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Thin-shell concrete structures, multi-purpose, for low embodied and operating energy and durability

Thin-shell concrete structures, necessarily quasi-spherical in shape, consequently limited to large radii of curvature to achieve structural integrity, also provide durable, low-cost, multi-purpose shelter with low embodied and operating and maintenance (O&M) costs. Built on-site, about one structure per forms set, per four days. California's extant concrete construction industry will easily adapt to this construction method, for residential and diverse uses -- perhaps, at first, to accommodate a wave of COVID-caused homelessness, and to welcome temporary ag workers.
Structure cost will depend primarily upon finish level: insulation (interior: sprayed, closed-cell urethane foam); plumbing and wiring; cabinetry and appliances -- if any. Concrete shell cost is relatively low; shell thickness ~ 2 cm; < 1 inch.
Please consider scaling-up our proof-of-concept, scale model, prototype work from 2009, in Juneau, AK. About $ 250 - 500 K investment will be needed for CAD, building the tools by which the concrete forms sets may be manufactured, by which the thin-shell concrete structures are built on-site, and for building several sets of forms for field tests and shelters production. Please see: www.AlaskaAppliedSciences.com/thin-shell-concrete-structures Please see attached slide presentation; larger slide presentation available on request. The original forms set, by which the prototype scale models were built in 1990, are available for further R&D use, although they were not designed for, nor probably durable enough for, production of more than a few structures.

Additional submitted attachment is included below.

Thin-shell Concrete Structures for Low Embodied and Operating Energy and Durability

TechConnect 2015
Abstract # 747
Washington, DC 14-18 June 15

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For: CEC 20-DECARB-01
Submitted: 8 Aug 20

Juneau, AK 1977: 16' diameter concrete dome: ½" thick, ~ 5/8 sphere

2010 Juneau, Alaska

~ 1/2” thick concrete shell

46% proof-of-concept scale model of 18 ft diam

Interior sprayed UR foam super-insulation

Goals

1. Minimize imported:
    a. Materials, including aggregate
    b. Tooling
    c. Tools
    d. Expert labor
    e. Use local sand, water, semi-skilled labor
    f. Minimize Earth impact
2. Build many on-site, in-situ
    a. Reusable forms set
    b. One every 3 – 4 days
3. Non-ferrous primary reinforcement
4. Spray-in insulation
5. Durable, strong, fireproof, vermin-proof, waterproof
6. Earth sheltered: compatible
7. Alaska village housing replace

Prototype: 8' 6" equatorial ID concrete shell, ~ 5/8 sphere

Framed Entry

Foam Insulated

2-pound UR,

closed cell

Treated wood floor framing and plywood


ZOOMBOOM
TYLER RENTAL
8044


CATERPILLAR

Proof - of – Concept Prototype

Slide 1 of 3

- 46% scale model of 18’ ID full-size concrete dome
- ~ 5/8 sphere (volume)
- 8’ 6” equatorial ID (concrete shell)
- < 1/2” thick concrete shell
  - Need engineering to confirm adequate structurally at full scale
  - FEA necessary for stress concentrations
  - Integral waterproofing: no coating needed
  - Earth berming or burying compatible
- Unique, reusable tooling
- Mortar:
  - Rich, portland cement
  - Sand only aggregate
  - High-fiber
- Reinforcement:
  - Primary: Chomarat C-Grid
  - Secondary: Fibermesh 150
- 13-part dome form (12 side + top cap)
- Teflon dome form release surface
- UR foam insulated + protection layer

Proof - of – Concept Prototype

Slide 2 of 3

- **Prototype mortared:**
  - **12 Nov 09**
  - **Hand troweled; no vibration**
  - **Dome form removed 14 Nov**
- **No shrinkage cracking in dome; cracks in entry roof**
- **Concrete form sets:**
  - **Foundation, dome sets**
  - **Hand-made tooling**
  - **Reusable; many cycles → refurbish**
  - **Teflon release surface**
- **"Circus ring" minimal foundation: 3" x 4" cross-section**
- **5/8 sphere (volume) dome**
  - **Shim- assembled dome: unique**
  - **Easy assembly, removal: team of two**
  - **Easy removal from cured shell**
  - **Staples captured by outer rubber plies**
- **Foundation + dome + entry = integrated structure**

Proof - of – Concept Prototype

Slide 3 of 3

- Shoestring R+D project
- No engineering: concept only
- No load testing:
  - Prototype not representative: poor mortar application QC
  - Establish protocol
- Concrete Form Sets: Hand-made tooling
  - Foundation: plywood + foam + "Integument" Teflon
  - Dome:
    - Wet-layup epoxy glass: 12 + 1 pieces
    - 60 mil EPDM roofing
    - 30 mil butyl PSA
    - 5 mil Teflon
- Non-ferrous, non-corroding reinforcements
  - C-Grid primary (carbon-epoxy fiber grid)
  - SS staples tile rectangles to form
  - 1/4" self-stick rubber chairs
  - Fibermesh 150: 1/4 " + 3/4 " cut, in mortar mix
- Easy mortar application:
  - Sand-only aggregate
  - Trowel
  - Spray
  - Shotcrete
- Ideal for superinsulation:
  - Minimum surface area for volume
  - No thermal bridging through structural elements
  - Easy UR foam and interior finish spray application

