Toroidal tank development for upper-stages

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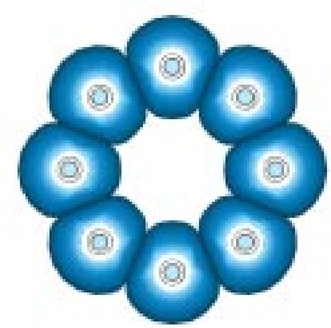


Background

- Past interest in upper stages
  - Orbit transfer vehicle programs; toroidal tanks were under study
    - Compact LOX Feed System Study AFRL TR-86-045
- Current interest
  - SLI architecture studies
  - JPL satellites
- Potential Benefits
  - Packing efficiency
  - Weight savings
- Challenges
  - Manufacturing methods
  - Fluid acquisition

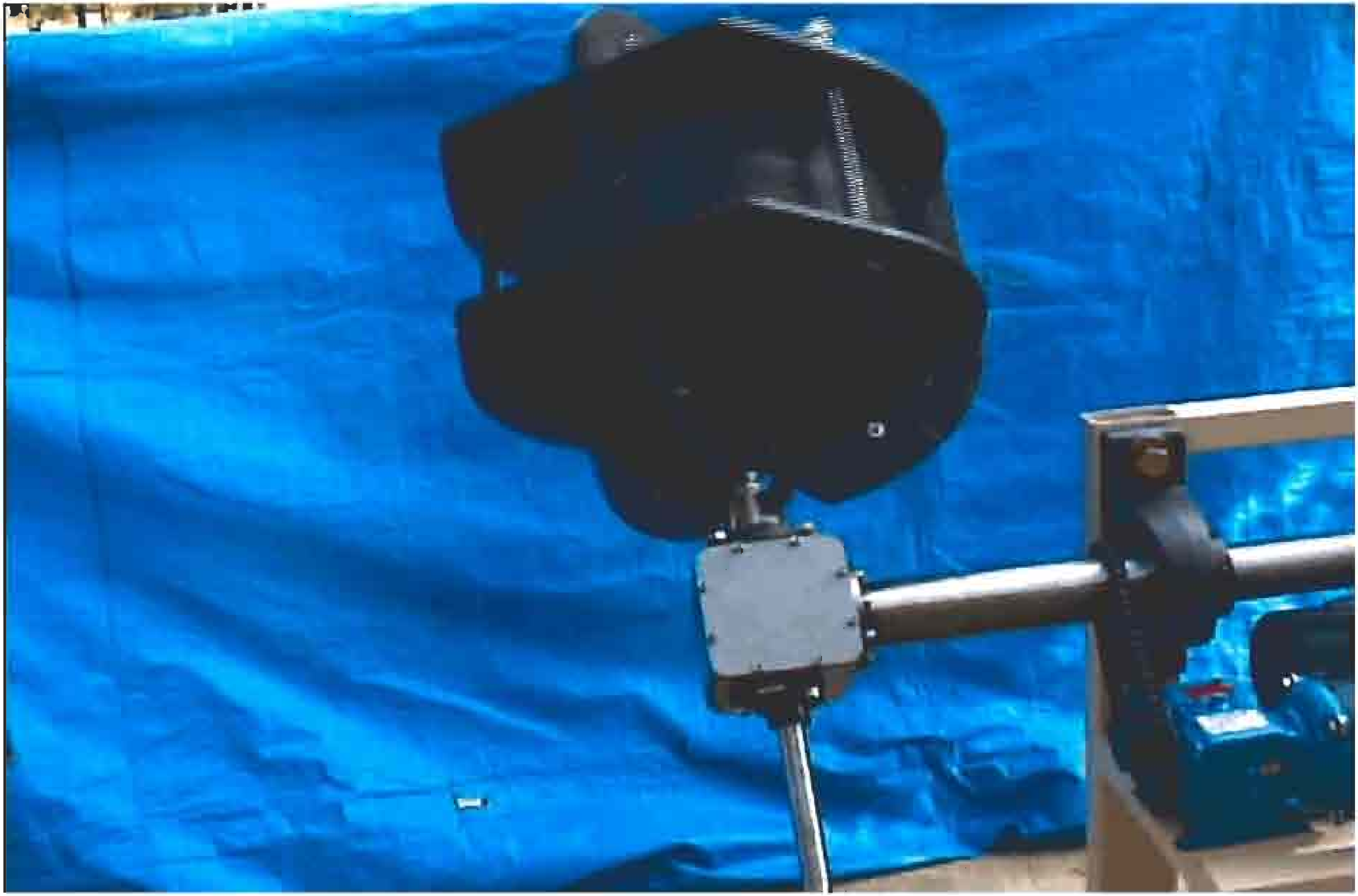
Why are we building toroidal tanks?

