Importance of Nuclear Data
to the Naval Nuclear Propulsion Program

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NAVAL NUCLEAR PROPULSION PROGRAM

Field Offices
- REPORT TO DIRECTOR
  - Ensures focus on mission
  - Immediate identification of concerns

NAVAL REACTORS FACILITY
- Dry Storage Program
- Expended Core Facility

DEDICATED LABORATORIES
- Bettis Atomic Power Laboratory
- Knolls Atomic Power Laboratory
- GOCO

SPECIALIZED INDUSTRIAL BASE
- 1 dedicated equipment prime contractor
- Hundreds of suppliers

DON
DOE

NAVAL REACTORS
440 people

NUCLEAR POWERED FLEET
- 82 warships
- Over 40% of major combatants

SHIPYARDS
4 Public / 2 Private

R&D/TRAINING REACTORS
- Train 3500 students/year

SCHOOLS
- Nuclear Power School
- Nuclear Field "A" School

103 reactors operating worldwide
Transport Equation

\[ \frac{m_n}{2E} \frac{\partial \psi}{\partial t}(\mathbf{r}, \Omega, E, t) + \nabla \cdot \mathbf{\Omega} \psi(\mathbf{r}, \Omega, E, t) + \Sigma_s(\mathbf{r}, E, t) \psi(\mathbf{r}, \Omega, E, t) = \int d\Omega' \int dE' \Sigma_s(\mathbf{r}, \Omega' \rightarrow \Omega, E' \rightarrow E, t) \psi(\mathbf{r}, \Omega', E', t) + \frac{1}{4\pi} \int d\Omega \Sigma_f(\mathbf{r}, E, t) \psi(\mathbf{r}, \Omega, E, t) + S_{ex}(\mathbf{r}, \Omega, E, t) \]

Diffusion Approximation

\[ - \nabla \cdot D(\mathbf{r}, E) \nabla \varphi(\mathbf{r}, E) + \Sigma_t(\mathbf{r}, E) \varphi(\mathbf{r}, E) = S(\mathbf{r}, E) \]
Five Narratives

• Use of Early RPI Measurements
• Light Water Breeder Reactor
• Elimination of Mockup Cores
• Project Prometheus
• Some Very Recent Criticality Analyses
Use of Early RPI Measurements

• Criticality Analyses of Under-moderated Systems
  • Most Reactive Condition – Highest Water Density/Lowest Liquid Temperature
  • Not Necessarily True – Due to Temperature Dependence of Scattering Properties of Water
• Consider LEU-COMP-THERM-002 Benchmark from ICSBEP handbook
  • “Water-Moderated U(4.31)O₂ Fuel Rods in 2.54 cm Square-Pitched Arrays”
  • 10 x 11 array (+5)
  • Under moderated lattice with high leakage & reflector savings.

Figure 2: Arranging Fuel Rods.

Figure taken from NEA/NSC, “International Handbook of Evaluated Criticality Safety Benchmark Experiments,” NEA/NSC/DOC(95)03, 2009.
MC21 Analysis of LEU-COMP-THERM-002

Variation in lattice pitch shows lattice is under-moderated - optimum pin spacing at between 2.70 and 2.80 cm.

Calculation with no reflector – multiplication factor decreases with increasing temperature/decreasing water density – as expected.
MC21 Analysis
of LEU-COMP-THERM-002

However, calculation with water reflector shows the multiplication factor as a function of temperature has a maximum reactivity above 0°C - at about 38°C or 100°F.

This is a result of the interplay between the temperature-dependent scattering and leakage. Reflector savings is increasing with temperature – as shown in this artificial calculation.
Validation of $S(\alpha,\beta,T)$ Sampling Method for Bound Hydrogen in Water in Naval Reactor Monte Carlo Codes

From Ballinger (KAPL) 1995

Double differential scattering cross section for 0.225 eV neutrons scattering at 25 deg. In 296 K H-H$_2$O

Double differential scattering cross section for 0.33 eV neutrons scattering at 14 deg. In 296 K H-H$_2$O
RPI LENIS Experimental Apparatus
(Circa mid-1960’s)
Most Recent Bound-Hydrogen Moderator Evaluation
ENDF/B-VII & JEFF-3.1.1

From Mattes and Keinert (IKE) - 2005

- Use of LENIS LINAC measurements for validation
- This work is basis for bound-hydrogen scattering data in modern data sets used for reactor design.

