선도형 원자력 R&D를 위한 핵연료 실험 기반 시설 강화 필요성

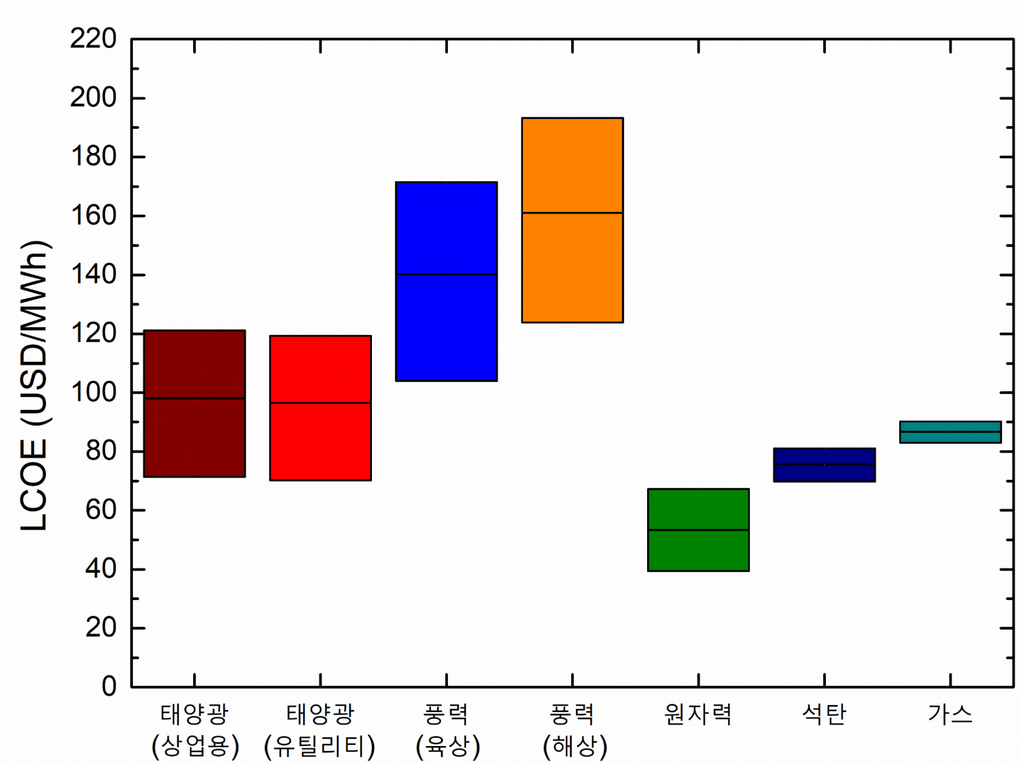
혁신 원자력 시스템의 핵연료 및 원자력 재료기술

한국원자력학회 2023 추계학술대회 워크샵 C

서울대학교 원자핵공학과

이유호
leeyouho@snu.ac.kr

원자력 균등화발전비용 (Levelized cost of electricity)



높은 수준의 안전성을 담보해야하는 원자력 발전소가 타 발전원에 비해 높은 건설비용과 운영 및 관리비용을 필요로 함에도 불구하고 낮은 발전 단가를 유지할 수 있는 이유는 ?

[Data from International Energy Agency (IEA) Projected Costs of Generating Electricity, 2020 Edition. Comparison of estimated **LCOE of Korea in 2025**]

한계에 봉착한 가동 원전 경제성 확보 문법과 핵연료

가동원전 경제성 확보 문법:
출력 밀도, 에너지 밀도 (연소도), 가동률 극대화

	대형원전	관련 핵연료 재료 기술 현안
출력 밀도	100 W/cm^3	정상운전 내부식성 핵연료
에너지 밀도 (방출 연소도)	60 MWd/kgU	농축도, 정상운전 내부식성 핵연료, FFRD 문제
가동률	0.8 – 0.9	Failure rate: 10^{-5}
노심 손상빈도 (CDF)	$10^{-5} - 10^{-6}$/year	사고저항성 향상 (extended accident coping time)

경수로가 봉착한 한계를 돌파할 수 있는 기술 ?

대형원전 경제성 확보 문법으로 바라본 SMR

	Large Plant (APR 1400)	SMR (i-SMR)	Is SMR better ?
Size (Electric Power)	1400 MW (e)	680 MW (e) (170 Mwe x 4 units)	X
Power Density	100 W/cm^3	~50 W/cm^3	X
Discharge burnup (Energy density)	60 MWd/kgU	30 – 40 MWd/kgU	X
Core damage frequency	2.25×10^{-6} /RY	< 1.0×10^{-9} /RY	O
Construction method	Heavy on-site construction	Heavy Factory and modular manufacturing	O
Target construction period	48 months (usually more delayed)	<24 months (needs field testing)	O
Construction cost	5 Billion USD (~$3,600/kW)	3 Billion USD (~$4,000/kW)	Δ

-기존 대형원전 경제성 확보 문법에 대한 도전: 건설업 → 제조업

-SMR 도 기존 대형경수로의 경제성 확보 문법에서 자유로울 수 없음
(일체형 원자로, 사고시 항시침수 등의 조건을 만족하는 조건으로 **출력밀도 및 연소도 극대화** 설계방향 유효)

경수로 핵연료 주요 기술개발/상용화 현안

진행중인 경수로 주요 핵연료 연구개발 및 상용화 현안

- **HANA-6 인허가 (2023년도 말 신청) 및 연소도 상향 (62MWd/kgU)**
- **Cr 코팅 사고저항성 핵연료 개발 및 상용화 (62MWd/kgU)**
- **사용후핵연료 건식저장 안전성 연구**

예견된 경수로 주요 핵연료 연구개발 및 상용화 미래수요

- **HANA-6 연소도 허용가능 연소도 증진 (68MWd/kgU)**
- **LEU+ (농축도 5-10%) 적용 Cr 코팅 사고저항성 핵연료**
- **LEU+ 적용 초장주기/출력밀도 상향 SMR 핵연료 개발**
- **ATF 적용 노심의 출력밀도 증진**
- **차세대 사고저항성핵연료 (Next ATF)**
- **고연소도 건식저장 핵연료 안전성 연구**

비경수로 핵연료 주요 기술개발/상용화 현안

비경수형 핵연료 연구개발 및 상용화 미래수요

- 세라믹 입자기반 초고온 핵연료 (예: TRISO) 개발 → 우주추진 원자로 핵연료
  → 고온 원자로 핵연료
- 고속로 핵연료 (금속 핵연료, HT-9 피복관)
- MSR용 액체 핵연료
- MSR 구조재 연구

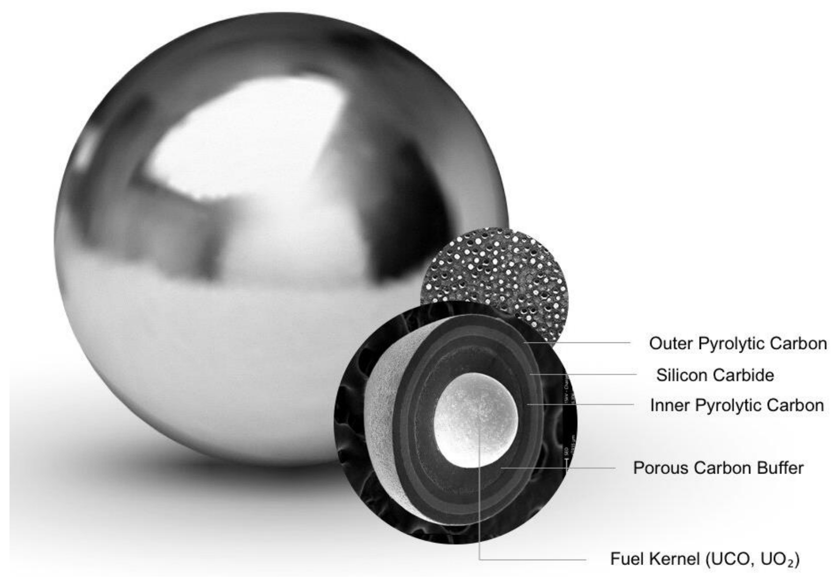
Space propulsion fuel particle in TRISO testing 'first'

15 March 2023

Share

A coated particle fuel for nuclear thermal propulsion applications, fabricated by TRISO-X LLC, has undergone testing in extreme conditions representing those experienced in space.

