U.S. DEPARTMENT OF ENERGY | Office of Science

BESAC Neutron Subcommittee Report

July 30, 2020

BESAC Neutron Subcommittee

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Subcommittee Report

The Scientific Justification for a

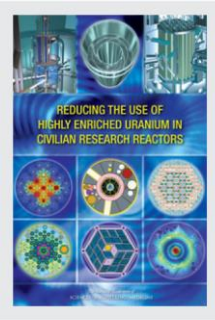
U.S. Domestic High-Performance Reactor-Based Research Facility

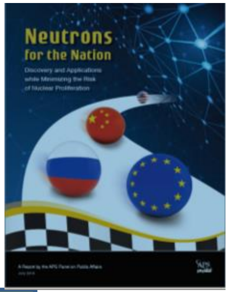
REPORT OF THE BASIC ENERGY SCIENCES ADVISORY COMMITTEE

U.S. DEPARTMENT OF ENERGY | Office of Science

Neutron Subcommittee Charge
Background

- ORNL's High Flux Isotope Reactor (HFIR) was completed in 1965
  - **Designed for isotope production**
  - **Equipped for neutron scattering – small-sample research**
  - **Materials: irradiation and neutron activation analysis**
- No high-performance research reactor commissioned in the U.S. since 1967
  - INL's Versatile Test Reactor (at CD-0) to address large engineering studies
- Academies report (2016): **Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors –** conversion to low enriched uranium (LEU) fuel
- American Physical Society Panel on Public Affairs (APS POPA) report (2018): **Neutrons for the Nation –** reduce proliferation risk while keeping neutrons available for science and industry





- **BESAC Neutron Subcommittee Charge** (March 3, 2019)**:**
  - **Assess the scientific justification for a domestic high-performance reactor-based research facility**

New BESAC Charge from Dr. Binkley (March 3, 2019)

The U.S. Department of Energy (DOE) has maintained long-term stewardship of neutron capabilities for the Nation. The combination of the Spallation Neutron Source (SNS) and the High Flux Isotope Reactor (HFIR), under the auspices of Basic Energy Sciences (BES) in the Office of Science, has provided the U.S. scientific community with leading neutron capabilities in support of DOE's missions in science, energy, environment, and national security. With the planning process for both the PPU and STS projects under way in 2019, I am writing to seek the input of BESAC on the long-term strategy concerning HFIR, which complements SNS and is among the highest-flux reactor-based sources in the world. With HFIR entering its 6th decade, its long-term future requires careful thought and planning, especially in the context of the U.S. domestic high-performance neutron research facilities.

This charge is also in part informed by the 2018 "Neutrons for the Nation" report, commissioned by the American Physical Society's Panel on Public Affairs, which focuses on the competing goals of reducing nuclear proliferation risk while maintaining intense controlled sources of neutrons for vital scientific and industrial work. The report highlighted the continued need for the U.S. to support its diversity of neutron R&D capabilities, as well as to initiate planning for a new generation of high-performance research reactors.

New BESAC Charge from Dr. Binkley (March 3, 2019)

I am asking BESAC to form a subcommittee to assess the scientific justification for a U.S. domestic high-performance reactor-based research facility, taking into account current international plans and existing domestic facility infrastructure.

