Quasi-spherical Thin-shell Concrete Small Buildings: Low CAPEX, Low Embodied and OPEX Energy, Rapid and Remote Construction, Earth-shelterable, for Comfort and Security: Storm, Tsunami, Fire, and Combat Survival

CATEGORY 3, BUILDING EFFICIENCY SUBCATEGORY E: Envelope

Budget: $ 420,000 Match, in-kind: $ 110,000 Total: $ 530,000 Duration: 24 months

Applicant and Prime Recipient: Alaska Applied Sciences, Inc. (AASI)
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Qualified vendors: unconfirmed candidate partners:

- University of Alaska: CAD design for forms tooling design and fabrication
- Janicki Industries: Tooling design and fabrication; test forms sets production
- LafargeHolcim: cementitious mix design; dry bag mix for in-site use, remote, export
- Chomarat, C-Grid: primary reinforcements placement engineering assistance
- NREL, Cold Climate Housing Research Center: test structures; experiment design; data acquis

A. Concept See Figures 1-5 and the complete construction process, and simple strength testing, of the prototype scale model, which is 2.8 m ID, ~ 5/8 sphere (volume), ~ 1 cm thick, 3 cm interior foam insul: www.AlaskaAppliedSciences.com/thin-shell-concrete-structures
Thin-shell concrete, ~ 2-3 cm thick at ~ 7 m equatorial diameter, with non-ferrous reinforcements, is ideal for quasi-spherical structures with large radii of curvature, allowing large volumes to be enclosed with minimum embodied energy and CAPEX as "domes". This project will scale-up our successful proof-of-concept, ~46% scale model manufacturing process demo to 6-7 m equatorial ID, useful for human scale: shelter and housing, storage, clinic and classroom, and will demonstrate elongation.

We will develop the manufacturing process whereby, on-site, worldwide, at low cost, rapidly, we may:

1. Greatly reduce the volume of concrete and embodied energy in structures, per unit area and volume;
2. Build thin-shell-concrete buildings on-site, with minimum import of material, tools, tooling, and expert labor; maximize use of local, on-site materials - primarily water, sand, with fine aggregates in the foundation ring -- and local semi-skilled labor, energy. Important for remote areas, disasters;
3. Greatly reduce LCC, via both CAPEX and OPEX -- energy, maintenance, and survivability in stress from storm, tsunami, earthquake, flood, fire, and vermin;
4. Use Earth berm and burial to further protect structure from extreme weather, small arms, shrapnel;
5. Divide the interior space and volume into structurally-sound public, private, and storage places.

B. Impacts Portland cement manufacture is energy intensive; we will advance, to TRL 6-7, an on-site construction process for low-energy, long-lifetime, low-cost structures, scaled-up from the scale model in Figs 1-5, with very efficient use of concrete: ~ 2 m^3 total, 2-3 cm thick for a 6-7 m diameter quasi-spherical structure, "dome". This human-useful-size envelope may then be inexpensively well insulated with interior-sprayed, closed-cell, bio-based UR foam; also may be Earth-sheltered to resist complete spectrum of natural and man-made threats. Add barrel vault forms sections for any size buildings.

R.B. Fuller was right: "domes" are the most efficient, economical, durable, enclosure of volume; over their lifetime they will prevent a large quantity of CO2 and GHG emissions from CAPEX and OPEX. This project's dome construction method presents uniquely-high Life Cycle Efficiency Ratio (LCER) and economic rewards, but it requires this project's R&D to perfect the method, to transform small buildings construction, to both prevent and survive GCC's escalating dangers. The large global market is transformational, enabling economy, safety, Earth-sheltering, with great reduction in materials and GHG emissions, for all human populations and purposes, anticipating, now, looming GCC emergencies. Demonstration Goals: (1) Likely 2/3 reduction in CAPEX, OPEX, embodied energy, and construction time vs conventional stick-built; (2) Survive repeated 3 g horizontal seismic shocks; (3) Survive 2 years subarctic Earth-sheltered freeze-thaw cycling; (3) Techn-Econ Analysis (TEA) to justify (1), above.

C. Work Figs. 1-5 background: based on this success, we must now build several full-scale, human-useful buildings, 6 to 7 m equatorial diameter, so that everyone may see and experience advantages:

1. Attractive, economical, durable, liveable, and amenable to expansion or for GCC threat "hardening";
2. Test for thermal efficiency and for survival of seismic, fire, freeze-thaw, and other loads, threats;
3. Estimate construction costs and time, CAPEX and OPEX, including thermal and maintenance

1: Tooling vendor will design and build state-of-art production tooling to produce sets of durable, low-cost, lightweight forms sets for 6-7 m diam "dome", upon which thin-shell-concrete R&D structures will be built. Three tools of simple curvature must be designed and built by the specialty tooling vendor:

- "Orange peel" segment (12 pieces per forms set; bolt together forming most of the dome)
- Top cap (1 piece per forms set)
- Barrel vault segment (2 pieces per forms set per meter cylindrical elongation of the building)