An artists' concept of an NTR mission (Image: DARPA)



결언 1: 핵연료/구조재료 성능 이해로 부터 출발하는 차세대 원자로 개발

지양해할 차세대 원자로 개발

시스템 성능 혁신 → 신재료 개발 및 테스트 → 인허가 및 현실화 불가능

합리적인 차세대 원자로 개발

가용한 핵연료/구조 재료 → 시스템 성능혁신 → 인허가 및 현실화 가능

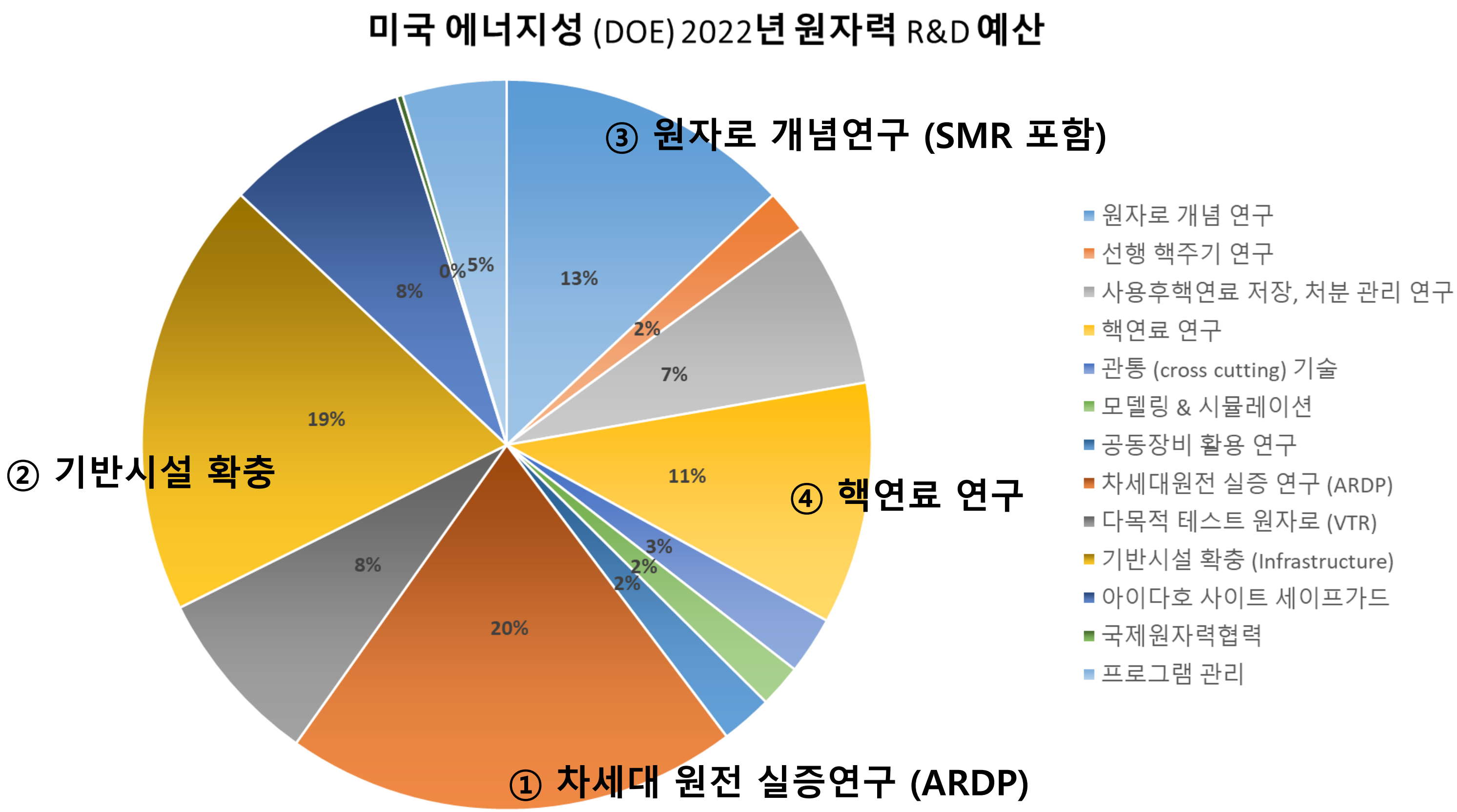
대한민국의 경수로 기술 국산화 DNA를 분별력을 가지고 지혜롭게 활용 하는것이 중요

□ **기술 추격형 원자력 R&D: 핵재료를 상수 (常數)로 두는 원자력 R&D, 기술개발**
[기존 원전 유지형 R&D 및 인력 양성]

□ **기술 선도형 원자력 R&D: 핵재료를 변수 (<u>變數</u>)로 두는 원자력 R&D, 기술개발**
[신형 원전 실물화 R&D 및 인력 양성]

미국 에너지성 (DOE) 2022년 원자력 R&D 예산

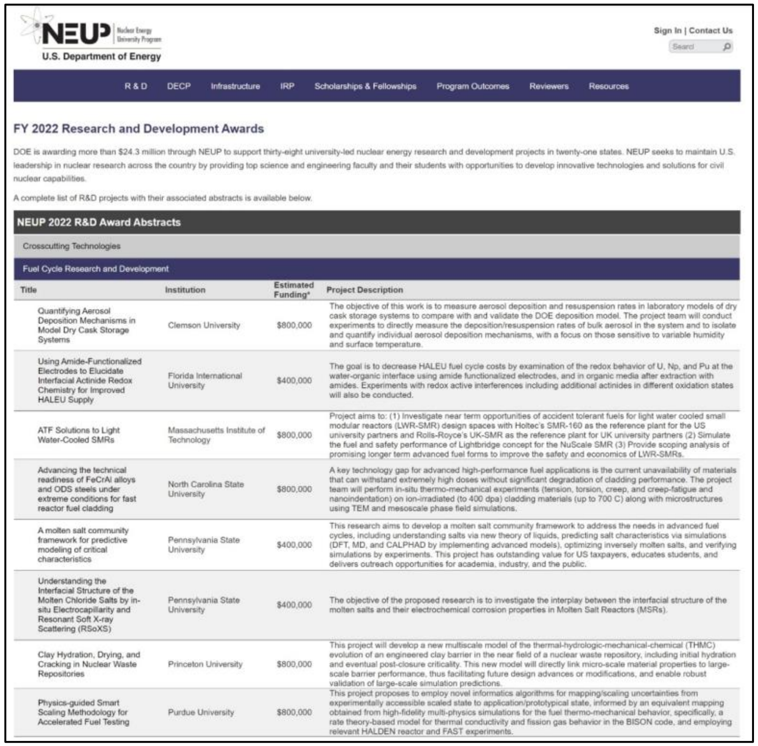
□ 예산 분석 (https://www.energy.gov/ne/our-budget), 총 예산 $18.455억 달러 (약 2.4 조)



미국 에너지성 (DOE) NEUP (Nuclear Energy University Program) 분석

☐ **NEUP 분석 (https://neup.inl.gov/), 연간 예산 2430만달러 (약 315억)**

<u>NEUP 프로그램의 의의:</u> 미국의 가장 주요한 대학 주도 원자력 연구개발 사업으로써 산·학·연의 팀으로 과제가 진행됨. DOE에서 기획되는 Top-down 형식의 과제로 미국 원자력 연구의 시류를 보여줌.



