University of Missouri-Columbia
Research Reactor

http://www.murr.missouri.edu
# University-operated Research Reactors

<table>
<thead>
<tr>
<th>Facility</th>
<th>Power Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massachusetts Institute of Technology</td>
<td>6 MW</td>
</tr>
<tr>
<td>University of California-Davis</td>
<td>2 MW</td>
</tr>
<tr>
<td>Rhode Island Nuclear Science Center</td>
<td>2 MW</td>
</tr>
<tr>
<td>Oregon State University</td>
<td>1 MW</td>
</tr>
<tr>
<td>University of Texas, Austin</td>
<td>1 MW</td>
</tr>
<tr>
<td>North Carolina State University</td>
<td>1 MW</td>
</tr>
<tr>
<td>Pennsylvania State University</td>
<td>1 MW</td>
</tr>
<tr>
<td>Texas A&amp;M University</td>
<td>1 MW</td>
</tr>
<tr>
<td>University of Massachusetts-Lowell</td>
<td>1 MW</td>
</tr>
<tr>
<td>University of Wisconsin</td>
<td>1 MW</td>
</tr>
<tr>
<td>Washington State University</td>
<td>1 MW</td>
</tr>
<tr>
<td>Ohio State University</td>
<td>500 kW</td>
</tr>
<tr>
<td>Kansas State University</td>
<td>250 kW</td>
</tr>
<tr>
<td>Reed College</td>
<td>250 kW</td>
</tr>
<tr>
<td>University of California-Irvine</td>
<td>250 kW</td>
</tr>
<tr>
<td>University of Maryland</td>
<td>250 kW</td>
</tr>
<tr>
<td>Missouri University of Science and Technology (Rolla, MO)</td>
<td>200 kW</td>
</tr>
<tr>
<td>University of Arizona</td>
<td>100 kW</td>
</tr>
<tr>
<td>University of Florida</td>
<td>100 kW</td>
</tr>
<tr>
<td>University of Utah</td>
<td>100 kW</td>
</tr>
<tr>
<td>Purdue University</td>
<td>1 kW</td>
</tr>
<tr>
<td>Rensselaer Polytechnic Institute</td>
<td>100 W</td>
</tr>
<tr>
<td>Idaho State University</td>
<td>5 W</td>
</tr>
<tr>
<td>University Of New Mexico</td>
<td>5 W</td>
</tr>
</tbody>
</table>

Providing quality nuclear research, education and service to a global community.
Facility Overview

**Location:** University of Missouri main campus in Columbia, Missouri, USA [200 km West of St Louis].

**History:**
- First critical on October 13, 1966 (Licensed at 5 MW).
- Started 100 hour/week operation at 5 MW in 1969.
- Uprated and licensed at 10 MW in 1974.
- Started 100 hour/week operation at 10 MW in 1974.
- Started ≥150 hours/week operation at 10 MW in 1977.
- Submitted relicensing application to the NRC in 2006.
- Became actively involved in the RERTR program to convert from HEU to LEU fuel in 2006.

**Purpose:** Multi-disciplinary research and education facility also providing a broad range of analytical and irradiation services to the research community and the commercial sector.
Facility Overview

• MURR operates 24 hours a day, seven days a week, and 52 weeks a year.

• 165 full-time employees.

• In 2014, MURR produced 36 different isotopes with 1,175 shipments to 7 different countries.

• Each and every week MURR supplies the active ingredients for FDA-approved Quadramet® (Sm-153) and TheraSpheres® (Y-90).
OPERATING EXPERIENCE
UNIVERSITY of MISSOURI RESEARCH REACTOR

ENERGY PER QUARTER (MWD/QUARTER)

10MW - 150 Hrs/wk
100% of Scheduled Operating Time

5MW - 100 Hrs/wk

TOTAL ENERGY

CALIBERD YEAR


0 100 200 300 400 500 600 700 800 900 1000 120000

0 20000 40000 60000 80000 100000 120000
Key Reactor Parameters

MURR® is a pressurized, reflected, heterogeneous, open pool-type, which is light-water moderated and cooled:

- Maximum power: $10 \text{ MW}_{th}$
- Peak flux in center test hole: $6.0 \times 10^{14} \text{ n/cm}^2\text{-s}$
- Core: 8 fuel assemblies (775 grams of U-235/assembly)
- Control blades: 5 total - 4 BORAL® shim-safety, 1 SS regulating
- Reflectors: beryllium and graphite
- Forced primary coolant flow rate: 3,750 gpm (237 lps)
- Primary coolant temps: 120 °F (49 °C) in, 136 °F (58 °C) out
- Primary coolant system pressure: 85 psia (586 kPa)
- Forced pool coolant flow rate: 1,200 gpm (76 lps)
- Pool coolant temps: 100 °F (38 °C) in, 106 °F (41 °C) out
- Beamports: three 4-inch (10 cm), three 6-inch (15 cm)
Cross-section View of Core (MCNP Model)