Simple approximate specs, for the tooling design vendor, for the finished thin-shell-concrete envelope:

- Shape: ~ 5/8 sphere by volume
- Building ID = assembled form OD: ~ 6 - 7 m at equator (largest diameter)
- Number of "orange peel" geometry quasi-spherical forms segments: 12
- Number of "top cap" forms segments: 1
- Number of barrel vault segments: two for each
- Target thin-shell-concrete average structure thickness: 2 to 3 cm; optimistically 1.5 to 2.5 cm
- "Orange peel" segments assembly: ~ 6 to 8 bolts in each joint, with reinforced holes in one side of segment, with mating threaded female embedded fittings on other side of segment
- Shims: Assume 2 cm thick shim in each "orange peel" segment joint, for easy post-concrete-cure removal, to enable "orange peel" segment removal
- Top cap: After "orange peel" segments and shims assembly is complete, top cap is placed on top, to close the opening. Fastened in place via 12 elastic "bungee" cords inside the dome form.

2: The fiberglass form segments would be manufactured as relatively-stiff, durable, foam-core pieces, by vendor design & process. They need to have built-in handles for safe and convenient storage and assembly, and for disassembly from the interior of the cured concrete shell, for removal and reuse.

We have an estimate from Janicki Industries, WA state, for tooling design + build, and for forms sets:

- 3 tools, on which to build forms sets segments: spherical, top cap, barrel vault $ 55,000
- Forms set: 12 pcs spherical, 1 top cap, 2 barrel vault, foamcore fiberglass $ 214,000

To all fiberglass form segments, exterior surfaces, we then apply a Teflon coated rubber layer, ~ 3 mm thick, probably via sheet laminations, to capture the SS staples by which the Chomarat "C-Grid" primary reinforcements tiles are applied, prior to concrete mortar application. This is a major area for experimentation and optimization. In our proof-of-concept work, we used 60-mil EPDM roofing rubber.

3: One or more building envelopes will be built for structural properties testing, for design, materials, and process evolution, and to guide tooling, materials, and process improvements:

1. Window, door, entry transition integration with dome, concrete reinforcement; complete integrity;
2. FEA; ultimate strength, NDE and failure modes analysis (FMA): variety of static & dynamic loads;
3. Optimum placement of C-Grid primary reinforcement: tiling; positioning in center of concrete shell;
4. Optimum portland cement mortar mix: "sacks" & other ratios, admixtures, fibers, slump, airentrain;
5. Optimum methods for mortar placement, consolidation, vibration, tooling, curing, form removal;
6. Improve form panels design: surface coating for staple retention, concrete release, durability; handle and anchor locations for safe, easy, fast assembly and removal from inside cured thin-shell structure.

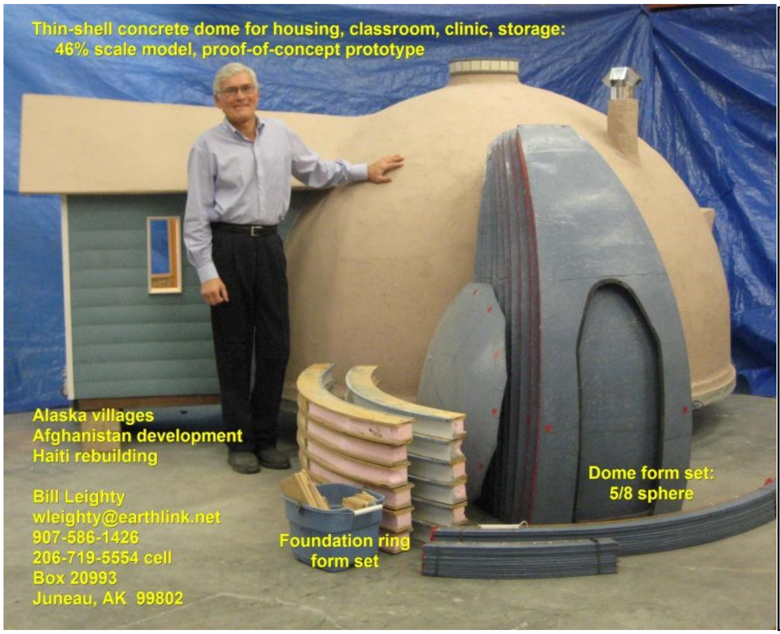

Figure 1. Prototype, 5/8 sphere volume, proof-of-concept, 46% scale model, Juneau, AK, 2009. 1 cm thick concrete shell with Chomarat "C-Grid" primary reinforcement. 4 cm UR closed-cell foam sprayed internal insulation. Foreground: forms set, reusable XX times before refurbish > Base ring arcs: interior, exterior > Teflon-coated EPDM rubber on fiberglass segments + top cap > Teflon-coated shims bolt between 5/8 sphere segments, for easy removal from cured concrete shell. 10 cm thick foam floor. Total weight 1,100 kg. Total concrete ~ 0.3 m^3. Wood-frame entry with concrete roof, standard door. Vents: skylight and combustion heater. For on-site construction with minimum imported material, tools, tooling, expert labor: use maximum local.