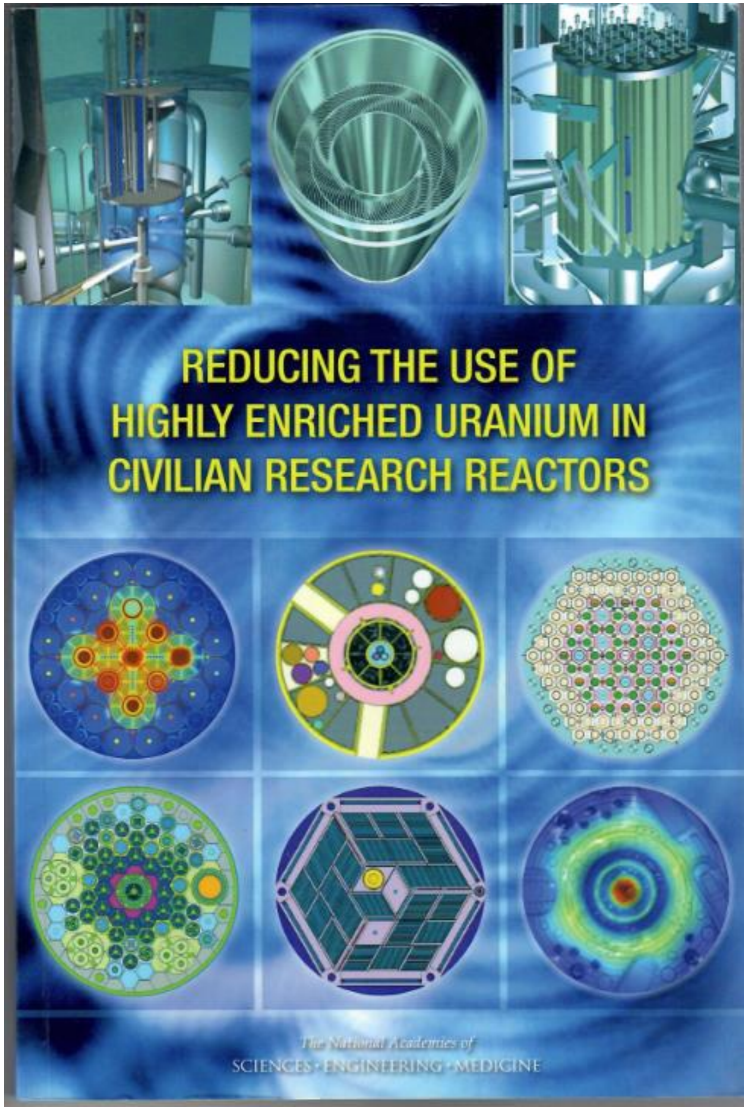
- *What is the merit and significance of the science that could be addressed by a high performance, steady-state reactor, and what is its importance in the overall context of research in materials sciences and related disciplines?*
- *What are the capabilities of other domestic and international facilities, existing and planned, to address the science opportunities afforded by such a domestic research reactor?*
- *What are the benefits to other fields of science and technology and to industry of establishing such a capability in the U.S.? In particular, consider applications such as isotope production, materials irradiation, neutron imaging, dark matter research, and neutron activation for trace element analysis.*
- *What are the strengths and limitations of a steady-state research reactor compared to a pulsed spallation neutron source for science, engineering, and technology?*
- *Are there feasible upgrade paths for HFIR to provide world-leading capabilities in serving the Office of Science missions well into the future?*
- *Can Low Enriched Uranium (LEU) and High Assay LEU (HALEU) fuels (defined as<20% enriched U-235) replace Highly Enriched Uranium fuels in research reactors while preserving the needed characteristics of neutrons produced by steady-state reactors? What R&D would be needed to support LEU and HALEU fuels development?*

Neutron Subcommittee Charge

Framing Questions in Charge Letter

- **Science case:** Significance in overall context of research in relevant disciplines
- **Other facilities:** Domestic and foreign, that could address the science case
- **Applications:** Isotope production, materials irradiation, neutron imaging, dark matter, neutron activation for trace element analysis
- **Spallation sources:** Strengths, limitations, capabilities relative to research reactors
- **HFIR upgrade paths:** For world leadership in reactor-based sources
- **Fuels development:** Replacing Highly Enriched Uranium (HEU) with LEU and High Assay LEU (HALEU), for non-proliferation