NEUP Nuclear Energy University Program
U.S. Department of Energy

Sign In | Contact Us

R & D DECP Infrastructure IRP Scholarships & Fellowships Program Outcomes Reviewers Resources

FY 2022 Research and Development Awards

DOE is awarding more than $24.3 million through NEUP to support thirty-eight university-led nuclear energy research and development projects in twenty-one states. NEUP seeks to maintain U.S. leadership in nuclear research across the country by providing top science and engineering faculty and their students with opportunities to develop innovative technologies and solutions for civil nuclear capabilities.

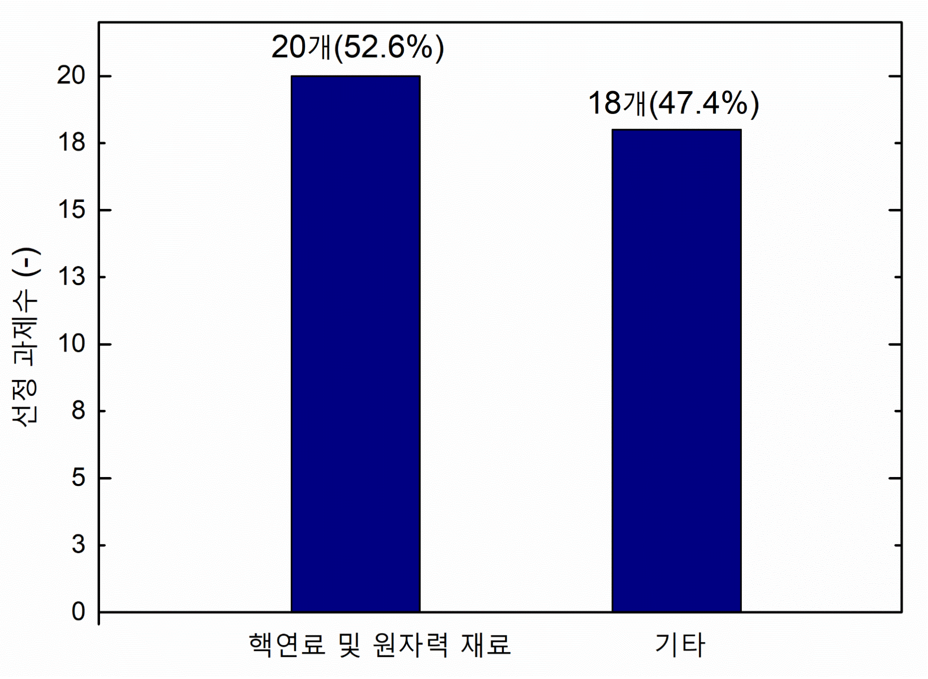
A complete list of R&D projects with their associated abstracts is available below.

NEUP 2022 R&D Award Abstracts

Crosscutting Technologies

Fuel Cycle Research and Development

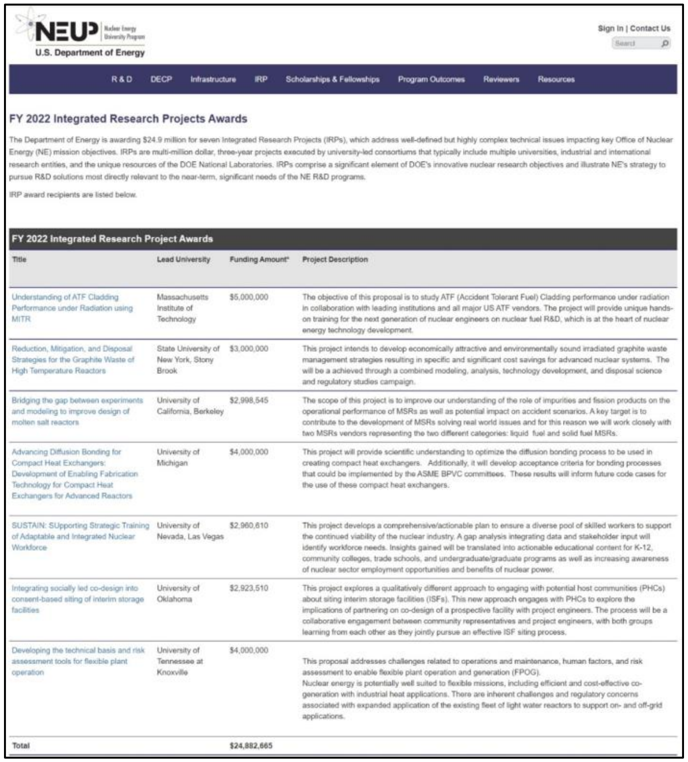
Title	Institution	Estimated Funding*	Project Description
Quantifying Aerosol Deposition Mechanisms in Model Dry Cask Storage Systems	Clemson University	$800,000	The objective of this work is to measure aerosol deposition and resuspension rates in laboratory models of dry cask storage systems to compare with and validate the DOE deposition model. The project team will conduct experiments to directly measure the deposition/resuspension rates of bulk aerosol in the system and to isolate and quantify individual aerosol deposition mechanisms, with a focus on those sensitive to variable humidity and surface temperature.
Using Amide-Functionalized Electrodes to Elucidate Interfacial Actinide Redox Chemistry for Improved HALEU Supply	Florida International University	$400,000	The goal is to decrease HALEU fuel cycle costs by examination of the redox behavior of U, Np, and Pu at the water-organic interface using amide functionalized electrodes, and in organic media after extraction with amides. Experiments with redox active interferences including additional actinides in different oxidation states will also be conducted.
ATF Solutions to Light Water-Cooled SMRs	Massachusetts Institute of Technology	$800,000	Project aims to: (1) Investigate near term opportunities of accident tolerant fuels for light water cooled small modular reactors (LWR-SMR) design spaces with Holtec's SMR-160 as the reference plant for the US university partners and Rolls-Royce's UK-SMR as the reference plant for UK university partners (2) Simulate the fuel and safety performance of Lightbridge concept for the NuScale SMR (3) Provide scoping analysis of promising longer term advanced fuel forms to improve the safety and economics of LWR-SMRs.
Advancing the technical readiness of FeCrAl alloys and ODS steels under extreme conditions for fast reactor fuel cladding	North Carolina State University	$800,000	A key technology gap for advanced high-performance fuel applications is the current unavailability of materials that can withstand extremely high doses without significant degradation of cladding performance. The project team will perform in-situ thermo-mechanical experiments (tension, torsion, creep, and creep-fatigue and nanoindentation) on ion-irradiated (to 400 dpa) cladding materials (up to 700 C) along with microstructures using TEM and mesoscale phase field simulations.
A molten salt community framework for predictive modeling of critical characteristics	Pennsylvania State University	$400,000	This research aims to develop a molten salt community framework to address the needs in advanced fuel cycles, including understanding salts via new theory of liquids, predicting salt characteristics via simulations (DFT, MD, and CALPHAD by implementing advanced models), optimizing inversely molten salts, and verifying simulations by experiments. This project has outstanding value for US taxpayers, educates students, and delivers outreach opportunities for academia, industry, and the public.
Understanding the Interfacial Structure of the Molten Chloride Salts by in-situ Electrocapillarity and Resonant Soft X-ray Scattering (RSoXS)	Pennsylvania State University	$400,000	The objective of the proposed research is to investigate the interplay between the interfacial structure of the molten salts and their electrochemical corrosion properties in Molten Salt Reactors (MSRs).
Clay Hydration, Drying, and Cracking in Nuclear Waste Repositories	Princeton University	$800,000	This project will develop a new multiscale model of the thermal-hydrologic-mechanical-chemical (THMC) evolution of an engineered clay barrier in the near field of a nuclear waste repository, including initial hydration and eventual post-closure criticality. This new model will directly link micro-scale material properties to large-scale barrier performance, thus facilitating future design advances or modifications, and enable robust validation of large-scale simulation predictions.
Physics-guided Smart Scaling Methodology for Accelerated Fuel Testing	Purdue University	$800,000	This project proposes to employ novel informatics algorithms for mapping/scaling uncertainties from experimentally accessible scaled state to application/prototypical state, informed by an equivalent mapping obtained from high-fidelity multi-physics simulations for the fuel thermo-mechanical behavior, specifically, a rate theory-based model for thermal conductivity and fission gas behavior in the BISON code, and employing relevant HALDEN reactor and FAST experiments.