- CDDF (Center Director's Discretionary Fund)
  - SLI 2nd and 3rd gen programmatic interest
  - Manufacturing hurdles challenged before architecture is defined
- Joint IR&D
  - New pressure vessel technologies developed by MSFC
  - Conformal CNG tank technology developed at THIOKOL
  - Combined effort to leverage results

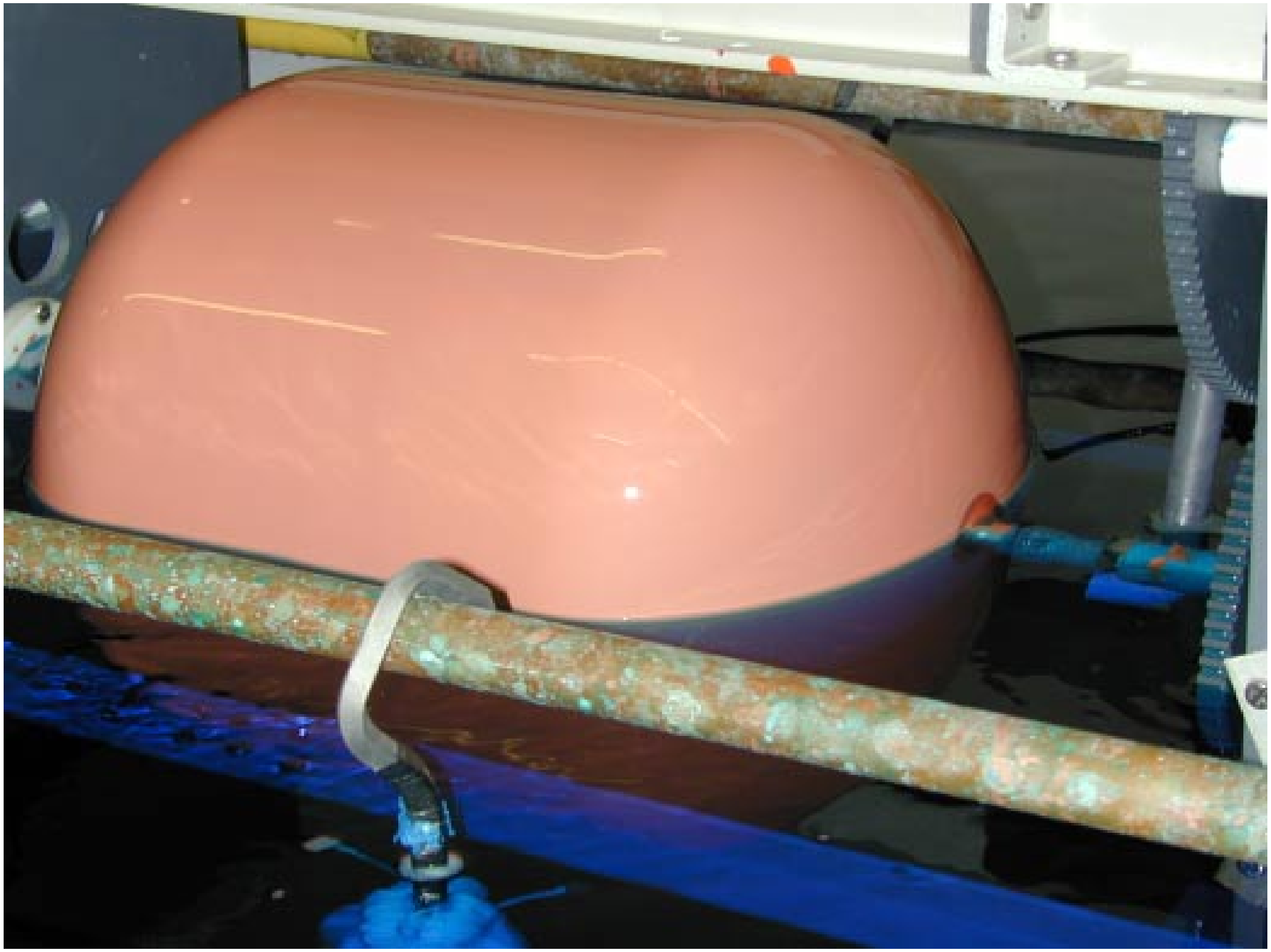
MSFC IR&D Effort

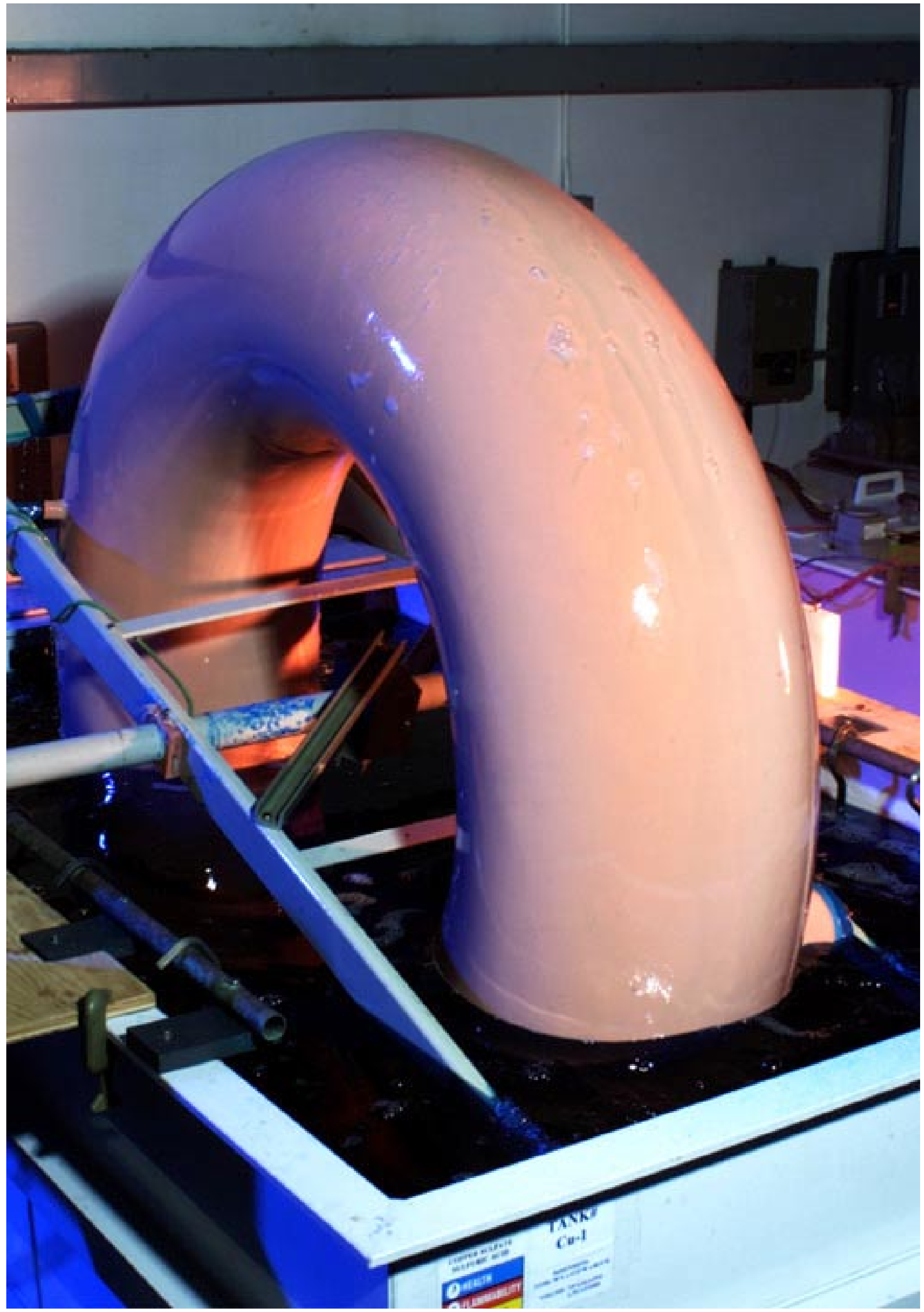
- Development of tank and pressure vessel concepts for upper stages