NAS Report



REDUCING THE USE OF
HIGHLY ENRICHED URANIUM IN
CIVILIAN RESEARCH REACTORS
The National Academies of
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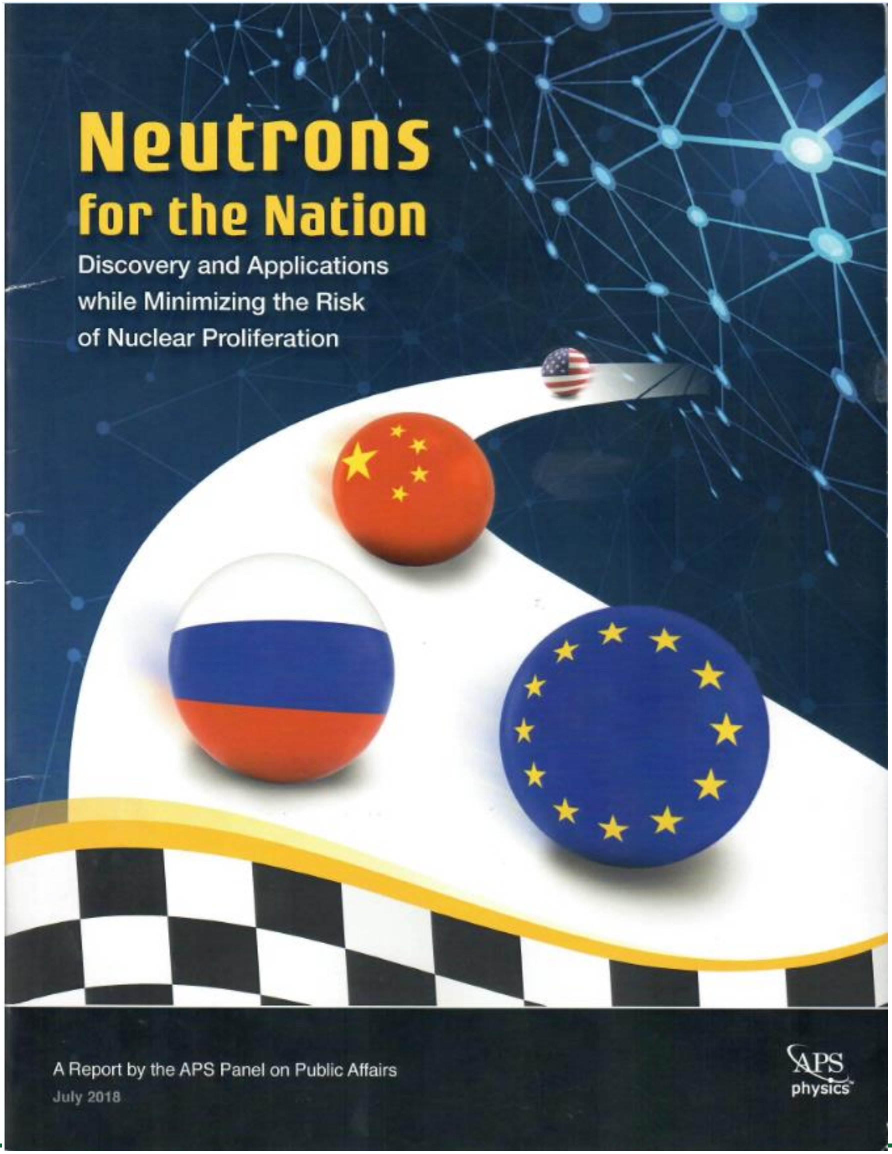
APS POPA Report



Neutron Subcommittee Charge

Subcommittee Members and Areas of Expertise

Birgeneau, Robert (Chair)	University of California, Berkeley	Neutron Scattering
Clark, Sue	BESAC/PNNL	Environmental Chemistry
Dai, Pengcheng	Rice	Neutron Scattering
Epps, Thomas	BESAC/University of Delaware	Neutron Scattering, Soft Matter
Heeger, Karsten	Yale	Neutrinos/particle physics
Hoogerheide, David	NIST	Biology
Kastner, Marc (BESAC Chair)	SciPhil	Neutron Scattering
Keimer, Bernhard	MPI-Stuttgart	Neutron Scattering
Louca, Despina	BESAC/University of Virginia	Neutron Scattering
Lyons, Pete	NEAC Member	General nuclear energy topics
MacDonald, Allan	BESAC/University of Texas, Austin	Theorist
O'Kelly, Sean	Idaho National Lab	Reactor technology and R&D
Olsen, Brad	MIT	Soft condensed matter physics
Phillips, Julia	Retired, SNL	POPA Study Chair
Robertson, David (Vice Chair)	Director, MURR reactor @ Missouri	Isotope production
Rollett, Anthony	BESAC/Carnegie Mellon	Structural materials; NNSA DPSC connection
Ross, Kate	Colorado State	Neutron Scattering
Rowe, Mike	NIST (retired)	Neutron Scattering
Stevens, John	ANL	LEU Conversion
Wirth, Brian	FESAC/U of Tennessee - Knoxville	Fusion materials, materials under irradiation