- Fuel Element (1 of 8)
- Control Blade (1 of 5)
- Flux Trap
- 2-inches Below Core Centerline
- Beryllium Spacer (1 of 5)
- Beryllium Reflector
- Graphite Reflector
- Beamport (1 of 6)
Research and Development

• Life Sciences
  ✓ Radiopharmaceutical Research
  ✓ Trace Element Epidemiology
  ✓ Boron Neutron Capture Therapy
  ✓ Radioisotope Tracers

• Social Sciences
  ✓ Archaeometry

• Material Sciences
  ✓ Triple Axis (TRIAX) Spectrometer
  ✓ Neutron Reflectometer
  ✓ Multi-detector Powder Diffractometer
  ✓ High Resolution Powder Diffractometer
Education and Training

• Graduate and Undergraduate Programs
  ✓ MS and PhD in Nuclear Engineering (Nuclear Power, Health Physics and Medical Physics)
  ✓ MS and PhD in Chemistry (Radiochemistry)
  ✓ MA and PhD in Archaeology (Anthropology, Art History and related fields)
  ✓ Integrative Graduate Education and Research Traineeship (IGERT) – PhD Level
    ▪ Condensed Matter / Neutron Scattering

• Secondary Science Teachers
  ✓ NE7313 Course

• Radiopharmaceutical Chemistry
Products and Services

• Radioisotopes and Radiochemicals
  ✓ cGMP-grade Radioisotopes and Radiochemicals
  ✓ Bulk and Research-grade Radioisotopes and Radiochemicals
  ✓ 16 MeV Cyclotron - F-18 and Cu-64

• Irradiation Services

• Contract Manufacturing
  ✓ Drug Master Files (DMF) with the FDA
    ▪ MURR has filed multiple DMFs

• Analytical Services
  ✓ Neutron Activation Analysis (NAA)
  ✓ Inductively Coupled Plasma (ICP) Instrumentation (ICP-MS, ICP-OES, LA-ICP-MS and MC-ICP-MS)
  ✓ X-ray fluorescence (XRF)
Products and Services

….from research to manufacture

Semiconductors used for power electronics require nearly perfect and uniform material characteristics because of the high power levels flowing in the devices.

- Neutron Transmutation Doped (NTD) silicon process developed in the 1970s
  - MURR
  - MU College of Engineering
  - Monsanto Electronics
- Some applications of NTD silicon power diodes
  - Hybrid Automobiles
  - Bullet Trains
### Isotope Supply Activities

<table>
<thead>
<tr>
<th>36 Different Isotopes Supplied by MURR in 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Au-198</strong></td>
</tr>
<tr>
<td><strong>Au-199</strong></td>
</tr>
<tr>
<td><strong>Ba-131</strong></td>
</tr>
<tr>
<td><strong>Ca-45</strong></td>
</tr>
<tr>
<td><strong>Cd-115</strong></td>
</tr>
<tr>
<td><strong>Ce-141</strong></td>
</tr>
<tr>
<td><strong>Co-60</strong></td>
</tr>
<tr>
<td><strong>Cr-51</strong></td>
</tr>
<tr>
<td><strong>Cu-64</strong></td>
</tr>
<tr>
<td><strong>Fe-59</strong></td>
</tr>
<tr>
<td><strong>Lu-177</strong></td>
</tr>
<tr>
<td><strong>Hg-203</strong></td>
</tr>
</tbody>
</table>
Lutetium-177

$^{177}$Lu from MURR is currently being evaluated in over 30 clinical applications for radiotherapy of cancer.

- Metastatic prostate cancer
- Non-hodgkins lymphoma
- Neuroendocrine tumors
- Ovarian cancer
- Metastatic bone cancer
- Colon cancer
- Lung cancer

Phase III Clinical Trials in Europe and U.S.
Metastatic gastro-entero-pancreatic neuroendocrine tumors
Survival benefit of 40 to 72 months
Isotope Research Activities

- Carrier free lanthanides
  - Indirectly produced (Lu-177, Pm-149 and Ho-166)
    - DOE Advanced Nuclear Medicine Initiative
  - Electromagnetic isotope separation (Sm-153)
    - DOE SBIR
- Mo-99
  - n, gamma produced for novel generator technologies
    - Industry partnership with NorthStar
  - Fission produced with uranium recycle
    - Industry partnership with Northwest Medical Isotopes
- Rh-105
  - Carrier free from uranium fission using selective gas extraction
    - Subcontract with General Atomics/DOE Isotope Program
- Re-186
  - Accelerator produced and separations for high specific activity
    - DOE Isotope Program
- As-72, As-77 and Cu-67
  - High specific activity with target recycle
    - DOE Isotope Program
Isotope Research Activities

