exerted by saturated soils.

Geothermal Heat Transfer and the Kasuda Model

The foundational principle of an earth-sheltered cellar is the complete decoupling of the internal environment from the high-frequency, high-amplitude diurnal temperature swings of the surface. By leveraging the immense thermal inertia of the earth, surface temperature fluctuations are forced to propagate downward as heavily damped, phase-shifted thermal waves, ultimately arriving at the structure months after they occur on the surface [cite: 1,

249-254].

To mathematically predict the soil temperature at any specific depth and time of year, geotechnical engineers utilize the analytical model formulated by Kasuda and Archenbach, derived from the one-dimensional Fourier heat conduction equation⁸. Frequently integrated into dynamic simulation software such as TRNSYS, the subsurface temperature $T_{soil}(z, t)$ is expressed as:

$$T_{soil}(z, t) = T_{mean} - T_{amp} \cdot \exp\left(-z\sqrt{\frac{\pi}{\alpha\tau}}\right) \cdot \cos\left(\frac{2\pi}{\tau}(t - t_{shift})\right)$$

Where T_{mean} is the mean annual surface temperature, T_{amp} is the amplitude of the annual surface temperature wave, z is the depth below the surface in meters, α is the thermal diffusivity of the soil, τ is the period of the temperature cycle (typically 365 days), t is the current day of the year, and t_{shift} is the day of the year corresponding to the minimum surface temperature⁸.

The exponential term in the Kasuda equation governs the amplitude attenuation. Because of the high thermal inertia of the soil, short-period diurnal temperature variations effectively vanish beyond a depth of 0.5 to 1.0 meters. The cosine term dictates the temporal phase lag. Empirical data demonstrates that at a depth of 2 to 4 meters, the maximum ground temperature occurs approximately 160 days (5 to 6 months) after the peak surface temperature⁸. Therefore, embedding the root cellar exactly within this shallow active zone allows the structure to capture the extreme phase-shifted cold of the winter just as it arrives in mid-summer.

Soil Physics and the Johansen Method

The velocity and penetration of the thermal wave are entirely dependent on the thermal diffusivity (α) of the soil, which is mathematically defined as the ratio of thermal conductivity (λ) to volumetric heat capacity (C_v). However, soil is a multiphase system consisting of solid mineral particles, liquid water, and air⁸. Because air is a poor thermal conductor, as the volumetric water content of the soil increases, water displaces air within the pore spaces, drastically altering the thermal properties of the matrix. The Johansen method calculates the thermal conductivity of the soil as a linear interpolation between its completely dry (λ_{dry}) and completely saturated (λ_{sat}) states, weighted by the dimensionless Kersten number (K_e)⁸. As a dry soil begins to wet, conductivity increases

much faster than heat capacity, causing diffusivity to rise sharply. Diffusivity typically reaches its absolute maximum at a moderate volumetric water content before slowly declining as total saturation approaches⁸. If a root cellar is constructed in a high-diffusivity medium, such as highly compacted saturated sand, it will suffer from rapid thermal bridging to the surface, necessitating deeper excavation and augmented engineered insulation⁸.

Structural Mechanics and Geotechnical Forces

The burial of a rigid structure under several feet of earth exposes it to immense, continuous gravitational and geotechnical forces. The vertical pressure exerted on the roof diaphragm is dominated by the dead load of the backfilled soil, calculated by multiplying the depth of the soil cover by the bulk unit weight of the soil (typically 120 to 135 pounds per cubic foot for loam or sandy clay)⁸. A cellar roof buried beneath 3 feet (0.91 meters) of loam must support a constant vertical dead load of approximately 360 pounds per square foot (psf), or 17.2 kPa⁸.

Simultaneously, the subterranean walls must resist lateral earth pressure. Because root cellar walls are rigidly propped by the floor slab at the base and the roof diaphragm at the top, they cannot yield enough to mobilize the "active" earth pressure state. Therefore, engineers must

design for the considerably more severe At-Rest Earth Pressure (K_0) condition⁸. The coefficient of at-rest earth pressure is commonly estimated using Jaky's simplified empirical relation based on the effective internal friction angle of the soil (ϕ') :

$$K_0 \approx 1 - \sin(\phi')$$

For an 8-foot (2.44-meter) high cellar wall embedded in silty sand with an Equivalent Fluid Pressure (EFP) of 60 psf/ft, the maximum soil pressure at the base of the wall is 480 psf (23 kPa)⁸. The bending moment generated by this pressure profile is immense, mandating the use of heavy reinforced concrete. To safely span these forces without catastrophic shear failure or excessive deflection, walls and roof slabs typically require a minimum of 8 to 10 inches (200-250 mm) of high-strength concrete, heavily gridded with rebar⁸. Unconventional architectures, such as buried corrugated steel shipping containers, experience rapid inward buckling and catastrophic collapse because their monocoque walls possess minimal lateral yield strength⁸.