Concepts Proven

Slide 1 of 2

1. Dome form removable, reusable
   a. Removable shims liberate segments
   b. Teflon surface releases concrete
2. Non-ferrous, non-corroding reinforcements
   a. C-Grid primary (carbon-epoxy fiber grid)
      I. 1/4” self-stick rubber chairs center C-Grid
      II. Rectangles easily “tile” spherical surface
      III. SS staples tile C-Grid rectangles to form
   b. Fibermesh 150: 1/4 “ + 3/4 “ cut, in mortar mix
3. < 1/2” thick concrete shell achievable
4. Easy mortar application
   a. Trowel proven, but poor QC in prototype
   b. Unproven: Spray or shotcrete

Concepts Proven

Slide 2 of 2

5. Minimal “circus ring” foundation adequate
    a. 3” x 4” cross-section
    b. One #3 rebar continuous, centered
    c. Continuous embedded fiberglass mesh: dome tie-in
    d. 6 embedded lifting lugs
    e. Entry framed structure bolted to ring
    f. Easy to build on-grade
    g. Many floor options
6. Integral concrete structure combines:
    a. Foundation ring
    b. Dome
    c. Entry roof

Designed for:

- Alaska village housing, classroom, clinic, storage
- Permanent structures built on-site
- Minimum
  - Embodied energy
  - Operating energy: UR foam superinsulation
  - First cost
  - LCC
- Minimum imported
  - Tooling and tools
  - Materials
  - Expert labor
- External structural shell
  - Durable
  - Waterproof
  - Fireproof
  - Impervious to corrosion, vermin
- Rapid replication of shell
- Reusable male form; long life

Also useful for:

- **Strategies combining development + combat**
- **Afghanistan and others**
- **Civilian**
- **Military**
- **Disaster relief**
- **Low cost housing**
- **Classrooms**
- **Clinics**
- **Storage**
- **Emergency shelter**
- **Potentially transportable**

Dome Reusable Form System

Slide 1 of 2

- Fiberglass structure
- 13 pieces
  - 12 identical side “orange peel” segments;
  - Door opening in one
  - Integral threaded inserts for bolted assembly
- Top cap
- Outer adhered plies:
  - 60 mil EPDM unreinforced roofing membrane
  - “Integument”:
    - P500W-MX-36 Fluorogrip MX membrane
    - 30 mil butyl adhesive
    - 5 mil Teflon film concrete release surface
    - Adhered over 60 mil EPDM
  - 95 mil outer plies capture primary reinforcement staples