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Recommendations (1/3)

- <u>**Option 1:**</u> Continue to operate HFIR "as is" with the existing pressure vessel.
- There are unacceptable issues associated with this.
- Consistent with U.S. policy, HFIR has committed to convert to LEU fuel when available, c. 2035. This will require an extensive reactor shutdown. The end of the life of the pressure vessel, by 2060 but quite possibly sooner, will require another extensive shutdown.
- With the current pressure vessel, investments in instrumentation will add some capability and capacity to HFIR, but will fall far short of meeting the needs of the neutron science community.
- <u>**Recommendation:**</u> This is the least desirable option. Investment in fuel conversion or instrumentation without replacing the pressure vessel results in an unacceptable risk of a short life of the reactor.

Recommendations (2/3)

- **Option 2:** Replace the pressure vessel of HFIR. If possible, coordinate this replacement with the conversion of HFIR to LEU fuel so that a single shutdown would accomplish both objectives.

- Potential benefits include:
  - Increased capability and capacity for both in-reactor (isotope production, materials testing, etc.) and beamline (neutron scattering) work – larger beam tubes, improved cold source, improved access for in-reactor work, reduced background
  - Modified fuel assembly (more manufacturable, less expensive)
  - Power increase to restore the original 100 MW HEU operations
  - Increase in irradiation site and cold-source capabilities

- **Recommendation:** Pursue this approach immediately with the goal that the fuel conversion and pressure vessel replacement be performed during the same shutdown. The significant risk of HFIR failure will be removed, and important capabilities will result.

Recommendations (3/3)

- **Option 3:** Perform a “scoping study” for a green field research reactor optimized to perform neutron studies and isotope production that are uniquely suited to a very high flux reactor such as HFIR.

- Designed to operate on LEU fuel and to simultaneously optimize reactor performance and fuel assembly manufacturability.

- Optimized for neutron needs as now understood and for flexibility of configuration to enable future, currently unanticipated, applications.

- Likely to take several decades from initial design through approval, construction, and commissioning. Beginning now will allow time to evaluate options and to take the required steps to ensure continuing availability of a domestic multiply capable high-flux research reactor.

- **Recommendation:** Pursue study of a new high-flux reactor in parallel with the shorter-term replacement of the pressure vessel and conversion of HFIR to LEU fuel.

Subcommittee Meetings and Site Visits

- August 19-20, 2019: Kickoff meeting (Berkeley, CA), facility-oriented
- November 14-15, 2019: Workshop in Washington, DC, science/research-oriented
- November 15, 2019: Site visit to NCNR (Gaithersburg)
- January 7-8, 2020: Site visit to HFIR and SNS (Oak Ridge, TN)
- February 25 and 27, 2020: Site visits to Jules Horowitz Reactor (France) and Belgian Reactor 2 (Belgium)
- March 4 and 6, 2020: Scheduled site visits to FRM-II (Germany) and ILL (France) – canceled by COVID-19
- April 24, 2020: Virtual meeting, organization of the report

DOE Questions (1/6)

- ***Question:*** *What is the merit and significance of the science that could be addressed by a high-performance, steady-state reactor, and what is its importance in the overall context of materials sciences and related disciplines?*

- Neutron scattering plays a foundational role in all of materials science, including solid state/quantum materials, soft matter, industrial materials, and, with increasing importance, biological systems.

- Forefront research in complex materials involves multiple probes, including steady state neutron sources, spallation neutron sources, synchrotron light sources (ARPES, etc.), optics, electron microscopy, transport, and thermodynamic measurements.