  - Address permeation issues with pressurant gasses (Helium)
  - Develop processes adaptable to conformal tanks
  - Consider lined and unlined composite tank concepts
    - Liner development based on contained fluids
  - Produce ultra-light vessels that are suitable for satellites and scalable to upper stages
  - Develop technology that may be transferred to industry

MSFC IR&D Effort



MSFC IR&D Effort

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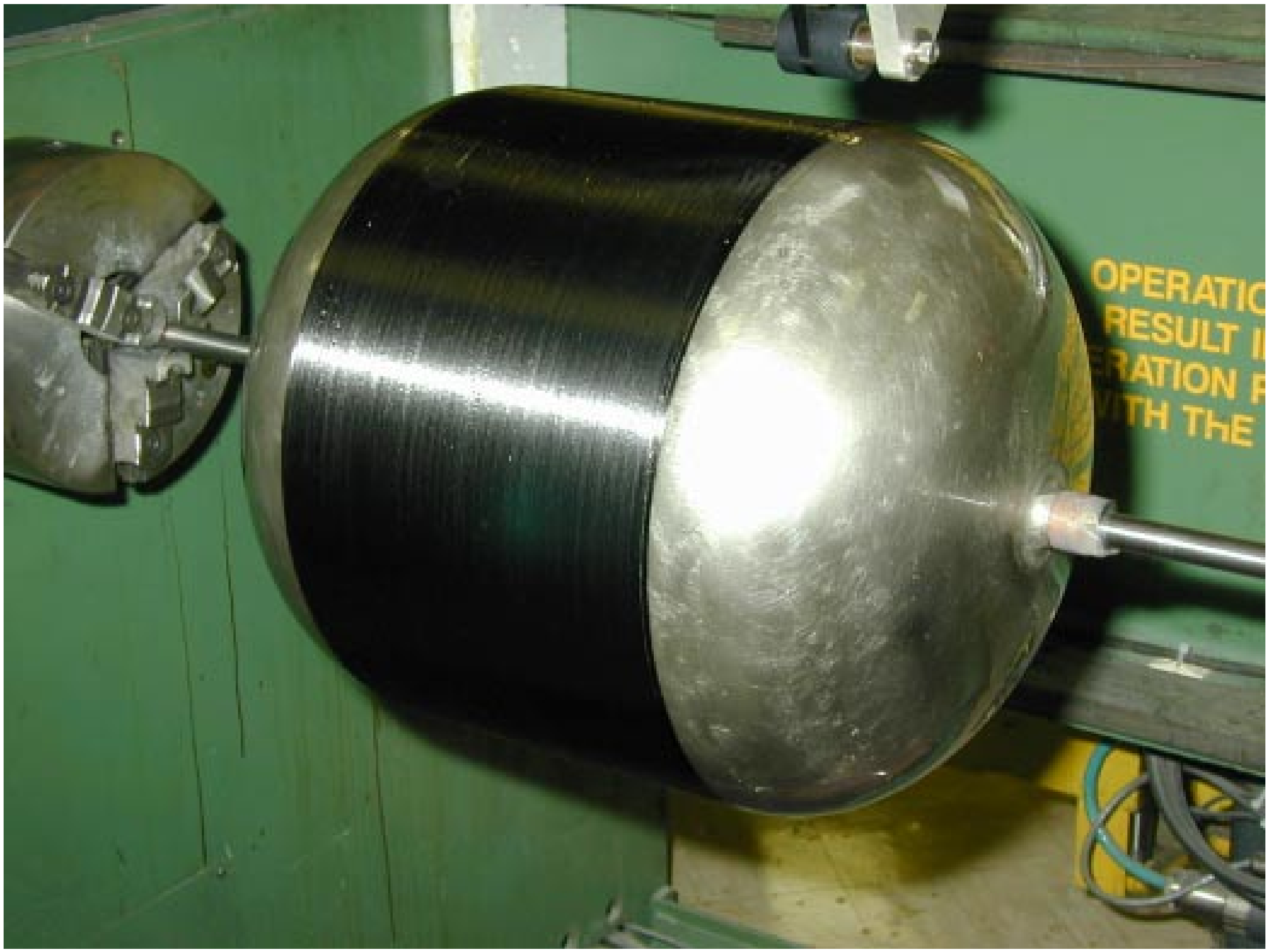
MSFC IR&D Effort