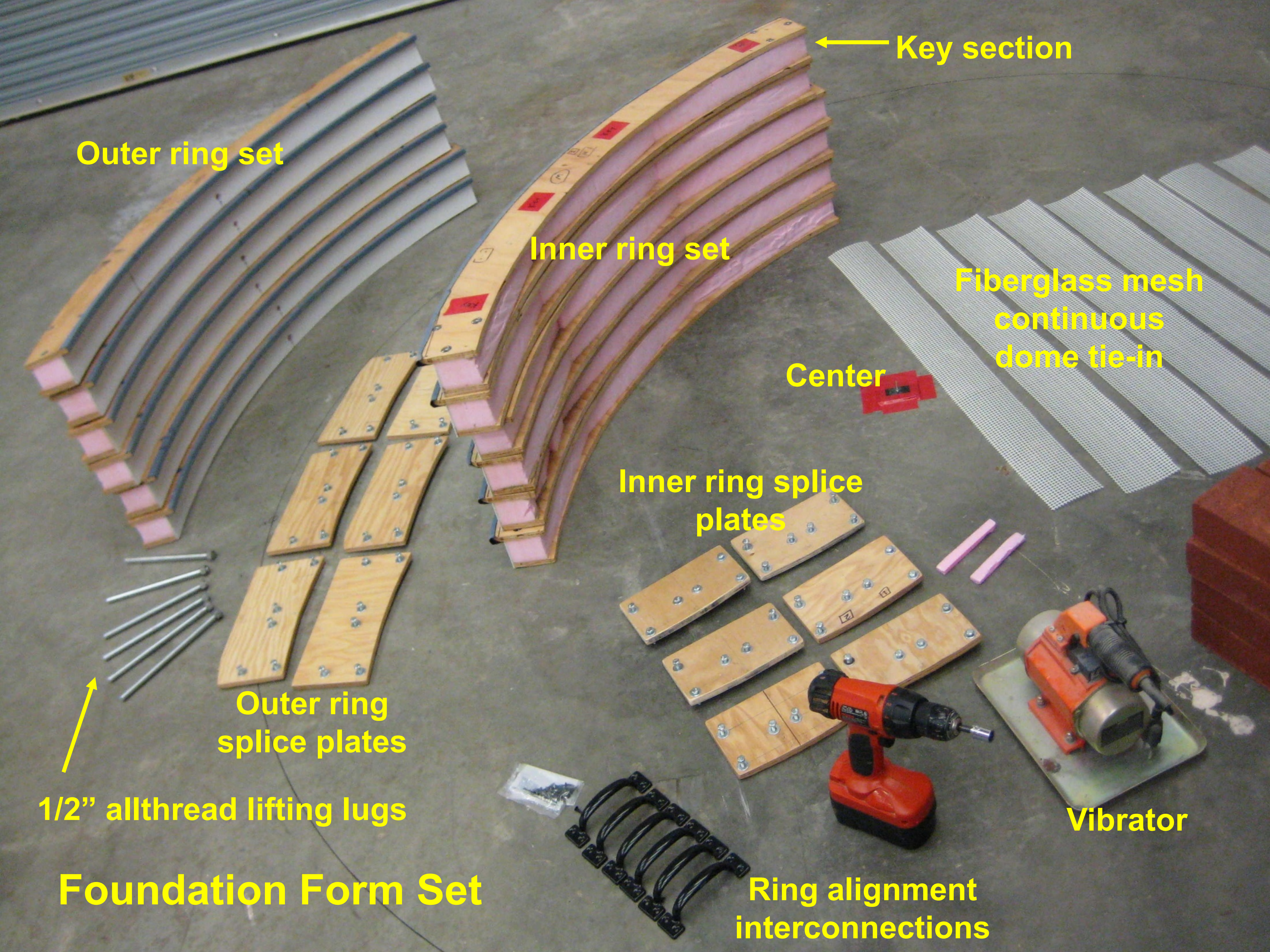
Dome Reusable Form System

Slide 2 of 2

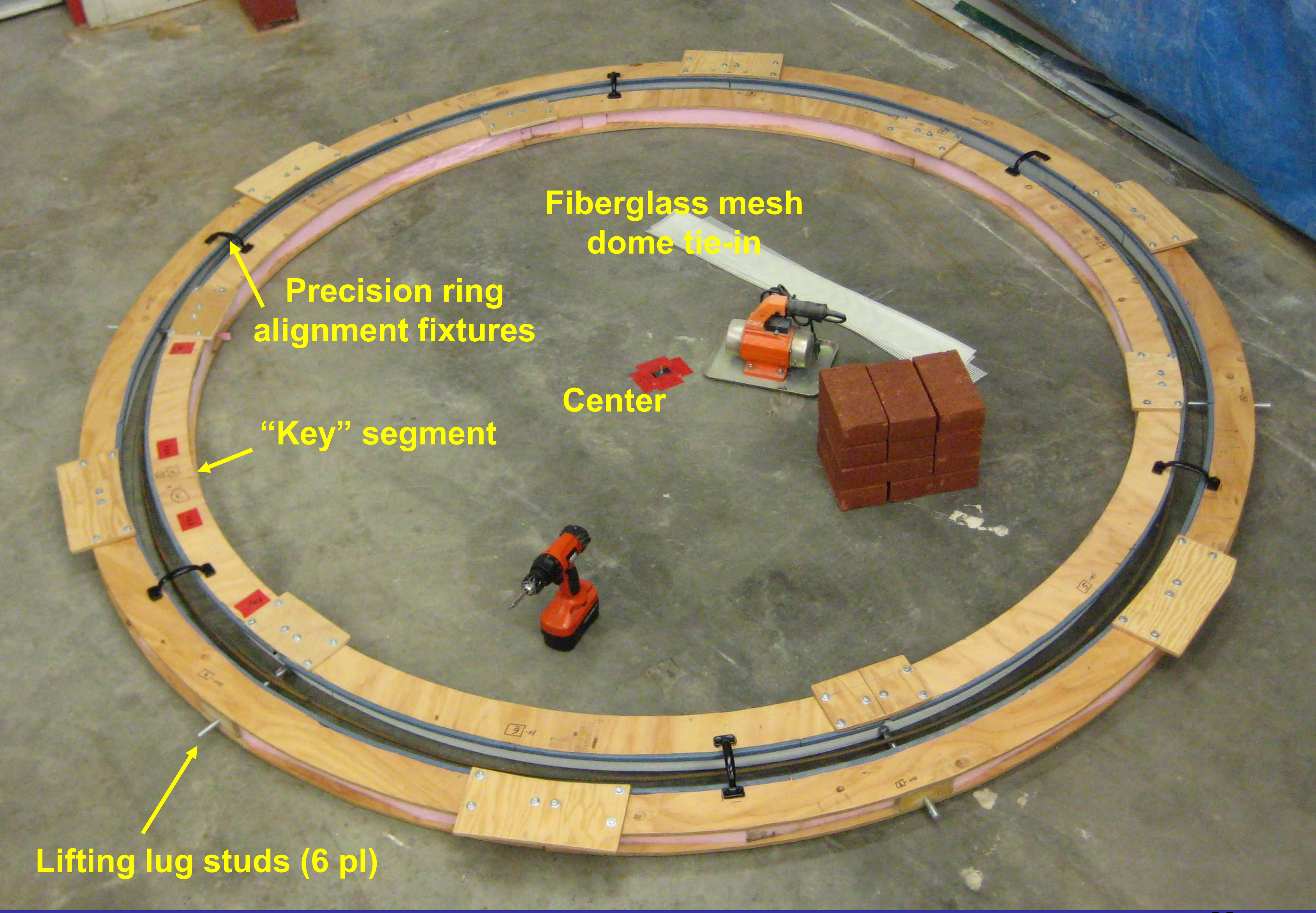
- Two-person assembly and removal
- 12 removable side shims
  - Assemble between 12 side segments
  - 1/4” plywood + “Integument” Teflon
  - ~ 5/16” total thickness
- 12 removable bottom shims
  - Assemble under 12 side segments
  - 1/4” plywood + “Integument” Teflon
  - ~ 5/16” total thickness
- 12 removable sheet steel skid plates
  - Placed on concrete foundation
  - Ease bottom shim removal