미국 에너지성 (DOE) IRP (Integrated Research Projects) 분석

☐ **IRP 분석 (https://neup.inl.gov/), 연간 예산 2490만 달러 (약 323억)**

<u>IRP 프로그램의 의의:</u> 미국의 가장 주요한 대학 주도 대형 원자력 연구개발 사업으로써 산·학·연의 팀으로 과제가 진행됨. DOE에서 기획되는 Top-down 형식의 과제로 미국 원자력 연구의 최우선적 기술개발 현안을 보여줌.



NEUP Nuclear Energy University Program
U.S. Department of Energy

Sign In | Contact Us

R & D DECP Infrastructure IRP Scholarships & Fellowships Program Outcomes Reviewers Resources

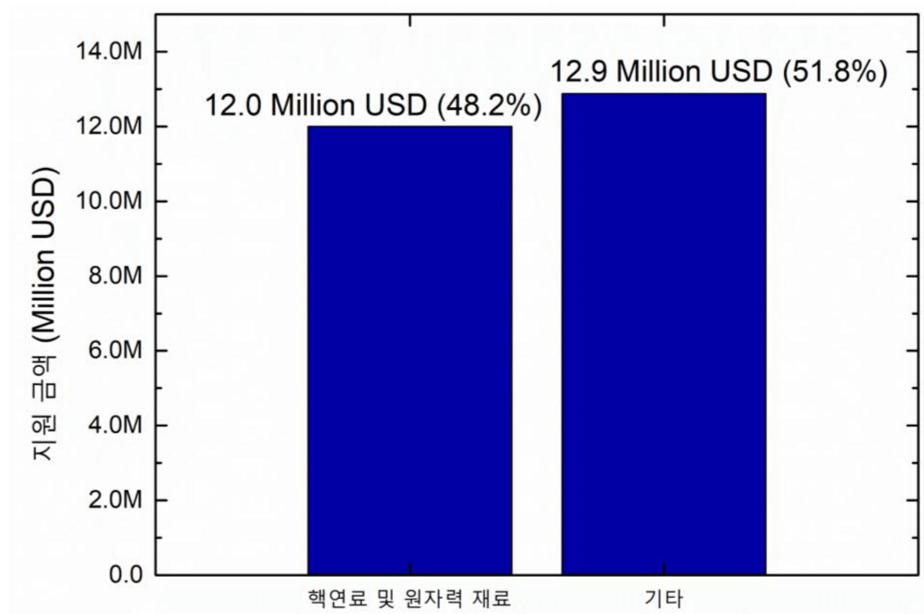
FY 2022 Integrated Research Projects Awards

The Department of Energy is awarding $24.9 million for seven Integrated Research Projects (IRPs), which address well-defined but highly complex technical issues impacting key Office of Nuclear Energy (NE) mission objectives. IRPs are multi-million dollar, three-year projects executed by university-led consortiums that typically include multiple universities, industrial and international research entities, and the unique resources of the DOE National Laboratories. IRPs comprise a significant element of DOE's innovative nuclear research objectives and illustrate NE's strategy to pursue R&D solutions most directly relevant to the near-term, significant needs of the NE R&D programs.

IRP award recipients are listed below.

FY 2022 Integrated Research Project Awards

Title	Lead University	Funding Amount*	Project Description
Understanding of ATF Cladding Performance under Radiation using MITR	Massachusetts Institute of Technology	$5,000,000	The objective of this proposal is to study ATF (Accident Tolerant Fuel) Cladding performance under radiation in collaboration with leading institutions and all major US ATF vendors. The project will provide unique hands-on training for the next generation of nuclear engineers on nuclear fuel R&D, which is at the heart of nuclear energy technology development.
Reduction, Mitigation, and Disposal Strategies for the Graphite Waste of High Temperature Reactors	State University of New York, Stony Brook	$3,000,000	This project intends to develop economically attractive and environmentally sound irradiated graphite waste management strategies resulting in specific and significant cost savings for advanced nuclear systems. The will be a achieved through a combined modeling, analysis, technology development, and disposal science and regulatory studies campaign.
Bridging the gap between experiments and modeling to improve design of molten salt reactors	University of California, Berkeley	$2,998,545	The scope of this project is to improve our understanding of the role of impurities and fission products on the operational performance of MSRs as well as potential impact on accident scenarios. A key target is to contribute to the development of MSRs solving real world issues and for this reason we will work closely with two MSRs vendors representing the two different categories: liquid fuel and solid fuel MSRs.
Advancing Diffusion Bonding for Compact Heat Exchangers: Development of Enabling Fabrication Technology for Compact Heat Exchangers for Advanced Reactors	University of Michigan	$4,000,000	This project will provide scientific understanding to optimize the diffusion bonding process to be used in creating compact heat exchangers. Additionally, it will develop acceptance criteria for bonding processes that could be implemented by the ASME BPVC committees. These results will inform future code cases for the use of these compact heat exchangers.
SUSTAIN: SUpporting Strategic Training of Adaptable and Integrated Nuclear Workforce	University of Nevada, Las Vegas	$2,960,610	This project develops a comprehensive/actionable plan to ensure a diverse pool of skilled workers to support the continued viability of the nuclear industry. A gap analysis integrating data and stakeholder input will identify workforce needs. Insights gained will be translated into actionable educational content for K-12, community colleges, trade schools, and undergraduate/graduate programs as well as increasing awareness of nuclear sector employment opportunities and benefits of nuclear power.
Integrating socially led co-design into consent-based siting of interim storage facilities	University of Oklahoma	$2,923,510	This project explores a qualitatively different approach to engaging with potential host communities (PHCs) about siting interim storage facilities (ISFs). This new approach engages with PHCs to explore the implications of partnering on co-design of a prospective facility with project engineers. The process will be a collaborative engagement between community representatives and project engineers, with both groups learning from each other as they jointly pursue an effective ISF siting process.
Developing the technical basis and risk assessment tools for flexible plant operation	University of Tennessee at Knoxville	$4,000,000	This proposal addresses challenges related to operations and maintenance, human factors, and risk assessment to enable flexible plant operation and generation (FPOG). Nuclear energy is potentially well suited to flexible missions, including efficient and cost-effective co-generation with industrial heat applications. There are inherent challenges and regulatory concerns associated with expanded application of the existing fleet of light water reactors to support on- and off-grid applications.
Total		$24,882,665	