- Po-210
  - ✓ Produced and incorporated into nuclear batteries
    - Private Industry
- Pm-147 and Gd-148
  - ✓ Collection of long-lived isotopes from primary cooling loop at FRIB
    - DOE Isotope Program
- Os-191
  - ✓ Produced and incorporated into device
    - Industry partnership with CheckCap
MU’s Unique Set of Resources for Benchtop-to-Bedside Success in Targeted Radiotherapy
Material Condition Assessments

- Reactor Pool Liner
  ✓ Recorded visual inspection using rad-resistant camera, monitor and recorder
  ✓ Focused on liner welds and aluminum plate and components around the welds – areas where corrosion would likely occur
  ✓ Reviewed past water chemistry analyses and procedures
  ✓ Results indicated no evidence of any number of potential corrosion mechanisms, or forms of linear distress, including cracks, deformations (including bulges), buckling and tears (at anchorages or attachments)

- Reactor Containment Building Structure
  ✓ Visual inspection of the containment structure and an evaluation of the structure’s resistance to a seismic event
  ✓ Inspection indicated that the concrete structure, coating, roofing materials and penetrations were in very good condition with no significant signs of deterioration
  ✓ Containment structure was determined to be structurally adequate to resist the Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) seismic events – basis for the seismicity and seismic damage sections of the SAR

Material Condition Assessments (con’t)

• Major Primary and Pool Coolant System Components
  ✓ Evaluated the physical state and material condition of major primary and pool coolant system components
  ✓ Assessment noted that the MURR has been maintained in a satisfactory condition to support safe operation
  ✓ Assessment also noted that the facility is in good condition to support a 20-year life extension
  ✓ All recommendations from the assessment regarding facility operation and maintenance have been fully implemented

• Electrical Distribution System
  ✓ Assessment indicated that the overall condition of the electrical distribution system is to be commended and complimented
  ✓ Report documented that equipment is well labeled, clean, well-maintained, and adequate working space is generally provided
  ✓ All large, dry-type facility transformers have been replaced

Note 2: Performed by MU Design & Construction Services and Yount Engineering and Design.
Renewal and Relicensing Projects

- Replacement of Graphite Reflector Elements
  ✓ All 12 graphite reflector elements were replaced with new ones

- Radioactive Liquid Waste System Modification
  ✓ System was modified such that all radioactive drain piping is accessible for inspection, monitoring and maintenance

- Installation of a Fire Protection System
  ✓ A Detection System that consists of heat, smoke, and remote manual devices, and a Suppression System that incorporates a normal sprinkler system with a pre-action system used in areas with sensitive electrical equipment

- Replacement of the Primary & Pool Coolant System Heat Exchangers
  ✓ Shell and tube-type heat exchangers were replaced with plate-type heat exchangers and flow measurement instrumentation upgraded

- Reactor Control Blade fabrication
  ✓ Procured 20 BORAL® control blade “kits” to fabricate new control blades
Renewal and Relicensing Projects (con’t)

• Replacement of the Reactor Plant Make-up Water Tanks
  ✓ Replaced two 7,000 gallon phenolic-lined carbon steel demineralized water storage tanks with two stainless steel tanks of the same capacities

• Replacement of major facility Electrical Distribution Transformers and Motor Control Centers
  ✓ Installed two new 300-kVA transformers and distribution panels to increase the facility’s 120/208V load capacity
  ✓ Replaced and upgraded the facility’s main 1000-kVA transformer with a new 2000-kVA transformer
  ✓ Replaced and upgraded the cooling tower 500-kVA transformer with a 1500-kVA transformer
  ✓ Replaced and upgraded the Secondary Coolant Pump Motors from 125 to 150 HP with variable speed drives

• Replacement of the Cooling Tower
  ✓ Replaced and upgraded an old-style 3 cell, wood-framed 10 MW cooling tower with a new 3 cell stainless steel 15 MW cooling tower
Renewal and Relicensing Projects (con’t)