Foundation Reusable Form System

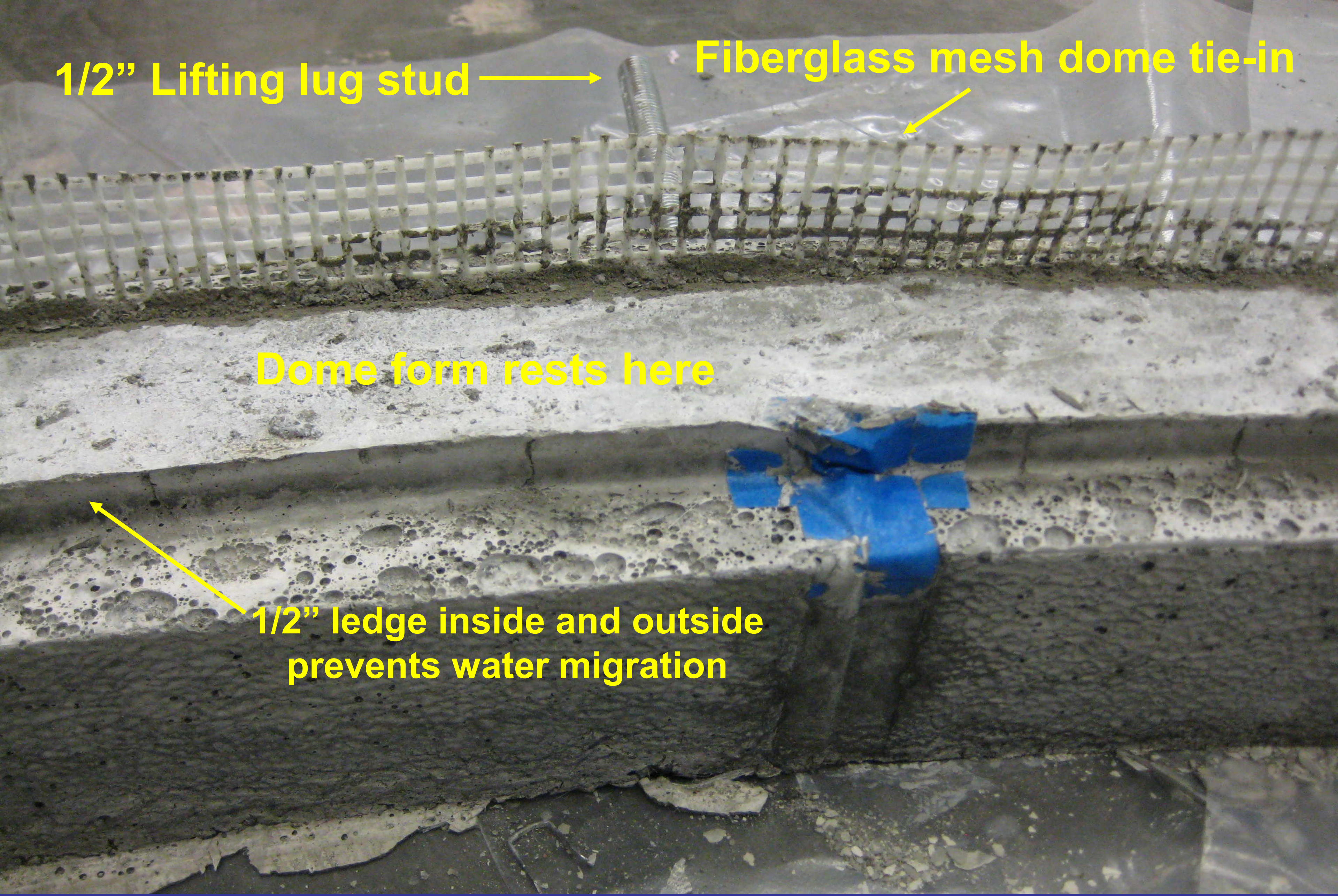
- Designed for on-grade, permanent construction
- May be truck-transportable, depending on size
- 4” wide x 3” high foundation ring cross-section @ 46% scale
- Outer 1/2” ledge prevents water migration
- Inner 1/2” ledge supports floor
- Concentric rings, 6 segments each
- Precision splice plate ring assembly
- Precision alignment of rings
- 5/16” foam shim on inner “key” segment
- One continuous circumferential #3 bar
- Embedded continuous Sto fiberglass mesh for dome tie-in
- Embedded 1/2” steel studs for outer lifting lugs
- Teflon and vinyl concrete release surfaces



Key section
Outer ring set
Inner ring set
Fiberglass mesh continuous dome tie-in
Center
Inner ring splice plates
Outer ring splice plates
1/2” allthread lifting lugs
Vibrator
Foundation Form Set
Ring alignment interconnections