(ATF 조사실험, 흑연 폐기물,
열교환기 diffusion bonding)

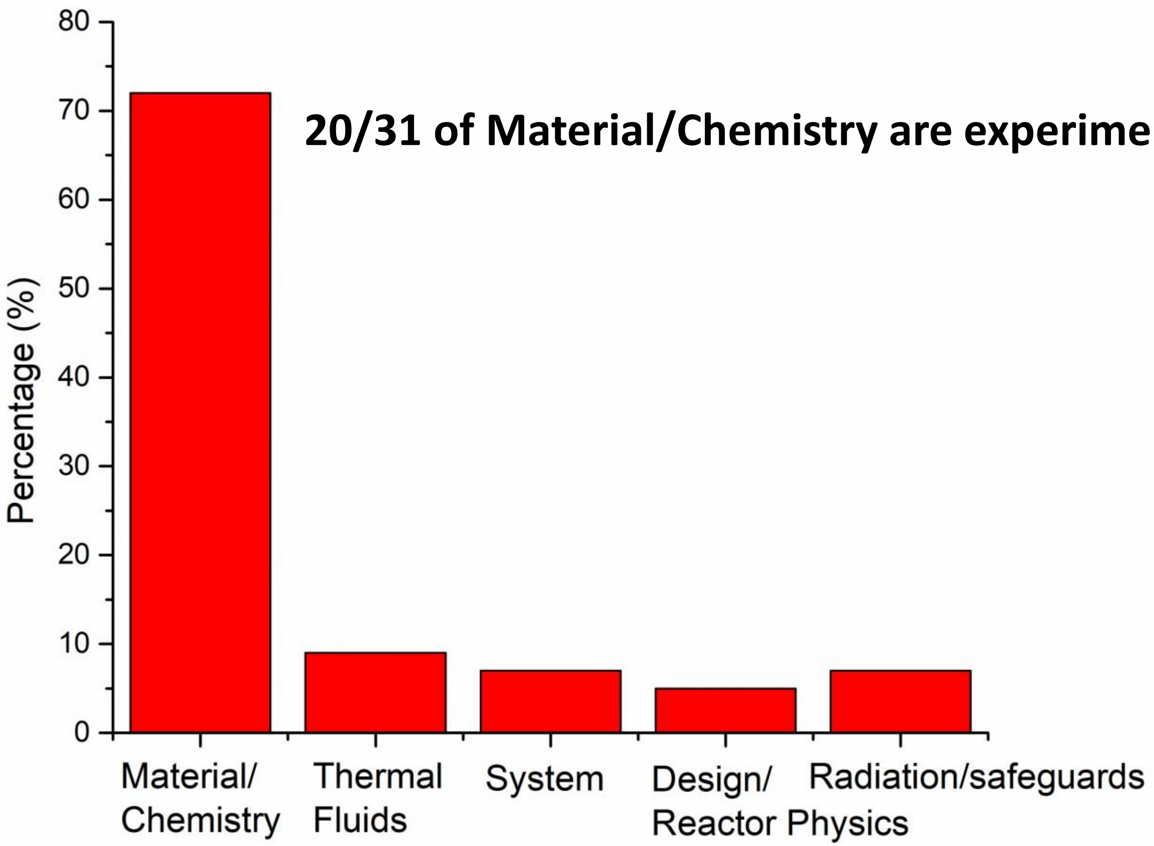
미국 에너지성 (DOE) NEUP (Nuclear Energy University Program) 선정 MSR 과제 분석

□ **NEUP 분석 (https://neup.inl.gov/),**

최근 6년간 (2017 – 2022)년간 선정된 44개 MSR 기술개발 과제 분석

과제당 3년간 400K – 800K (5억 - 10억)