**Figure 4.8** Double differential neutron scattering cross section of water around room temperature ($E_i = 154$ meV, $\theta=60^\circ$)

**Figure 4.9** Double differential neutron scattering cross section of water around room temperature ($E_i = 231$ meV, $\theta=60^\circ$)
Light Water Breeder Reactor (LWBR)

Axial View

WAPD-TM-1455, Dec 1983
Reproduction Factor Comparison

![Graph showing reproduction factor comparison for 233U, 235U, and 239Pu across different energies (MeV).]
Results

Measured FIR
Elimination of Physics Mockup Experiments

“...Unless one has already built a reactor very similar to a proposed design, one cannot even be sure that it will go critical – based on calculation alone... It is clear that successful design and operation of new high power reactors must rely heavily on critical and exponential experiments which closely adhere to the proposed design...” (1959 Viewpoint)
Homogenous Assembly Critical Experiments Bias

Monte Carlo Reactivity Bias (%Δρ)

Year

-1.20% -1.00% -0.80% -0.60% -0.40% -0.20% 0.00% 0.20% 0.40% 0.60% 0.80% 1.00%


Initial Data Set RDS5 RDS6 RDS7
Physics Testing for Project Prometheus

**Traditional NR Physics Testing Process**
- Analytical benchmarking
- Cross section measurements
- Critical mockup experiments
- Prototype testing
- Core certification testing

**For Project Prometheus**
- Modeling capability untested
- Limited benchmark experiments
- Compressed design time
- Need to develop confidence with existing experimental resources and capabilities
- LINAC cross section measurement capabilities a key element of physics test program
Notional Testing Schedule

• General-Purpose Critical Experiments

• Cross Section Measurement/Evaluation


• Prototype
  – GNT-2 (9/2013 – 2028)

• Flight Unit Cold Zero-Power Tests
  – Prometheus 1 (7/2013 – 8/2013)
Space Reactor Cross-Section Needs (High Energy)

**Primarily Refractory Metals:**

- Molybdenum
- Tungsten

**Rhenium**

- Rhenium
- Tantalum

| Isotopes |  
|----------|---|
| $^{92}$Mo, $^{94-98}$Mo, $^{100}$Mo | $^{185}$Re, $^{187}$Re |
| $^{182}$W, $^{183}$W, $^{184}$W, $^{186}$W | $^{181}$Ta |
Fukushima Daiichi Reactor Site Event
Reactivity Worth of Salt (NaCl)

Normal Seawater is 35 g/L

~12 g/L
~24 g/L
~46 g/L
~92 g/L
~185 g/L
350 g/L (brine)

Optimal Moderation
Criticality
Critical Moderation Limits
Comparison of Salt to Natural Boron Reactivity Worth

Normal Seawater is 35 g/L

Optimal Moderation  Criticality  Critical Moderation Limits
Summary

• Accurate Cross Section Data has played a key role in the NR Reactor Physics Program

• As long as there are new concepts, new problems, new materials to evaluate - the capability to measure accurate nuclear data will continue to play a key role.
Backup Slides
Figure 8. Fission and Capture Rates as a Function of Temperature.
Thermal Eta of U-233, WAPD-TM-691
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Figure 1. Thermal Eta of U-233 versus Neutron Energy
Space Reactor Design
Cross Section Measurements

Two domestic facilities
- ORELA – uncertain availability
- RPI LINAC – thermal/epithermal detectors

Decided to upgrade RPI LINAC to provide needed capabilities
- New injector and electron gun
  - 5 ns pulse width
- High-energy transmission detector
  - 0.5-20 MeV @ 250 m flight station
- High-energy scattering array
  - 4 keV – 20 MeV @ 30 m flight station
- Mid-energy transmission detector
  - 0.01 – 500 keV @ 100 m flight station
- Mid-energy capture detector (planned)
- Developed Fe-filtered transmission measurement technique
Potential Physics Testing