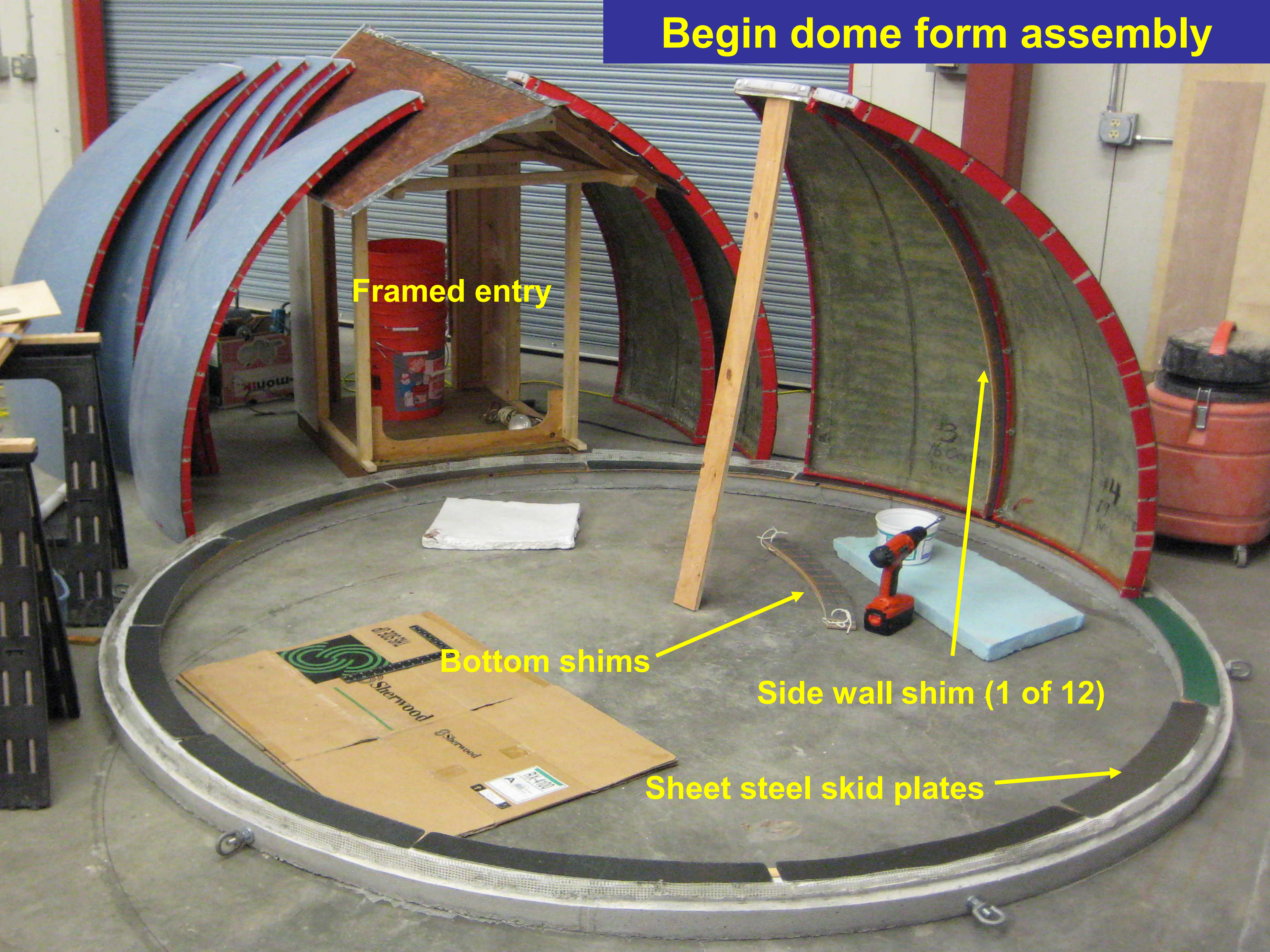


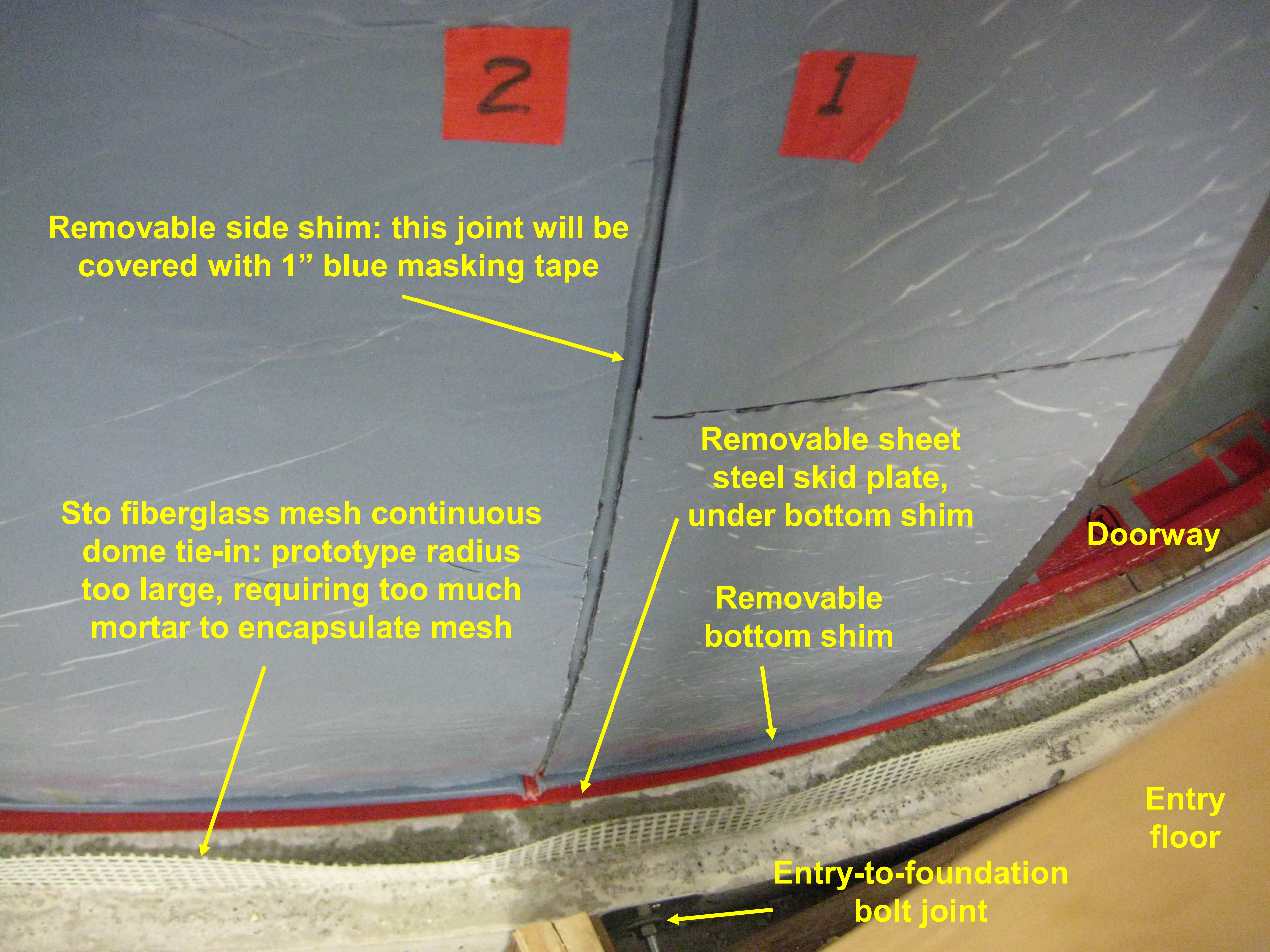
Assembled foundation form, ready for pour