Hydrological Defenses and Subterranean Waterproofing

Water management is the single most critical factor in subterranean engineering. The presence of groundwater fundamentally alters load calculations via hydrostatic uplift and creates an environment highly susceptible to uncontrolled biological contamination. The preeminent international framework for addressing external hydrological threats is the European DIN 18533 standard: *Waterproofing of Components in Contact with the Ground* [cite: 1, 33, 293-308].

DIN 18533 Exposure Class	Hydrological Condition	Prescribed Waterproofing
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		Strategy
W1.1-E / W1.2-E	Soil moisture and non-accumulating seepage water in highly permeable soils.	Polymer-modified bitumen thick coatings (PMBC), flexible mineral sealing slurries (MDS). Strict minimum dry film thicknesses apply.
W2.1-E / W2.2-E	Pressing water. W2.1-E is for moderate pressure (<3m head). W2.2-E is for high hydrostatic pressure (>3m).	W2.1-E permits robust PMBC. W2.2-E absolutely mandates heavy sheet waterproofing (bitumen/elastomeric membranes) or fully waterproof concrete.
W3-E	Non-pressing water on earth-covered ceilings/roofs.	Heavy structural drainage boards and robust sheet membranes (EPDM rubber) to prevent localized ponding.
W4-E	Splash water at the base plinth and capillary water migrating vertically.	Splash protection elevation to at least 15 to 30 cm above ground level, integrated with horizontal cross-sectional damp proof courses.

For retrofitting or constructing inside complex hydrostatic environments, British Standard BS 8102:2022 defines "Type C" waterproofing, which provides drained protection [cite: 315-326]. Rather than attempting to block high-pressure water entirely, a cavity drain system accepts that water may penetrate the outer structural shell. It utilizes an 8mm studded high-density polyethylene (HDPE) membrane fixed to the internal walls and a heavier 20mm studded membrane across the floor¹¹. The studs create a discrete depressurization cavity. Water breaching the concrete flows down behind the membrane under gravity, collects in a perimeter drainage channel (such as BaseDrain) at the floor-wall junction, and is directed to a mechanical dual-pump sump chamber for external evacuation [cite: 316-318].

To completely decouple the structure from summer solar heat gain and winter frost

penetration, engineered "umbrella insulation" must be deployed horizontally outward from the cellar roof. Organic foams like Extruded Polystyrene (XPS) or Expanded Polystyrene (EPS) are frequently compromised by compressive creep, vapor diffusion, and catastrophic destruction by tunneling rodents⁸. Therefore, cellular glass (e.g., FOAMGLAS or GLAPOR) is the mandated specification. Cellular glass achieves extraordinary compressive strengths (up to 1,600 kPa), remains entirely vapor-tight, and is fundamentally impervious to rodents, insects, and aggressive root penetration, ensuring a permanent thermal break⁸.

Psychrometrics, Condensation Control, and Aerodynamics

Root crops require a high internal relative humidity, typically between 80% and 95%, to prevent the desiccation and wilting of stored tissues. However, maintaining such extreme moisture levels places the environment perilously close to the dew point. The thermodynamic relationship between temperature, relative humidity, and condensation is governed by the

Magnus-Tetens equation⁸. The dew point temperature (T_d) calculation relies on the ambient dry-bulb air temperature (T) in degrees Celsius and the relative humidity (RH) :

$$\gamma = \frac{17.625 \cdot T}{243.04 + T} + \ln \left(\frac{RH}{100} \right)$$

$$T_d = \frac{243.04 \cdot \gamma}{17.625 - \gamma}$$

For a root cellar successfully maintained at $4^{\circ}C$ with a relative humidity of 90%, the calculation yields a dew point of approximately $2.5^{\circ}C$ ⁸. If any interior surface within the cellar drops to this temperature—a highly likely scenario during deep winter via thermal bridging—catastrophic condensation will spontaneously form. Liquid moisture dripping directly from a flat ceiling onto stored organic tissue promotes rapid fungal proliferation, botrytis blight, and bacterial soft rot, which can decimate an entire harvest in days⁸. To geometrically mitigate this psychrometric risk, architectural design principles universally mandate a vaulted or arched ceiling. The pitch prevents water droplets from exceeding their surface tension threshold, forcing condensation to adhere via capillary action and safely shed down the curvature of the arch to drain harmlessly into a gravel floor⁸.