<연구분야 과제 비율>



미국 에너지성 (DOE) NEUP (Nuclear Energy University Program) 분석

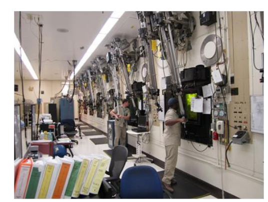
1	Year	Title	Amount (K)	Material/Chemistry	TH	System	Design/Reactor physics	Radiation/safeguards
2	2022	Functionally-graded Cermet Coatings for Molten Salt Technologies by High Throughput Finite Element Modeling and Additive Manufacturing	500	O				
3	2022	A molten salt community framework for predictive modeling of critical characteristics	400	O				
4	2022	Understanding the Interfacial Structure of the Molten Chloride Salts by in-situ Electrocapillarity and Resonant Soft X-ray Scattering (RSoXS)	400	O				
5	2022	Materials Accountancy During Disposal and Waste Processing of Molten Salt Reactor Fuel Salts	400	O				
6	2022	Optical Basicity Determination of Molten Fluoride Salts and its Influence on Structural Material Corrosion	400	O				
7	2021	Total Mass Accounting in Advanced Liquid Fueled Reactors	400					O
8	2021	Design and intelligent optimization of the thermal storage and energy distribution for the TerraPower Molten Chloride Fast Reactor in an Integrated Energy System (IES)	800			O		
9	2021	Probing Speciation of Light Elements in Molten Salts by Electrochemistry, High Temperature Liquid NMR, and Neutron Diffraction	600	O				
10	2021	Plasma-Bubble Spectroscopy: A Method for Real-Time Material Quantification in Molten Salts	400	O				
11	2021	Accelerating the development of reliable and robust machine learning-based interatomic potentials for the prediction of molten salt structure and properties	400	O				
12	2021	Machine-Learning-Accelerated Molecular Dynamics Approaches for Molten Salts	400	O				
13	2021	Enhancing Yellowjacket for Modeling the Impact of Radiation and Stress on the Corrosion of Molten-Salt-Facing Structural Components	700	O				
14	2021	High temperature Molten salt reactor pump component development and testing	800	O				
15	2020	Connecting Advanced High-Temperature X-ray and Raman Spectroscopy Structure/Dynamics Insights to High-Throughput Property Measurements	500	O				
16	2020	High Throughput Computational Platform for Predictive Modeling of Thermochemical and Thermophysical Properties of Fluoride Molten Salts	400	O				
17	2020	First-principles free energies by hybrid thermodynamic integration for phase equilibria and fission product solubility in molten salts	400	O				
18	2020	Gallium Oxide Schottky Diode Detectors for Measurement of Actinide Concentrations from Measured Alpha Activities in Molten Salts	400	O				
19	2020	Novel Diamond-Based Spectroelectrochemical Sensors for Advanced Understanding of Radioactive Molten Salt Chemistry	600	O				
20	2020	Multicomponent Thermochemistry of Complex Chloride Salts for Sustain-able Fuel Cycle Technologies	400	O				
21	2020	Improved Molten Salt Reactor Design with New Nuclear Data for the 35Cl(n,x) and 56Fe(n,n') reactions.	400				O	
22	2020	Extension of MSTDB to Provide a High-Quality, Validated Thermochemical Database for Predicting/Simulating Corrosion in Molten Salt Reactor Systems	600	O				
23	2020	Investigation of Novel Nickel-Based Alloys for Molten Chloride Fast Reactor Structural Applications	800	O				
24	2020	Development and Demonstration of Scalable Fluoride Salt Pump Seals and Bearings for FHRs	800		O			
25	2020	Non-Intrusive Flow Monitoring for Liquid Metal and Molten Salt Cooled Reactors	800		O			
26	2019	Modeling and Uncertainty Analysis of MSR Nuclear Material Accounting Methods for Nuclear Safeguards	800					O
27	2019	The Design and Investigation of Novel Mechanical Filters for Molten Salt Reactors	760			O		
28	2019	Validated, Multi-Scale Molecular Dynamics Simulations to Predict the Thermophysical Properties of Molten Salts Containing Fuel, Fission, and Corrosion Products	800	O				
29	2019	Ni-based ODS alloys for Molten Salt Reactors	800	O				
30	2019	Learning-based Computational Study of the Thermodynamic, Structural, and Dynamic Properties of Molten Salts at the Atomic and Electronic Scale and Experimental Validations	800	O				
31	2019	Understanding the Speciation and Molecular Structure of Molten Salts Using Laboratory and Synchrotron based In Situ Experimental Techniques and Predictive Modeling	800	O				
32	2019	Innovative In-Situ Analysis and Quantification of Corrosion and Erosion of 316 Stainless Steel in Molten Chloride Salt Flow Loops	800	O				
33	2019	Fuel Salt Sampling and Enriching System Technology Development	800			O		
34	2018	Development of an MC&A Toolbox for Liquid-fueled Molten Salt Reactors with Online Reprocessing	800					O
35	2018	Evaluation of the Thermal Scattering Law for Advanced Reactor Neutron Moderators and Reflectors	800				O	
36	2018	Corrosion Testing of New Alloys and Accompanying On-Line Redox Measurements in ORNL FLiNaK and FLiBe Molten Salt Flow Loops	800	O				
37	2018	Determination of Molecular Structure and Dynamics of Molten Salts by Advanced Neutron and X-ray Scattering Measurements and Computer Modeling	800	O				
38	2018	in situ Measurement and Validation of Uranium Molten Salt Properties at Operationally Relevant Temperatures	800	O				
39	2018	Understanding Molten Salt Chemistry Relevant to Advanced Molten Salt Reactors through Complementary Synthesis, Spectroscopy, and Modeling	800	O				
40	2018	Development of Corrosion Resistant Coatings and Liners for Structural Materials for Liquid Fueled Molten Salts Reactors	800	O				
41	2018	Advanced Alloy Innovations for Structural Components of Molten Salt Reactors	800	O				
42	2017	Methods to Predict Thermal Radiation and to Design Scaled Separate and Integral Effects Testing For Molten Salt Reactors	800		O			
43	2017	Bimetallic Composite (Incoloy 800H/Ni-201) Development and Compatibility in Flowing FLiBe as a Molten Salt Reactor (MSR) Structural Material	800	O				
44	2017	Radiative Heat Transport and Optical Characterization of High Temperature Molten Salts	800		O			
45	2016	-						
46	2015	-		31	4	3	2	3
47				0.720930233	0.09302	0.0698	0.046511628	0.069767442
48								
49								
50	2022	Bridging the gap between experiments and modeling to improve the design of molten salt reactors	5000	O			O	
51	2020	Molten Salt Reactor Test Bed with Neutron Irradiation	4800					
52	2019	-						
53	2018	-						

결언 2: 연구로 연소시험 및 조사후 핵연료 평가 실험 설비 강화 필요

<고연소도 핵연료 상용화를 위한 필요 연소시험, >4주기 (예시)>

- **해외에 의존할 수 밖에 없는 현상황 (국내 실물 핵연료 연구기능 복구 시급):**

1. 하나로 연구로 업그레이드:
-인허가 데이터 생산을 위한 업그레이드 논의/추진 필요 (PWR Loop 설치 및 계장 (instrumentation))
-기장 동위원소생산용 원자로와 역할 구분 필요