Figure 2, 3. Concrete dome, Fig 1, buried in sand; 1 m on top. Deformation ~ 0.25 mm vertical and horizontal. Asymmetric sand removal. No visible structural failures. Winter. Brief seismic. Not tested in freeze-thaw; Protect from climatic extremes, tsunami, fire, small arms & shrapnel.

Figure 4. Chomarat "C-Grid" carbon fiber epoxy grid primary reinforcing, SS-stapled to Teflon-coated 5/8 sphere reusable male form. ~ 30 mm mesh shown. Standard is ~ 45 mm mesh. Cost ~ $ 10 / m^2. Rich fiber-reinforced mortar applied by hand trowel, or "Gunnite" spray. Hand finished. Cure via resin spray or plastic tarp. Easy inside forms removal.

Figure 5. Foundation ring poured, using forms set on right, with tie-in fiberglass mesh embedded in ring. Twelve "orange peel" spherical segments are now bolted together, with a shim in each joint, to allow easy release of form segments from cured thin-shell-concrete dome. The gray surface is Teflon, for easy form segment release from cured concrete. Ready for installation of "tiled" C-Grid sections, with SS staples captured in 60 mil rubber layer under the Teflon: Figure 4. Proof-of-concept prototype is 2.8 m equatorial diam, 5/8 sphere vol. This project will scale-up to 6-7 m diam via tooling on which to build larger "orange peel" and top cap fiberglass forms panels, as shown.

4: Technical-Economic Analysis (TEA) to estimate value (multiple benefit:cost aspects), to assess markets; develop pre-commercialization plans, business models: sell or lease forms sets; add special tools; add packaged materials (bagged concrete mix, precut C-Grid tiles); add training and service.

5: Finish one or more buildings to residential standard to develop plumbing, wiring, furnishing plans; develop complete, optimized, tooling + tools + materials + logistics + envelope build + finish system. Build a demo elongated "sausage" structure: add two or more barrel vault sections to assembled form; demo "dome" morph to "sausage" of any length; half-hemisphere each end; entry door anywhere.

6: Strength and seismic tests on prototypes; further development of the tooling design, structure:

- Elongation options using the barrel vault forms sections; Finite Element Analysis (FEA)
- Interior partitions for private spaces; partial loft installation, without loading the concrete dome;
- Entry door options, including "arctic" entry; window placement and installation; HVAC options;
- Insulated floor options; plumbing and wiring installation techniques;
- Foam (closed-cell UR) installation and interior overcoating for durability and fire rating;
- Explore building code compliance options; engineering certifications for PE's; quality control.

7: Commence market research: Applications; acceptance; thermal performance and finish degree required; cost and profit goals; value of Earth-sheltering to endure multiple perils, from Nature and man.

8: Explore business models for commercialization if a market is confirmed; modify design to suit: Sell or lease forms sets ? Franchise ? License IP ? Supply bagged premix profitably ? Train, certify ?

Technical Risks are minimized by our year 2010 proof-of-concept work, Figures 1-5. Major challenges for R&D: (1) Positioning C-Grid offset from dome form surface for optimum strength and weather resistance; shell waterproofing by select mortar admixtures; (2) Process quality control for on-site aggregates and water, mortar application, consolidation, tooling, finishing, and curing; (3) Optimize portland, or other cement, mix recipe amenable to dry bag supply; (4) Prevent freeze-thaw cycling damage to Earth-sheltered (buried) buildings; (5) foundation-to-ground coupling; leveling in ground-freezing climates to minimize foundation costs; (6) mounting PV panels on S-facing roof sections.

Techno-economic challenges are benefit:cost, proving this value to adapt to threats from Climate Change; market acceptance; construction quality control; logistics; window placement shell reinforcement; insulation optimization and protective coating or covering; HVAC, plumbing, wiring options; morphing design to provide more-rectangular shape; engineering acceptance for safety and building code compliance, where required.

ARPA-E funds are primarily for tooling design and build, and for fabrication of two sets of forms segments: $420 K. Project management, testing assistance, documentation by AASI, applicant: $ 110 K. This risk capital is essential to deliver a proven complete construction and finish system to realize the extraordinary economy and durability of thin-shell concrete; to overcome bad reputation of "domes'.

D. Team   PI: William C. Leighty, Principal, AASI. BSEE '65, MBA '71, Stanford. Project mgmt and documentation. Applicant, AASI founded 1990.Business development team lead: selling the mature concepts to many global markets. DOE R&D project success: https://www.osti.gov/biblio/859303

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- NREL, Cold Climate Housing Research Center: test structures; experiment design; data acquisition; structural FEA and engineering analysis for building code compliance
- Alaska Housing Finance Corporation; regional Alaska Native corporations