Furthermore, stored root crops are living tissues that generate metabolic heat, carbon dioxide, and ethylene gas (a phytohormone that accelerates senescence)⁸. The respiration rate

generates significant thermal energy; for example, at $10^{\circ}C$, blueberries generate

approximately 6,380 Btu/ton per day¹⁶. To prevent toxic atmospheric buildup, passive cellars must maintain a minimum of 2 Air Changes per Hour (ACH) using buoyancy-driven stack effect ventilation⁸. By introducing dense, cold air through a low intake pipe and exhausting warmer, stale air through a high exhaust pipe at the ceiling's apex, the pressure gradient naturally flushes the environment without requiring mechanical fans⁸.

Root Cellar Space Requirements Calculation

Based on the dietary requirement of ~947 kg of fruits and root vegetables, the raw volumetric space required is approximately 50 cubic feet (1.41 cubic meters). However, bulk stacking leads to rapid decay due to localized metabolic heat buildup and restricted aerodynamic airflow. Produce must be stored in slatted wooden bins or wire racks to maximize exposed surface area for convective cooling and gas exchange. Accounting for an aggressive volumetric packing efficiency factor of 25% (to allow for structural shelving, geometric spacing, aerodynamic clearance, and human access aisles), the minimum internal volume required is exponentially larger.

Root Cellar Calculation:

$$50 \text{ ft}^3 (\text{raw volume}) \times 4 (\text{aerodynamic/access multiplier}) = 200$$

For a subterranean vaulted structure with an average internal ceiling height of 7 feet, the floor plan requires a minimum footprint of 6 feet by 5 feet. An expanded target of **250 cubic feet** is highly recommended to accommodate a thermally broken airlock vestibule at the entrance, which creates a transitional temperature zone that buffers the cellar from direct ambient air infiltration and convective thermal bridging⁸.

Dry Grain Silos

While root cellars manage highly hydrated living tissues, dry grain silos are engineered to store desiccated, free-flowing bulk solids. The engineering of grain bins is governed by structural load management, complex hopper flow dynamics, and the rigorous prevention of hygroscopic expansion.

Granular Mechanics and the Janssen Equation

Agricultural grains behave as semi-fluids, sharing physical characteristics of both solids and liquids¹⁸. When grain is poured into a silo, the pressure exerted on the vertical walls does not follow pure hydrostatic laws. In a fluid, pressure increases linearly with depth. However, in a granular solid, friction between the grain kernels and the silo wall supports a significant portion of the material's weight.

In 1895, Janssen developed the foundational theory demonstrating that vertical pressures in deep silos increase asymptotically, eventually plateauing at a certain depth [cite: 168-184, 235]. Janssen's equation remains the preeminent mathematical model integrated into modern global design codes, including Eurocode 1 (EN 1991-4) and ASABE EP433 [cite: 210, 214, 234-248]. The

vertical pressure (σ_z) and lateral pressure (σ_x) are expressed as:

$$\sigma_z = \frac{\rho g D}{4k\mu} \left[1 - e^{-\frac{4k\mu}{D}z} \right]$$

$$\sigma_x = k\sigma_z$$

Where D is the silo diameter, ρ is the bulk density of the grain, μ is the coefficient of wall friction, z is the depth of the fill, and k is the lateral-to-vertical pressure ratio¹⁹. The parameter k is highly sensitive to the internal friction angle of the specific grain²⁰. While Janssen's equation accurately predicts pressures for rigid concrete silos, modern corrugated steel silos feature flexible walls. Under lateral load, a flexible wall deforms slightly, which shifts the horizontal pressure distribution, concentrating stresses near corners or structural stiffeners²². Therefore, structural design must apply partial safety factors to the Janssen predictions to prevent localized buckling.

Hopper Flow Dynamics and Jenike's Theory

Silos are functionally divided by their discharge mechanisms into flat-bottom or hopper-bottom geometries. For a single-family unit storing a year's harvest, a gravity-discharge hopper-bottom silo is highly advantageous as it eliminates the need for motorized sweep augers²⁵.

The flow of granular material out of a hopper is governed by Jenike's flow theories, which mathematically define the shear strength, compressibility, and permeability of powders and grains [cite: 148, 159, 185-189]. Jenike distinguished between two primary flow regimes:

1. **Funnel Flow:** Material moves through a central vertical channel directly above the outlet. The material resting against the hopper walls remains entirely stagnant. This creates "dead zones" that lead to ratholing, mechanical arching, product degradation, and a catastrophic "first-in, last-out" discharge sequence²⁸.
2. **Mass Flow:** The entire bulk mass is in motion simultaneously. Friction along the walls is overcome, achieving a perfect "first-in, first-out" discharge. This prevents material segregation and ensures uniform residence time²⁸.