- Reactors play a dominant and often unique role in isotope production and materials irradiation studies.

- Reactors provide both neutrino beams and an isotropic stream of antineutrinos for fundamental physics studies.

DOE Questions (2/6)

- ***<u>Question:</u>*** *What are the capabilities of other domestic and international facilities, existing and planned, to address the science opportunities afforded by such a domestic research reactor?*

- Within the U.S., the major facilities are NCNR at NIST, HFIR and the SNS at ORNL, and the ATR at INL; the latter does not provide neutron scattering capabilities.

- Europe continues to dominate neutron scattering in virtually all aspects because of both reactor and spallation sources and investments in advanced instrumentation. Closure of HFIR would make this situation even worse.

- The U.S. remains strong on isotope production and materials irradiation, but again closure of HFIR would do serious damage to U.S. isotope production capabilities.

DOE Questions (3/6)

- ***Question:*** *What are the benefits to other fields of science and technology and to industry of establishing such a capability in the U.S.? In particular, consider applications such as isotope production, materials irradiation, neutron imaging, dark matter research, and neutron activation for trace element analysis.*

- Radioactive isotopes contribute to science and technology in a myriad of ways including treatments of cancers, as a human imaging agent, gas chromatography, oil and gas exploration, and in basic actinide physics and chemistry.

- Studies using both neutron diffraction and imaging of functional materials behavior in complex environments---turbines, automobile engines, etc.

- Neutron activation analysis of trace elements.

- Studies of radiation damage in fusion and fission structural materials.

- Fundamental physics experiments with both neutrons and antineutrinos, such as the search for sterile neutrinos.

DOE Questions (4/6)

- ***Question:*** *What are the strengths and limitations of a steady-state research reactor compared to a pulsed spallation neutron source for science, engineering, and technology? What functions currently performed by research reactors can be assumed by spalla-tion neutron sources?*

- There are many neutron scattering applications where a steady state source is either essential or preferable to a pulsed spallation source, such as polarized neutrons, studies of phase transitions especially in one- and two-dimensional materials, soft condensed matter, and biological materials. Many investigations are best carried out with both kinds of measurements on a given material.

- Isotope production, neutrino research, and most materials irradiation studies can only be carried out with a steady state reactor source.

- The fundamental challenge for the neutron scattering community is not which type of neutron source to use, but rather obtaining experimental beam time at all. This is a critical issue for graduate students and postdoctoral fellows.

DOE Questions (5/6)

- ***Question:*** *Are there feasible upgrade paths for HFIR to provide world-leading capabilities in serving the Office of Science missions well into the future? What can we learn from the experience at the Institut Laue-Langevin?*
- This question has been answered in detail in the ORNL HFIR strategy document; there is a clear, feasible path going forward.
- HEU-LEU conversion is of utmost importance; there is now a clear plan for moving forward on the conversion at HFIR.
- Because of continuing embrittlement of the pressure vessel welds and base materials, the vessel must be replaced in the next decade. The ILL experience gives us confidence that this can be done safely and effectively.
- Pressure vessel replacement will make possible a significant increase in HFIR's capabilities.

DOE Questions (6/6)

- ***<u>Question:</u>*** *Can Low Enriched Uranium (LEU) and High Assay LEU (HALEU) fuels (defined as <20 % enriched U-235) replace Highly Enriched Uranium fuels in research reactors while preserving the needed characteristics of neutrons produced by steady-state reactors? What R&D would be needed to support LEU and HALEU fuels development?*

- This is discussed in detail in the report. The simple answer is "YES".

- In 2019, the U3Si2 dispersion fuel system was adopted as the HFIR baseline solution. The necessary research and development is ongoing.

- <u>A WARNING</u>: There is by no means a 100% guarantee of success in the upgrade of HFIR including the HEU-LEU conversion, due to either technical or political reasons. Therefore DOE-BES must have an alternative strategy, namely, design of a green field high flux research reactor operating on LEU fuel optimized for neutron scattering, isotope production, and materials irradiation studies.

Recommendations (1/3)

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Recommendations (2/3)

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Thank You