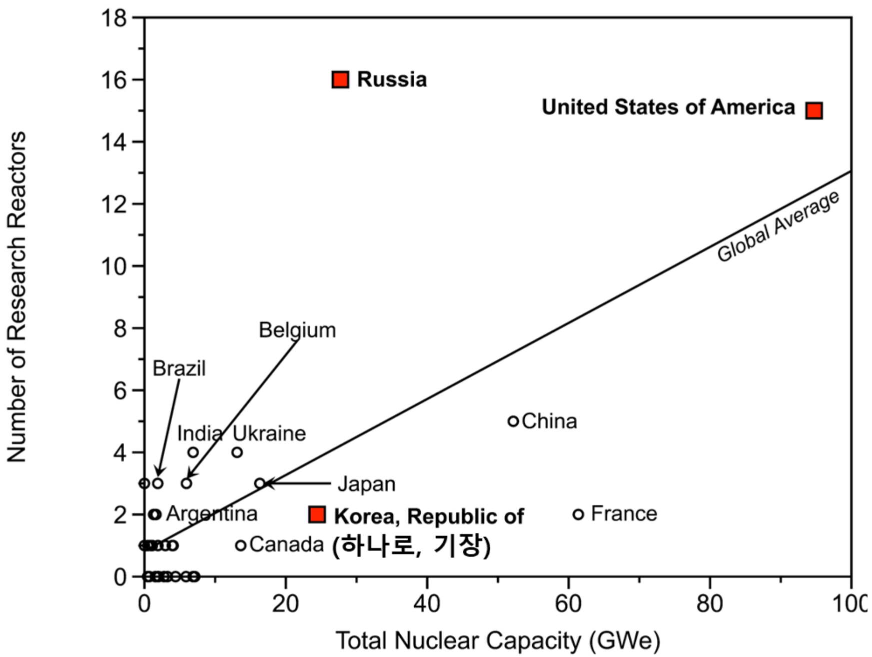


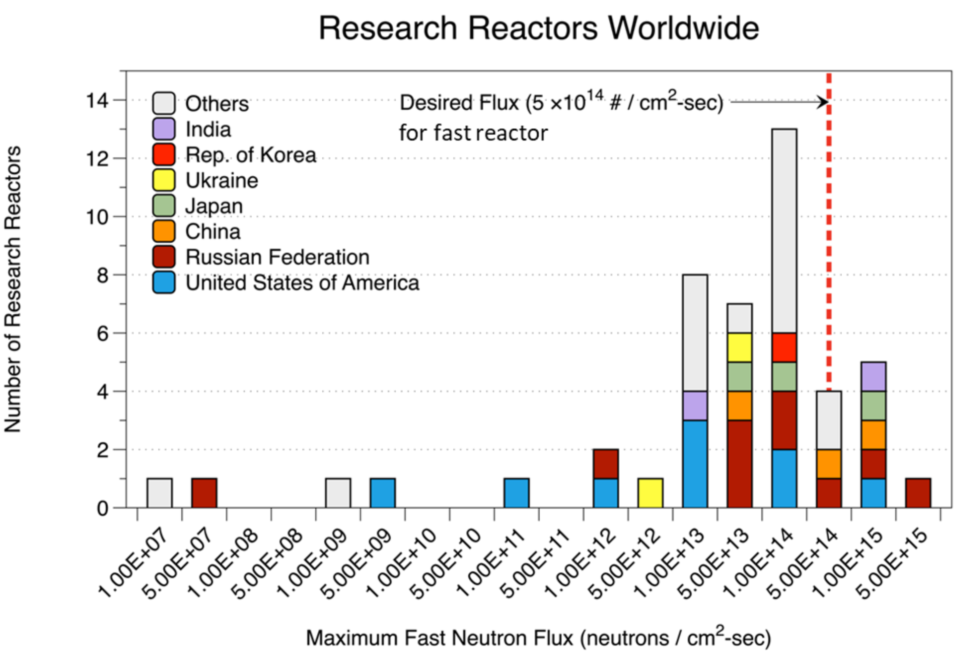
2. 국내 사용후핵연료 조사후 시험 (PIE) 설비 운영 필요:
-관련 제도 정비 및 예산 확보 시급
-사업화 및 시험 수출까지 가능

핵연료 연구 수요를 감당하기 위해 필요한 핵심 설비

- 핵연료 및 원자력 재료 조사용 원자로 구축, 하나로 업그레이드
  [Dream vs Dream Enabler]

IAEA RRDB (Research Reactor Database):
Material Test/Irradiation Test including Planned, Under Construction, Operational





결언 3: 우주 추진선 핵연료 - 자강과 협력, 지금은 자강의 때

- **핵연료 재료를 핵심 미지수/변수로 인식, 진정성 있는 지원 필요**

  - 미국에서 우주원자로 주관 부처가 DOE → DOD/DARPA로 변경되고 있는 추세

  - 현재 한미 원자력 연구협력 상황에서 미국으로부터의 우주 핵연료 기술이전이나 협력은 사실상 불가능에 가까움

  - 내실 있는 핵연료 기반시설 확충을 통한 제작 및 기초 실증연구 중요

- **경수로 핵연료 개발과의 차이점**

  [수월 할 수 있는 점] (조사 설비가 미비한 우리나라가 잘 할 수 있는 연구)
  - 경수로 대비 필요 조사실험 시간 (획기적) 단축 예상

  - 초고온 운전에 따른 방사선 조사 데미지 열처리 효과 → Nuclear 시험은 조사 데미지가 아닌 임계측면에 방점이 있을 것으로 짐작 → 임계/조사 시험과 열, 화학 효과 시험 분리 가능 (?) → 핵연료 Screening & Qualification 가속화

  [추가 난이도]
  - 경수로 대비 핵연료 설계의 높은 자유도.
    실물 SET연구를 통한 빠른 Screening 전략 추진을 통해 극복.

비경수형 차세대 핵연료 시험 기반시설과 실물연구 (Dream vs Dream Enabler)

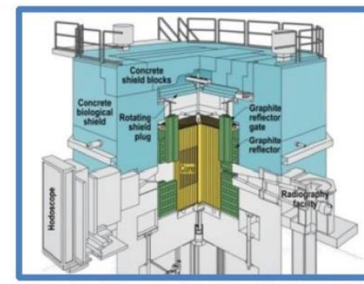
- **분리효과 (SET) 실험:Nuclear+Thermal+Chemical 종합 실증이 사실상 매우 어려운 환경**
  - 고도화된 분리효과 실험 필요
  - 관련 기반시설 준비 매우 중요
  - [우주추진 핵연료] 미국의 CFEET, NTREES 대응 실험 시설 추진. 중장기적으론 임계/조사 설비 확충 필요.

[NERVA XE in ETS-1, Wikipedia]

No one test facility provides everything needed, so multiple existing facilities are leveraged to obtain needed feasibility assessment information

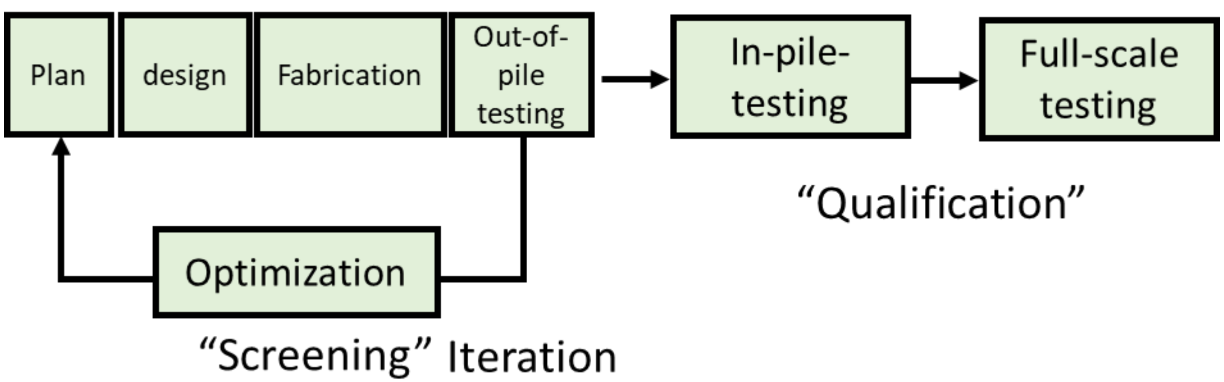
Compact Fuel Element Environmental Test (CFEET)

Nuclear Thermal Rocket Element Environmental Simulator (NTREES)



Transient Reactor Test Facility (TREAT)

- **실물연구 기반 핵연료 'screening' 과 'Qualification' 가속화**



Seeing is believing…

결언 4: 국내 TRISO 입자 핵연료 제작/실물 기반기술개발 복구

과거 KAERI TRISO 핵연료 제작 및 설계 기술

후속세대 기술 전달

'과제화 필요'