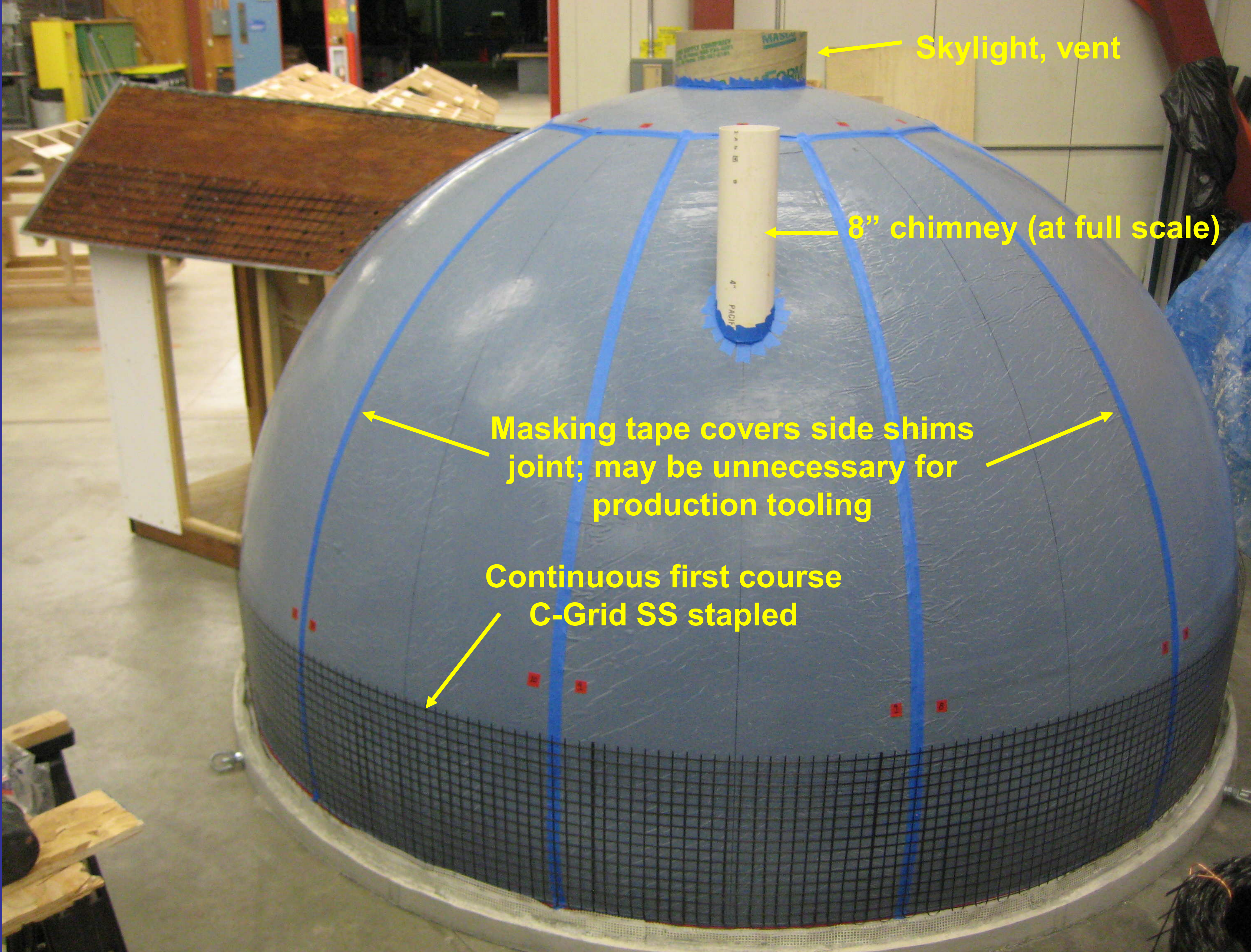


“Circus ring” foundation: 4” W x 3” H , outward view

Begin dome form assembly




2
1
Removable side shim: this joint will be covered with 1” blue masking tape
Removable sheet steel skid plate, under bottom shim
Sto fiberglass mesh continuous dome tie-in: prototype radius too large, requiring too much mortar to encapsulate mesh
Doorway
Removable bottom shim
Entry floor
Entry-to-foundation bolt joint



Skylight, vent
8" chimney (at full scale)