MSFC IR&D Effort

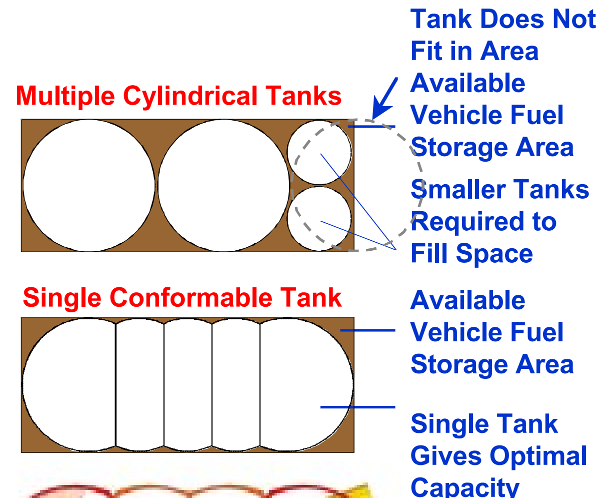


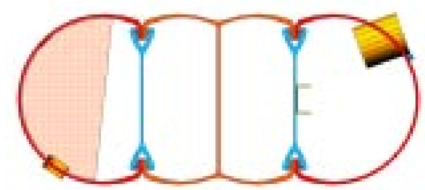
MSFC IR&D Effort

THIOKOL Conformal Tank Technology Development

Aluminum Propane Tank Product Overview

- **Cylindrical tanks provide near-optimum pressurized fuel storage**
- **Cylinders often do not fit well within the available vehicle space**
- **Conformable concepts adapt to the available vehicle space**
- **New technology propane fuel storage tanks**
  – Interlocking aluminum extrusions reduce the number and criticality of longitudinal welds in the assembly
- **Unit cost is more than cylindrical tank, but offers significant advantages**
    - Extends vehicle **range**: up to 50%
    - Reduces **weight**: aluminum construction
    - Reduces system **complexity**:
      – Eliminates “ganged cylinders”
      – Lowers overall system cost
- **Complete family of ASME certified tanks available as commercial products**





Composite Tank Product Overview

- Composite tank development has been completed using Department of Energy funding
  - Both tanks are for gaseous fuel storage
    - CNG at 3,600 psig
    - Hydrogen at 5,000 psig
  - Both tanks are made using aluminum polar bosses, plastic liners, and TCR composite over wrap
  - Both tanks have been designed to fill Ford P2000 envelope (13 in. x 22 in. x 28 in.)