– General-Purpose Critical Assemblies
  • LACEF experiments (Nb-1Zr, Ta-2.5W, Mo, Re)
  • Potential follow on testing

– Cross Section Measurement/Evaluation
  • LINAC measurements
  • GNASH analyses to improve fast energy range cross section

– Special Physics Test Development/Qualification
  • Pulsed neutron, Rossi-alpha, rod oscillation techniques
  • Measure kinetics parameters for Be/BeO reflected fast critical assembly
    – Effective delayed neutron fraction
    – Prompt neutron lifetime
    – Effective delayed photoneutron group data
    – Subcritical reactivity
Potential Physics Testing

– Split Table Critical Experiments (ZPPR-like)
  • Medium fidelity material and geometry representation, cold zero-power
  • Qualify nuclear design methods, models, data

– Physics Mockup Critical Experiments
  • High fidelity material/geometry model of reactor
  • Cold zero-power test program
  • Potentially warmup and hot (electrically heated) zero-power test program

– Prototype Testing
  • Prototypical reactor and power conversion system with additional instrumentation
  • Full power test throughout life
  • Potentially two phases of prototype testing being considered

– Flight Unit Physics Testing
  • Cold zero-power physics testing
Analytical Benchmarks

- Completed documentation for SP-100 critical experiments (ZPPR-16 and ZPPR-20)
- Created ICSBEP Benchmarks for ZPPR-20
  - HEU-MET-FAST-075 (ZPPR-20 Phase C)
  - HEU-MET-MIXED-012 (ZPPR-20 Phase D)
  - SUB-HEU-MET-FAST-001 (ZPPR-20 Phase E)
  - SUB-HEU-MET-MIXED-001 (ZPPR-20 Phase D)
- Initiated general-purpose critical experiment program
  - Benchmark refractory metals of interests (Nb, Mo, Re and Ta)
  - Designed to bracket energy spectra of interest
  - Drive cross section measurement program
  - 1 critical experiment completed
    - HEU-MET-FAST-047 (Nb-1Zr)
  - 19 subcritical experiments completed
- NCSP IERs submitted for remaining Prometheus critical experiments (follow-up)
  - CED-1 approved
Critical Mockup Experiments

• No operating facility in US with split table machine
  – ZPPR mothballed

• Options Considered
  – Restart ZPPR
  – Install split table machine at DAF

Zero Power Physics Reactor (ZPPR) at INL
Reactivity Worth of Natural Boron

Worth of Boron Concentration

- Optimal Moderation
- Criticality
- Critical Moderation Limits

1000 ppm B-Nat
2000 ppm B-Nat
3000 ppm B-Nat
4000 ppm B-Nat
5000 ppm B-Nat

1.67E-04 B10/H1
3.33E-04 B10/H1
5.00E-04 B10/H1
6.67E-04 B10/H1
8.33E-04 B10/H1

Critical
Reactivity Worth of Various Poisons

**Worth of Salt Concentration**
- Normal Seawater is 35 g/L
- 1000 ppm B-Nat
- 2000 ppm B-Nat
- 3000 ppm B-Nat
- 4000 ppm B-Nat
- 5000 ppm B-Nat

**Worth of Boron Concentration**
- Critical
- 10.3 g Zy/g H2O
- ~13 g C-S/g H2O
- ~20 g C-S/g H2O
- ~26 g C-S/g H2O
- ~32.5 g C-S/g H2O

**Worth of Zircaloy Concentration**
- Critical
- 10.3 g Zy/g H2O
- ~21 g Zy/g H2O
- ~31 g Zy/g H2O
- ~41 g Zy/g H2O
- ~50 g Zy/g H2O

**Worth of Carbon Steel Concentration**
- Critical
- 1000 ppm B-Nat
- 2000 ppm B-Nat
- 3000 ppm B-Nat
- 4000 ppm B-Nat
- 5000 ppm B-Nat