Masking tape covers side shims joint; may be unnecessary for production tooling
Continuous first course C-Grid SS stapled

Prototype Mortar Mix Batch

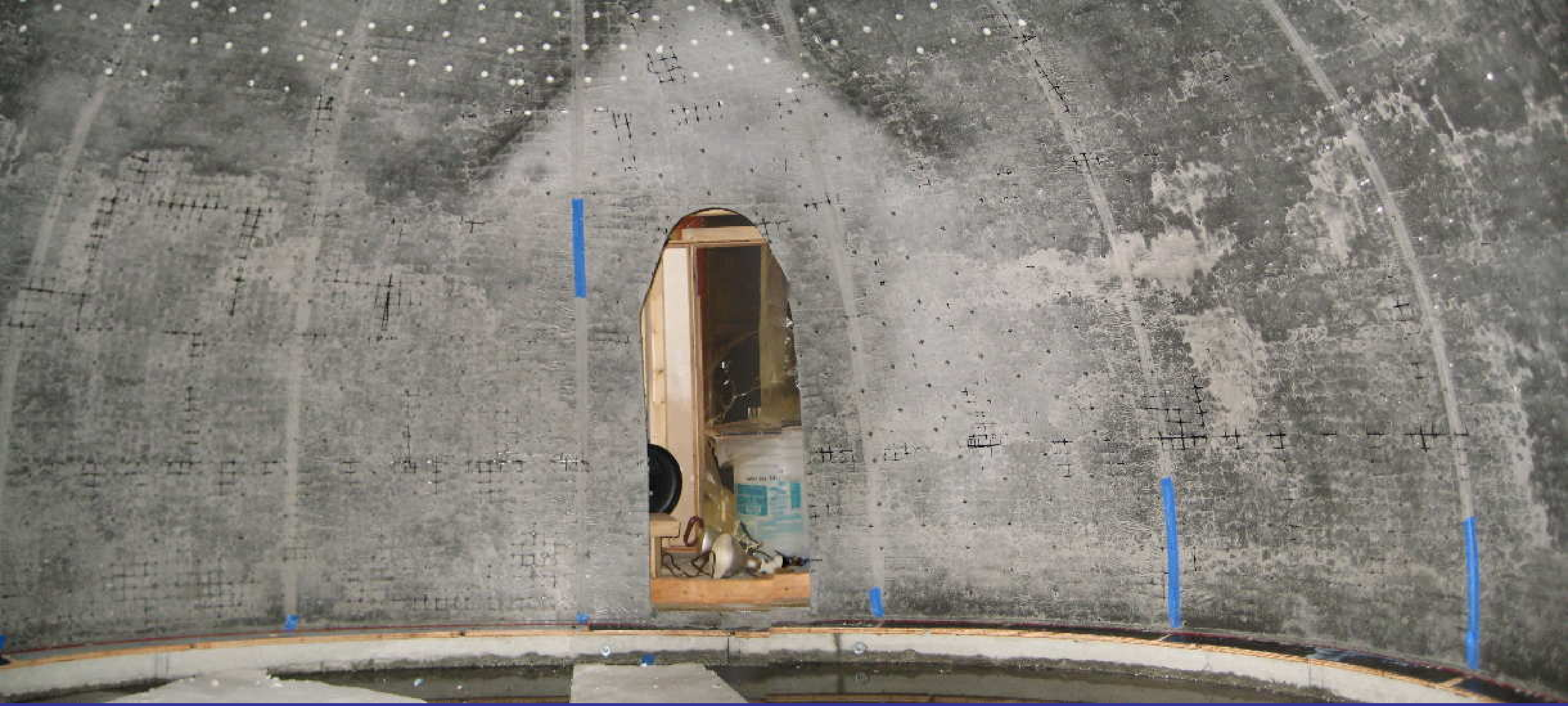
Sand – only aggregate

	Weight
• Sand, ungraded, bagged "play sand"	61 lbs
• Portland cement (Lafarge Type I & II)	25 lbs
• Water	17 lbs
• Silica Fume (BASF SF100)	6 lbs
• Xypex #500 crystalline waterproofing	7.4 oz
• Superplasticizer (BASF PS-1466)	1.5 oz
• Fibermesh 150: 1/4 " cut (polyprop)	1.5 oz
• Fibermesh 150: 3/4 " cut (polyprop)	1.5 oz
TOTAL	110 lbs