- Tanks are in the process of certification to industry standards
  - CNG tank has completed commercial NGV2-1998 certification testing
  - Hydrogen tank will also complete all certification testing by June 01 to modified NGV2-1998 standard
  - Next step is to address specific OEM test criteria
- Significant interest in both CNG and hydrogen tanks from after market and OEM customer base


THIOKOL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Approach To Producing Toroids

- Continuous circular toroid
  - Tooling
  - Materials
  - Design
  - Advantages and challenges
- Conformal/segmented toroid
  - Tooling
  - Materials
  - Design
  - Advantages and challenges

Continuous Composite Toroidal Tank fabrication

- Several methods approached to consider:
  - Scalability
    - What is the representative size that may be needed
    - Are the processes adaptable
  - Manufacturability
    - Tooling methods to be developed
    - Automation vs. hand-layup
  - Operational environment
    - Operational pressures
    - Fluid management, slosh
    - Chemical compatibility of fluid and permeability of gasses

Continuous Composite Toroidal Tank fabrication

- Tooling, materials, design
  - Rotationally molded thermoplastic liner/mandrels
  - Liner pressurized while over-wrapped and cured
  - Lower temperature cured graphite epoxy over-wrap
  - Nylon end fitting machined and bonded
  - 1/3 scale version of what could fit in delta 4 faring

Continuous Toroidal Tank fabrication

Continuous Toroidal Tank fabrication

Continuous Toroidal Tank fabrication

Continuous Toroidal Tank fabrication

Continuous Toroidal Tank fabrication

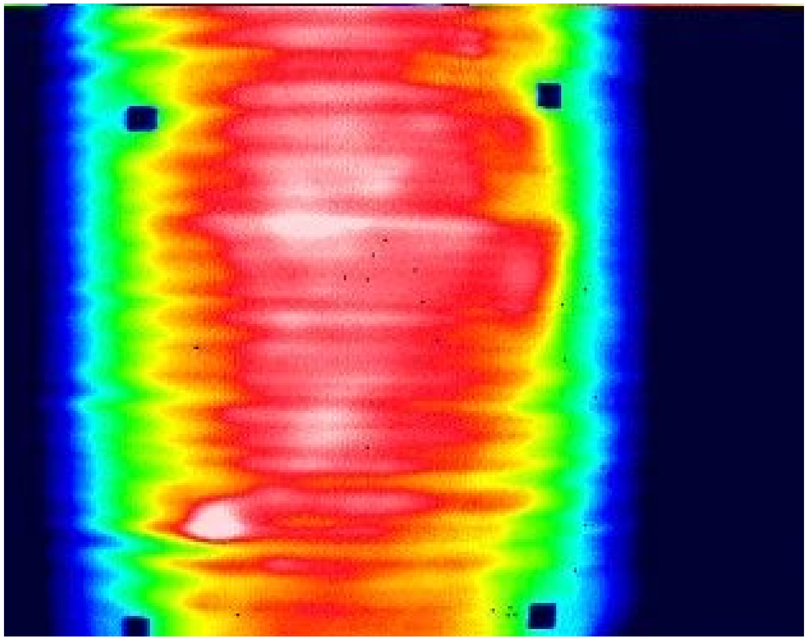
Continuous Toroid Traits

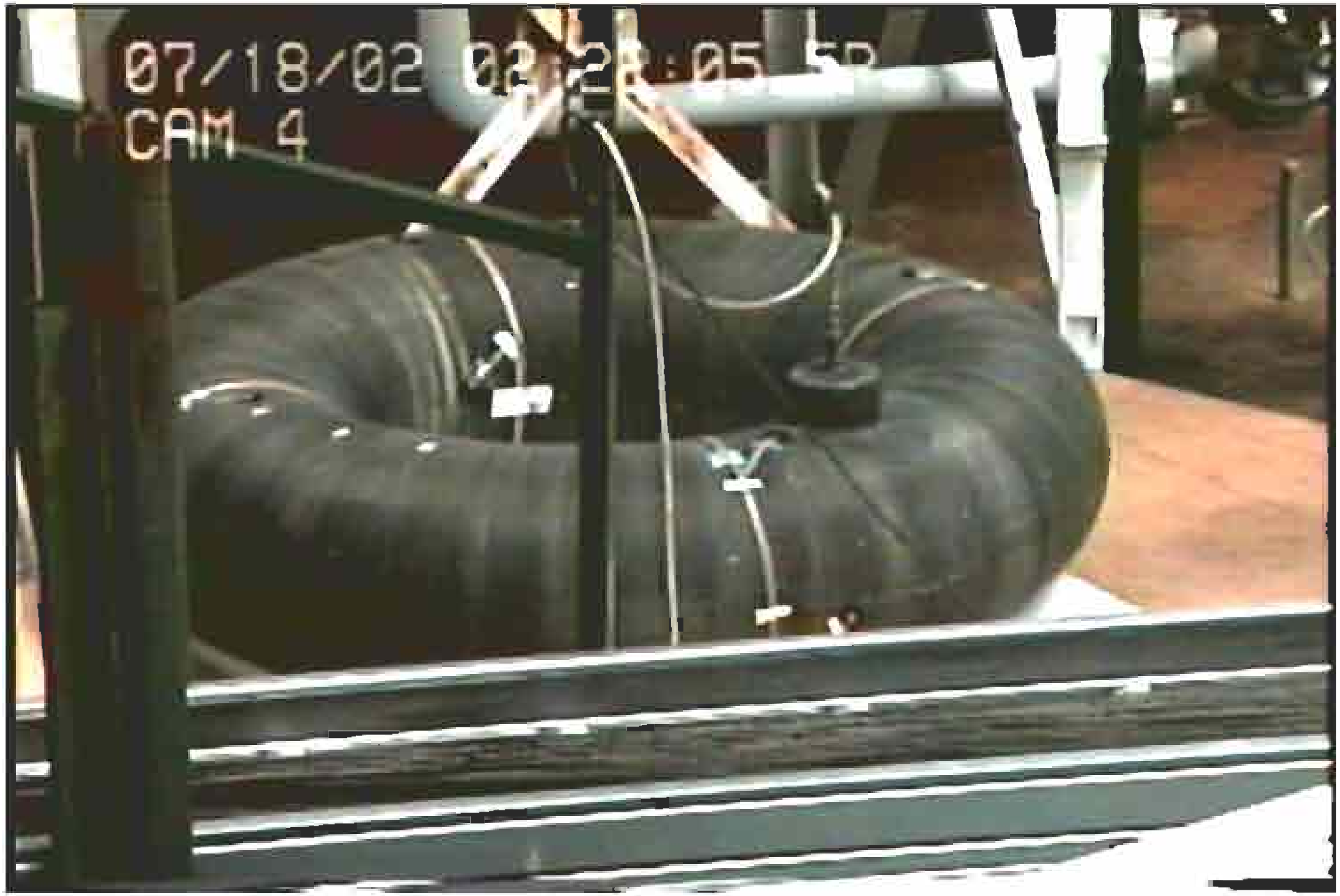
- 60 inch outside diameter, 16 inch cross section
- 5 inch diameter port 180 degrees on the opposite side of 1 inch port
- The composite toroid weighed less than 40 lbs.
- It contained 120 gallons of water, 27,793 cubic inches
- Total weight slightly more than 1,000 pounds,full
- Predicted burst pressure 375 psi
- Actual burst pressure 425 psi
- Area of highest strain, inner radius
- Packing efficiency(38% more volume than multiple spheres constrained by the same space)