To ensure reliable mass flow, the hopper wall must be sufficiently steep and smooth to overcome the internal friction angle of the grain and the kinematic wall friction²⁸. For agricultural grains like wheat and barley, industrial engineering standards generally dictate a bottom cone angle (hopper half-angle) of 45° to 60° ³³. If the angle is too shallow (e.g.,

$< 30^\circ$), the silo will inevitably suffer from funnel flow and mechanical arching across the discharge orifice²⁸.

Hygroscopic Expansion and Moisture Stresses

Grains must be dried and stored at a stable Equilibrium Moisture Content (EMC) to prevent fungal proliferation and respiration heat buildup. The EMC represents the final moisture content that grain will equilibrate to when exposed to specific ambient air conditions over time [cite: 143-146].

If dry grain is exposed to high ambient humidity or liquid moisture ingress, the individual kernels undergo rapid hygroscopic swelling [cite: 265-279]. Because the grain mass is confined within the rigid steel boundaries of the silo, the volumetric expansion induces immense, multidirectional internal stress. Experimental data indicates that an increase in grain moisture content of just 4% to 6% can cause lateral hoop stresses on the silo walls to multiply by a factor of five to nine times the initial static pressure³⁶.

Concurrently, as the grain expands, the vertical wall forces shift drastically, lifting upward and placing extreme shear stress and axial tension on the silo's anchor bolts and structural fasteners³⁶. Therefore, the silo must be entirely weather-tight, and aeration systems (measured in CFM per bushel) must only be engaged when the ambient air falls within the safe psychrometric bounds of the crop's EMC isotherm charts³⁹.

Grain Silo Space Requirements Calculation

The family unit requires the storage of 372 kg of dry grain. Wheat possesses a bulk density of approximately 772 kg/m^3 (or 60 lb/bushel)⁶. The absolute raw volume required is roughly 0.48 m^3 (17.0 cubic feet).

However, total silo capacity is the geometric sum of the cylindrical body, the hopper bottom cone, and the peaked roof cone. When grain is poured into a silo from an overhead hatch, it does not lay flat; it forms a conical mound defined by its Angle of Repose²⁵. The angle of repose for dry wheat and corn typically ranges from 25° to 28° ²⁷. This peak cone adds significant volume that cannot be ignored.

The total structural volume (V_{total}) is modeled as:

$$V_{total} = V_{cylinder} + V_{hopper} + V_{peak}$$

$$V_{total} = (\pi r^2 h_c) + \left(\frac{1}{3} \pi r^2 h_v \right) + \left(\frac{1}{3} \pi r^2 h_p \right)$$

Furthermore, a "pack factor" (settling compaction) of 3% to 6% naturally occurs under gravitational pressure over the storage season²⁷, and an architectural ullage (empty safety headspace) of 10% to 15% is strictly required to allow for aeration airflow, angle of repose variation, and expansion safety²⁵.

Grain Silo Calculation:

$$17.0 \text{ ft}^3 \text{ (raw volume)} \times 1.15 \text{ (ullage)} \times 1.25 \text{ (angle of repose \& hopper co}$$

To safely store the annual grain harvest, a micro-silo must be engineered to a minimum of **30 cubic feet** (approx. 0.85 cubic meters). A cylindrical steel bin featuring a 3-foot diameter, a 3-foot vertical sidewall, and a ^{60°} mass-flow hopper bottom perfectly satisfies this geometric demand while ensuring flawless "first-in, first-out" gravity discharge.

The Smokehouse and Meat Curing Architecture

Preserving a year's supply of meat (approximately 320 kg for a four-person family) without the use of active refrigeration relies entirely on the biochemistry of curing and cold-smoking. A smokehouse acts as an active dehydration and chemical preservation chamber, requiring precise control over airflow, mass transfer coefficients, and thermal boundaries.

Mass Transfer Physics and Case Hardening

In cold-smoking—typically operated at ambient temperatures strictly below ^{30° C (80° F)}—the primary preservation mechanism is the removal of unbound internal moisture (lowering water activity) alongside the deposition of antimicrobial phenolic compounds and formaldehydes from the smoldering wood⁴².