- **Containment Building Airlock Door System Upgrades**
  - ✓ Upgraded the analog control system to a PLC-based system and replaced certain door mechanical components
- **Installation of a new generation Exhaust Stack Monitor**
  - ✓ Installed a new, redundant off-gas radiation monitoring system
- **Installation of a service platform on the 15-ton crane**
  - ✓ Installed a service platform to the containment building 15-ton overhead rectilinear crane
- **Renovation of various Laboratories**
  - ✓ Various laboratories have been totally renovated, including the construction of an acid disposal laboratory
- **Installation of new efficient, low flow Fume Hoods**
  - ✓ Replaced and installed new low flow fume hoods in laboratories 216, 218, 227 and 244
Renewal and Relicensing Projects (con’t)

• Significant number of reactor instrumentation and control systems have been replaced
• Updated Safety Analysis Report in accordance with NUREG-1537
  ✓ Re-analyzed the reactivity addition, loss of flow, loss of coolant and maximum hypothetical accidents using newer models and updated computer codes
  ✓ Performed neutron fluence calculations of the aluminum reactor pool liner and pressure vessels
  ✓ Total fluence calculations (fast and thermal) for the reactor pool liner are an order of magnitude less than the thermal fluence calculations for aluminum series 5000 components that were replaced at the French High Flux Reactor (HFR) at Saclay and HFR at Petten
  ✓ Total fluence calculations on the reactor pressure vessels (peak is mid-core section of inner pressure vessel) indicate that both fluence and fatigue stress are well with the measured envelop for aluminum 6061-T6
Reactor Design and Programs

- Reactor design is modular, where all components are replaceable, including the reactor pressure vessels.
- Beryllium reflector is replaced every 26,000 MWd (approximately 8 years); prior to the combined stresses $[^1H^3, _2He^3, \text{and thermal}]$ reaching the beryllium’s yield point.
- Reactor pool is designed such that the entire reactor pool and pool liner are above the elevation of the beamport floor and not in contact with any soil. With the exception of the base, all areas of the reactor pool are visible and accessible. The base of the pool is situated on a 16-foot by 16-foot monolith of reinforced concrete which extends straight downward to bedrock.
Reactor Design and Programs (con’t)

- Spare reactor pressure vessels are on hand, including stock material to fabricate additional vessels, if needed.
- Spare electrical motors and pumps are maintained for all major reactor plant circulation pumps; primary, pool and secondary coolant.
- Spare instrument and equipment is maintained for all reactor instrumentation and control systems.
- Comprehensive preventative and corrective maintenance, and material/machinery history programs.
Recent Building Additions

- Construction of a 3-level, 30,239 ft$^2$ North Office Addition that houses offices, classrooms, a lunch room, a 16 MeV cyclotron and associated laboratories, a teaching laboratory, a microbiology suite and a ICP laboratory.
- Construction of a 1-level, 3,217 ft$^2$ Shipping and Receiving Building within the licensed area – this building supports the necessary equipment to open and analyze incoming packages prior to being released into the main facility – also provides a staging area for outgoing packages.
- Construction of a 2-level, 2,800 ft$^2$ expansion to the MURR Industrial Building to support a processing laboratory.
<table>
<thead>
<tr>
<th>Date</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 2009</td>
<td>Completed Conversion Feasibility Study</td>
</tr>
<tr>
<td>June 2011</td>
<td>Completed Preliminary Safety Analysis Report</td>
</tr>
<tr>
<td>February 2012</td>
<td>Submitted letter to NRC for consideration of an exemption to a “test facility” in support of a required power uprate to 12 MW</td>
</tr>
<tr>
<td>August 2012</td>
<td>Completed Steady-State Thermal-Hydraulic Analyses</td>
</tr>
<tr>
<td>September 2012</td>
<td>Completed Neutronics Analyses</td>
</tr>
<tr>
<td>January 2013</td>
<td>Completed draft Chapter 4, Reactor Description</td>
</tr>
<tr>
<td>June 2013</td>
<td>Completed Preliminary Accident Analyses (Phase I)</td>
</tr>
<tr>
<td>September 2013</td>
<td>Completed Transition Fuel Cycle Report</td>
</tr>
<tr>
<td>December 2014</td>
<td>Completed Accident Analyses (Phase II)</td>
</tr>
</tbody>
</table>
Current Fuel Conversion Work

- Refining the MURR RELAP thermal-hydraulic model.
- Designing a new control blade with a heavier boron loading for increased shutdown margin.
- Studying the potential changes to the lifetime of the beryllium reflector based on changes in thermal heating, gas production and material properties.
- Working with the MU College of Engineering on FSI studies on fuel plate stiffness – proposed LEU fuel element design has thinner fuel plates.
- Base fuel demonstration – irradiation of a full-sized MURR LEU fuel element in the BR-2 reactor in Belgium.
- Draft conversion Safety Analysis Report to be submitted to the NRC by end of CY 2015.
Thanks for your attention, questions?