Inspection and test of continuous toroid

- Vessel was inspected with thermography
  - No surface wrinkles, very minor de-bonds
- Triaxial strain gauges used to help predict burst

Inspection and test of continuous toroid

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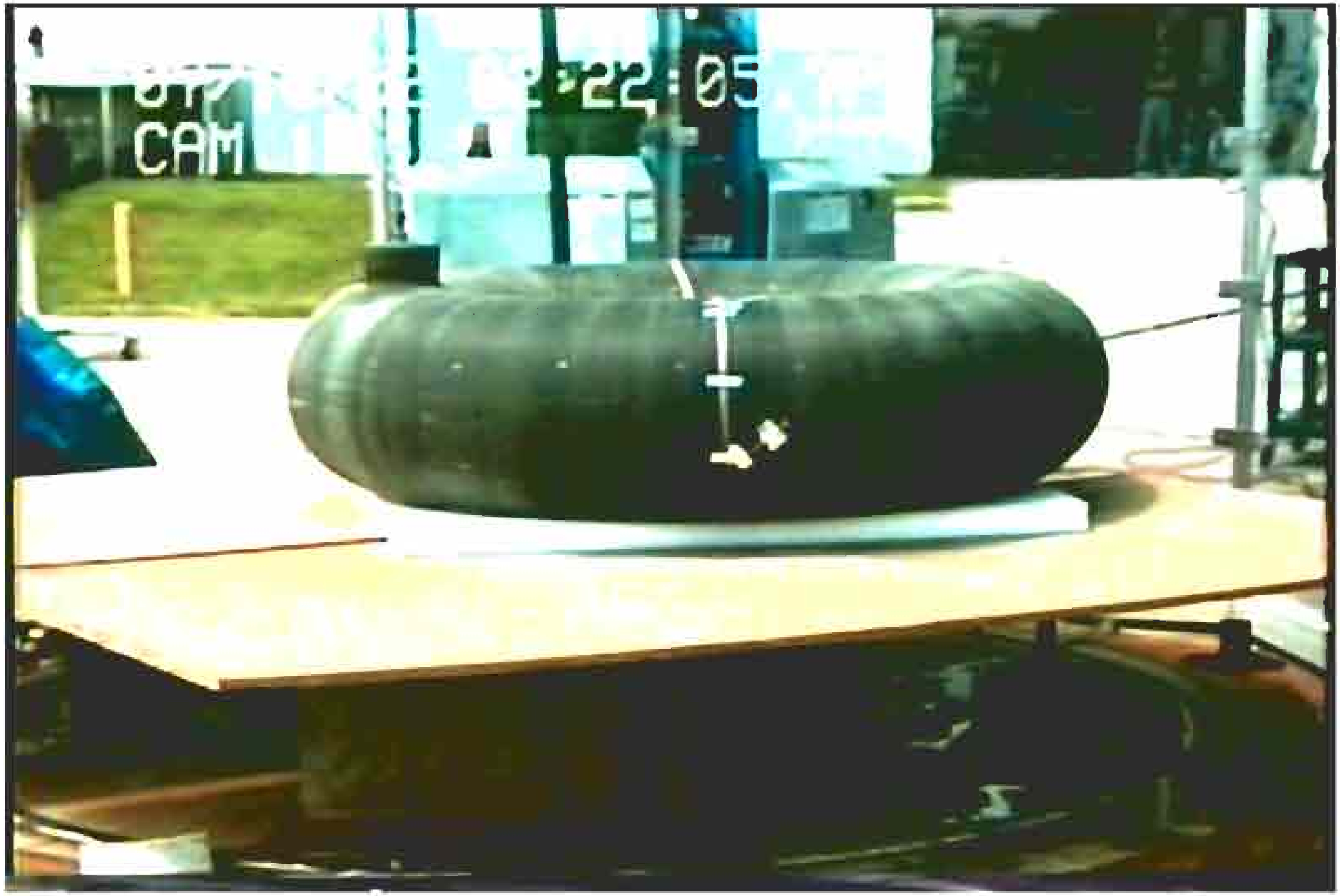
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Segmented Composite Toroidal Tank fabrication