The drying of meat involves two simultaneous physical phenomena: the convective mass transfer of moisture from the meat's surface into the surrounding air, and the internal diffusion of moisture from the center of the meat outward to the surface⁴³. The rate of surface evaporation is dictated by the convective mass transfer coefficient, which is highly dependent on the air velocity passing over the product⁴³.

If the air velocity inside the smokehouse is too high, or the relative humidity too low, surface moisture evaporates significantly faster than internal moisture can diffuse outward. This imbalance results in "case hardening"—the rapid formation of a dry, impermeable exterior protein shell that permanently traps lethal moisture inside the meat⁴³. Case hardening effectively halts the curing process and guarantees internal putrefaction. Therefore, a smokehouse must be designed with highly adjustable intake and exhaust dampers to meticulously regulate draft velocity, ensuring a gentle, laminar flow of cold smoke that maintains perfect equilibrium with the internal diffusion rate of the muscle tissue⁴⁶.

Thermodynamics and Construction Materials

To support the cold-smoking process, the heat source (firebox) must be physically separated from the smoking chamber to allow the smoke to cool to ambient temperatures before

entering the curing zone. This is typically achieved via an underground trench or an external offset flue pipe measuring 6 to 8 feet in length [cite: 58-62, 73].

The structural envelope of the smokehouse must possess sufficient thermal resistance to retain ambient warmth during the colder months to prevent the meat from freezing, yet reflect

solar gain in the summer to prevent the internal temperature from crossing the 30°C cold-smoking threshold. A heavy timber-frame construction is standard. While wall assemblies in residential construction often utilize rigid PIR (polyisocyanurate) insulation due to its highly

efficient thermal conductivity (λ) of 0.022 W/mK ⁵⁰, PIR is combustible (Euroclass F).

Therefore, non-combustible mineral wool (such as Rockwool, Euroclass A1) with a thermal conductivity of 0.035 W/mK is heavily preferred for the interior framing of smokehouses due to its extreme fire resilience, acoustic dampening, and hydrophobic properties⁵⁰.

Smokehouse Space Requirements Calculation

Hanging 320 kg of meat requires strict geometric clearances. Curing flitches, hams, and sausages must be hung from structural dowels with several inches of clearance between each cut. If meat surfaces touch, capillary moisture becomes trapped, airflow is blocked, and the smoke cannot penetrate the boundary layer, inevitably leading to localized bacterial blooming and spoilage⁵².

Traditional European and American homestead smokehouse architecture has long converged on an optimal volumetric ratio for a single family to ensure adequate laminar smoke diffusion. Standard structural dimensions utilize a 4-foot by 4-foot or 4-foot by 8-foot footprint, with an interior ceiling peak ranging from 6.5 to 7 feet to accommodate the rising smoke column and hanging racks⁴⁸.

Smokehouse Calculation: A structure built with a 4-foot wide by 8-foot deep footprint and a 7-foot ceiling provides exactly **224 cubic feet** of internal volume⁵⁴. This configuration easily accommodates the overhead structural dowels, lower stainless steel distribution baffles⁴⁹, and the strict spatial spacing required to safely hang 320 kg of carcass weight without initiating boundary layer interference or risking case hardening.

Conclusion

To achieve complete, off-grid food security for a full year's harvest for a single-family unit of four, the architectural space requirements are strictly bound by complex mechanical, thermodynamic, and biological limits. Based on the calculated mass requirements, bulk densities, and the aerodynamic and structural spacing mandated by preservation physics, the definitive volumetric requirements are:

1. **Earth-Sheltered Root Cellar: ~250 cubic feet** (approx. 7.0 m^3). Engineered with a vaulted ceiling to mitigate Magnus-Tetens condensation, protected by DIN 18533 and BS 8102:2022 cavity drain waterproofing alongside cellular glass insulation, and utilizing stack-effect buoyancy ventilation to clear metabolic ethylene gas and respiration heat.
2. **Dry Grain Silo: ~30 cubic feet** (approx. 0.85 m^3). Constructed as a 60° conical

hopper-bottom steel bin to ensure true Jenike mass flow discharge, and structurally reinforced against the intense lateral wall pressures modeled by Janssen's equation and the extreme forces induced by hygroscopic expansion.

3. **Meat Smokehouse: ~224 cubic feet** (approx. $6.3\ m^3$). Framed in fire-resistant timber and Euroclass A1 mineral wool, utilizing external offset fireboxes to manage convective mass transfer coefficients and safely cure meat without inducing lethal case hardening.

By adhering to these stringent volumetric constraints and integrating the governing geotechnical and psychrometric principles, these three distinct architectural structures form a scientifically viable, multi-generational food storage system capable of successfully arresting the decay of an entire agricultural harvest.

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