7 batches used = 770 lbs
770 lbs / 3,915 lbs / cu yd = 0.2 cu yd = 5.4 cu ft x 1,728 = 9,330 cu in
Total area (dome + entry roof) = 172 sq ft = 24,800 sq in
Inferred average concrete thickness: 9,330 / 24,800 = 0.38 inch


After dome ~ 80%
mortared, hinged entry
roof dropped into place
for continuous concrete
structural continuity


Hinged Entry roof dropped into place
Continuous C-Grid embedded for structural integrity of dome and entry
Removable entry roof form Z-flashing (4 pcs)
Entry roof hinge



14 Nov 09

- Interior concrete shell after form set removed
- Blue masking tape sealed joints; easily removed
- 1/4” high UR rubber self-stick “chairs” on lower region
- Thinner white felt chairs used on upper region
- Mortar consolidation, penetration and C-Grid capture varies
- No vibration used during mortar placement

Remaining Challenges + Opportunities

Slide 1 of 4

- Engineering design:
  - FEA for stress concentrations (windows, door, entry roof)
  - Reinforcing design at concentrations
  - Optimize C-Grid or other primary reinforcement
- Load testing: static, dynamic protocols
- Materials and process experiments
  - Mortar mix recipe
  - Indigenous aggregates: selection, qualification, preparation
  - Mortar application: potential spray or shotcrete
  - Mortar consolidation
    - Encapsulate C-Grid
    - Voids removal
    - Vibration
      - Multiple points
      - Devices integral to form
      - Manual control strategy
      - Air or electric
- Interior foam protection + finish
    - Spray: hopper gun or other
    - Same machine as concrete shell spray
    - Product: bagged mix, properties
    - Thickness required; control

Remaining Challenges + Opportunities

Slide 2 of 4

- **Process quality control:**
  - **Mixes**
  - **Thickness**
  - **Consolidation**
  - **Cure; insure hydration**
- **Special tools**
  - **Interior + exterior arc ladders**
  - **Form removal post-cure**
  - **Vibration, consolidation**
- **Potential to replace or eliminate primary reinforcement**
  - **May be necessary to capture and position mortar**
  - **C-Grid alternatives:**
    - **Lower cost**
    - **Easier to handle and apply**
    - **Fiberglass grid**
  - **"ECC" Engineered Cementitious Composite only**
- **Potential to replace EPDM + Integument Teflon release surface**
  - **Silicone paint, roofing**
  - **Bedliner spray**

Remaining Challenges + Opportunities

Slide 3 of 4

- Tool for "full size" ~ 18 ft diam @ equator: $300 – 500K ?
  - 3D CAD design
  - Mold tooling build:
    - Side wall "orange peel" segment
    - Top cap
    - Foundation outer ring
    - Foundation inner ring
  - Form sets build: fiberglass boat processes for precision
    - Foundation
    - Dome
  - Framed entry kit develop
- Full-size development work by contractor & subcontractors
  - Funding source(s)
  - Markets:
    - Customers and applications
    - Cost models: various
  - Business model:
    - Franchise: sell tooling and tool sets + training + QC
    - Others

Remaining Challenges + Opportunities

Slide 4 of 4

- **Revise design from field experience**
- **Window, skylight options**
  - **Add interior partition wall:**
  - **Support loft**
  - **Private space**
- **Ventilation options (climate and cost determined)**
  - **Manual vs powered**
  - **Air-to-air heat exchanger**
  - **Equipment in entry roof peak**
- **Heating / cooling options (climate and cost determined)**
  - **Stove – chimney system**
  - **Passive solar via south-facing window**
  - **Thermal mass**
- **Floor options (on grade; thermal break required)**
  - **Compacted earth**
  - **Foam board underlayment, closed cell, thermal insulation**
  - **Soil cement**
  - **Concrete**
- **Floor options (on pilings or stem wall; thermal break required)**
  - **Framed structurally supported by foundation ring**
  - **Other**

Goals

1. Minimize imported:
   a. Materials, including aggregate
   b. Tooling
   c. Tools
   d. Expert labor
   e. Use local sand, water, semi-skilled labor
   f. Minimize Earth impact
2. Build many on-site, in-situ
   a. Reusable forms set
   b. One every 3 – 4 days
3. Non-ferrous primary reinforcement
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6. Earth sheltered: compatible
7. Alaska village housing replace

References

Chomarat NA	http://carbongrid.com/
	"Broadway, Andrew" <andrew.broadway@chomaratna.com>
Integument	http://www.integument.com/
	"Jennifer Smyth" <jsmyth@integument.com>
CCHRC (Cold Climate Housing Research Center, Fairbanks, AK) http://www.cchrc.org/	
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Intershelter	http://intershelter.com/
	Don Kubley (907) 789-9273
Flexible concrete	Prof. V. S. Li, University of Michigan
	Prof. Michael Lepech, Stanford University

BASF (superplasticizer, silica fume, fibermesh)

Sto (fiberglass mesh, SilcoLastic paint)

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