- Several methods approached to consider:
  - Scalability
    - What is the representative size that may be needed
    - Are the processes adaptable
  - Manufacturability
    - Tooling methods to be developed
    - Automation vs. hand-layup
  - Operational environment
    - Operational pressures
    - Fluid management, slosh
    - Chemical compatibility of fluid and permeability of gasses

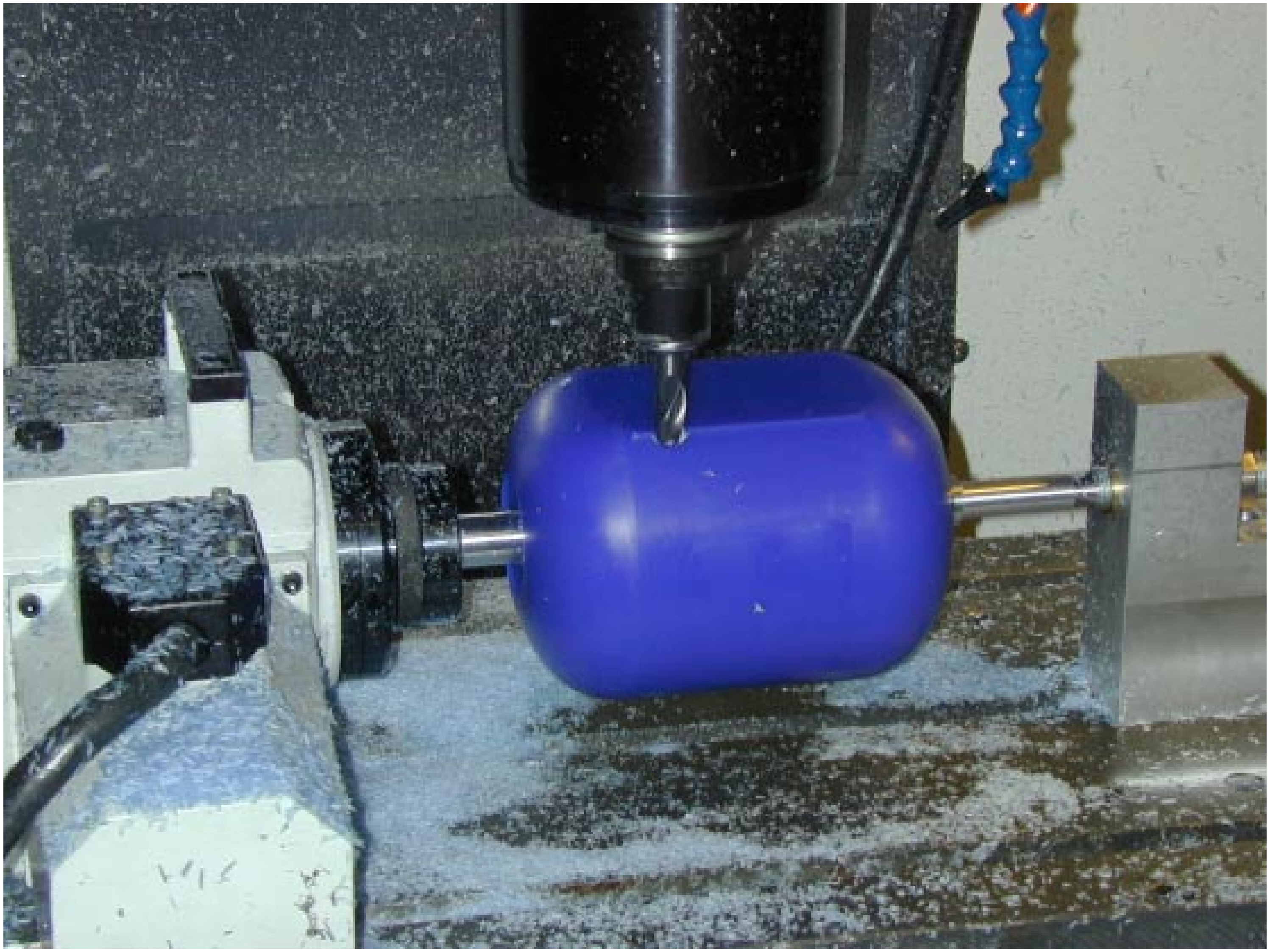
Segmented Composite Toroidal Tank fabrication

- Tooling, materials , design
  - Machineable wax mandrel outfitted with end fittings and copper plated
  - Graphite epoxy over-wrap
    - Each segment filament wound with graphite/epoxy
  - Conformal tank geometry proprietary
  - Slightly less volume than continuous toroid ;however, higher pressure applications likely
  - Process being scaled and modified
  - Sub-scale assembly useful for demonstrating concept

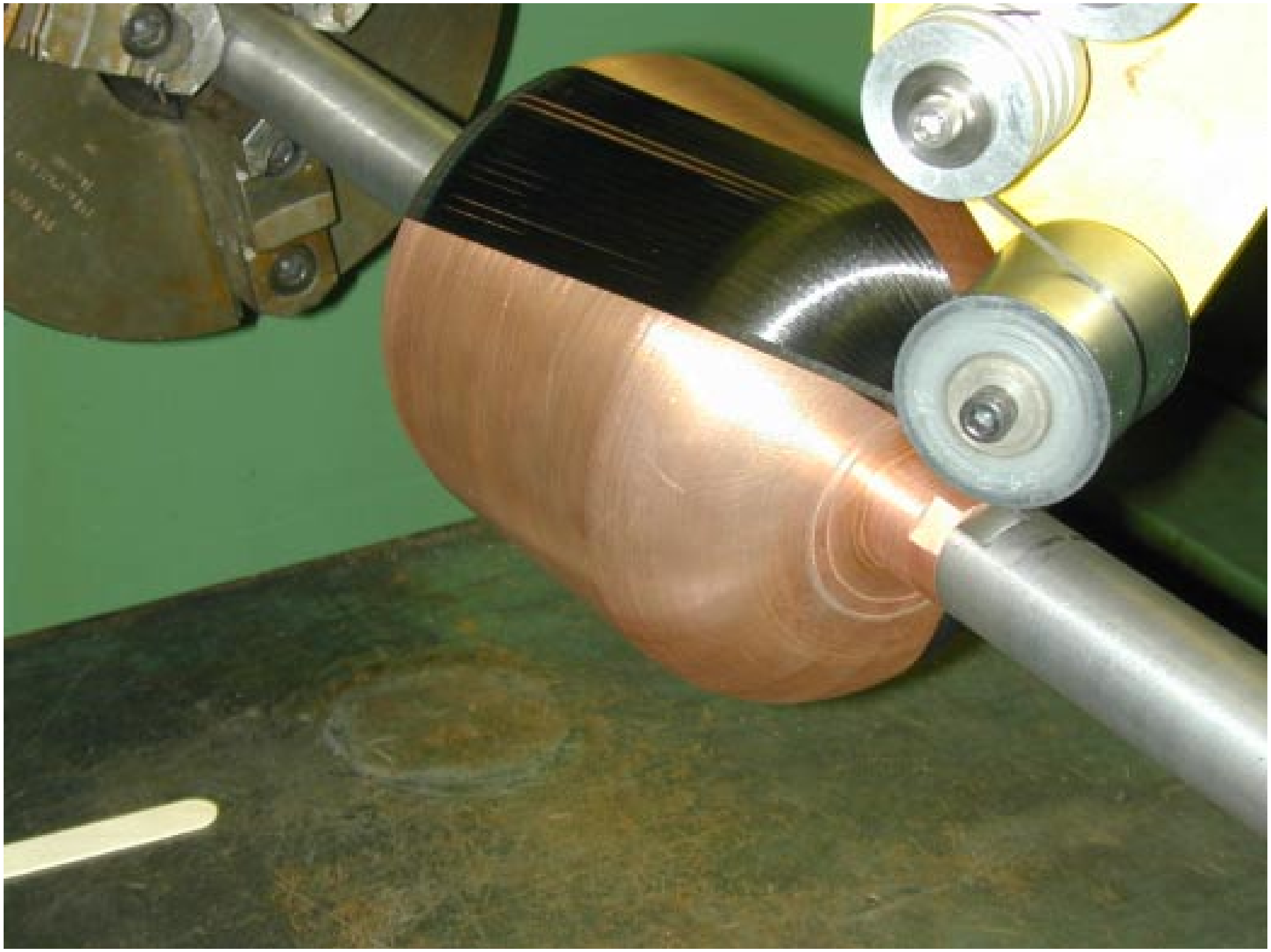
Segmented toroid

Segmented toroid

Segmented toroid



Segmented toroid



Segmented toroid

Potential advantages of segmented toroid

- Management of fluid acquisition
  - Slosh modes unique to toroids
- Packaging of oxidizers and fuels
  - Alternate tanks to control center of gravity
  - 10-20% more efficient than cluster of cylindrical tanks
- Replacement of damaged unit in the assembly
- Adaptable to very long toroid assemblies
- Customize to propulsion system requirements
  - Pressure fed system vs. pump fed

Where next?

- Continue development of segmented toroid
  - High cycle testing of assembly
  - Investigate application to SLI architecture or commercial applications
- Fabrication of additional circular toroids
  - Consider additional burst test or flow studies
  - Investigate slosh management
    - Positive expulsion bladder
- Consider partnerships if appropriate