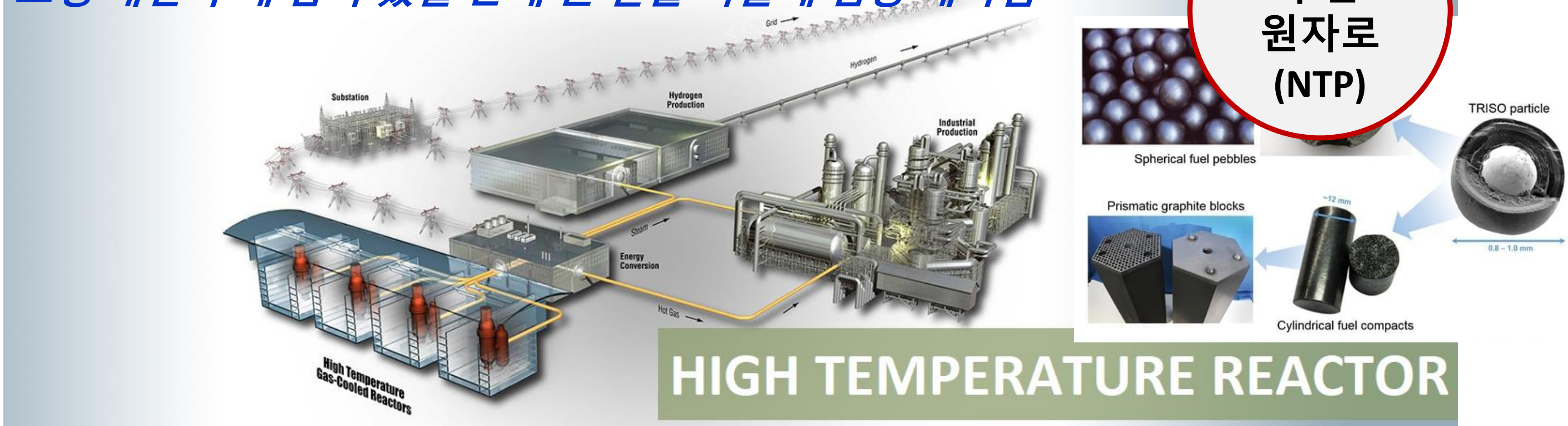
TRISO 핵연료 제작, 설계, 해석 기술 개선 및 고도화

차세대 고온 원자로

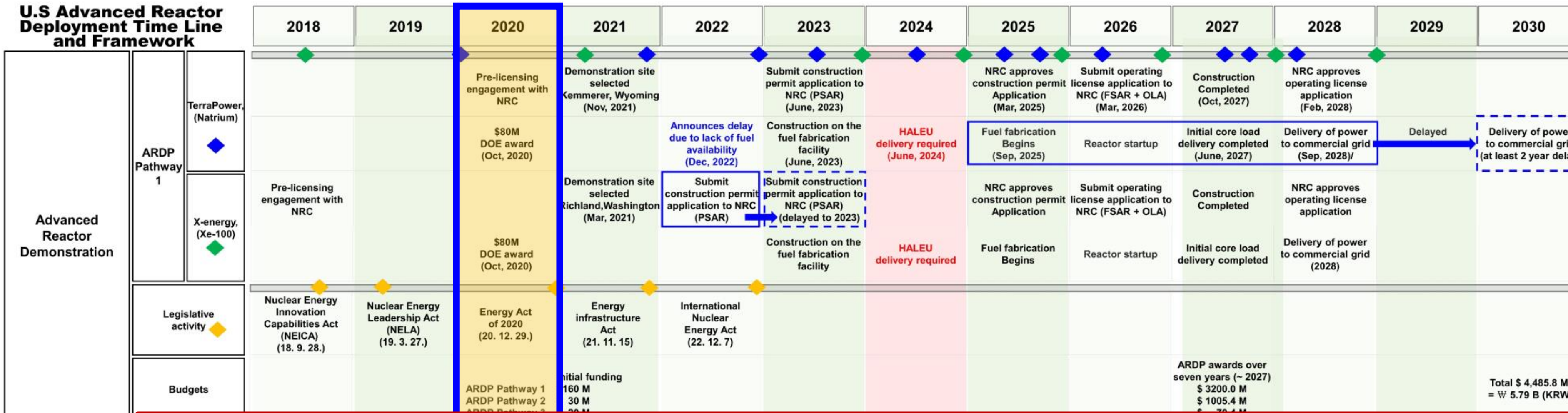
초소형 원자로

우주 추진 원자로 (NTP)

노형은 지나갈 수 있음.
노형 개발 후에 남아 있을 손에 쥔 실물 기술에 집중 해야함

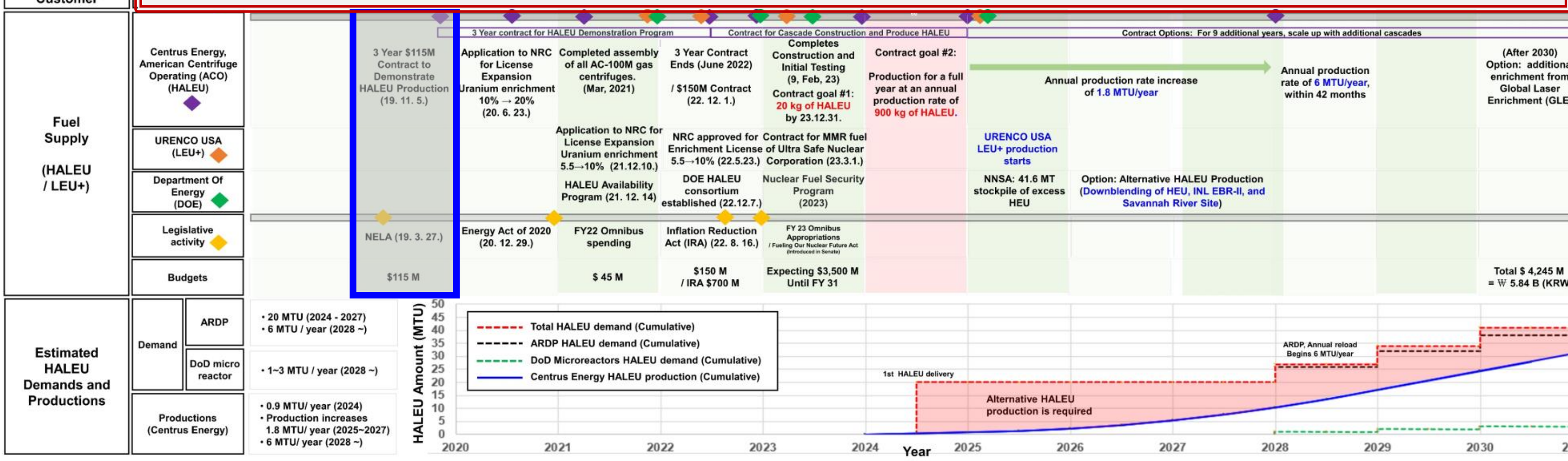


결언 5: 핵연료 공급 역량 강화



Lessons learned:

- <u>진정성 있는 실물 원자로 개발을 위해선 핵연료 공급 대책이 선행되어야 함</u>



결언 6: 분별력 있는 미국의 원전/핵연료 연구개발 이해 필요

미국 DOE 핵연료/원자로 개발 이해

- 미국이 개발중인 모든 종이 원자로 (Paper reactor)가 실물화 될 수 없음.
- 최근 미국에서 다양한 차세대 원자로 개발 민간 벤처회사가 등장한 배경에는 더 이상 손 쓸 수 없을 정도로 경쟁력을 상실한 자국내 신규 대형원전 건설사업이 있음.
- 그럼에도 정부에서 큰 투자를 하는 이유의 이면에는 ‘<u>인력</u>’과 ‘<u>기술 리더쉽</u>’ 유지 목적이 크게 자리잡고 있음.
- 미국은 DOE 부지를 활용한 원자로 실증이 가능하고 (U.S NRC 규제 우회) 과거 EBR 핵연료 조사 데이터를 활용할 수 있기에 VTR (Versatile Test Reactor)을 취소하는 결정을 함.
- 그럼에도 HFIR, ATR, TREAT, MITR, PIE 등을 활용한 기반 시설은 꾸준히 운영 중.
- **맹목적으로 미국을 따라 가는 것이 아닌 국내 환경 (예산, 규제, 실증환경)에 맞춘 실물 핵연료 연구개발 추진 필요 (K 핵연료 개발). 우리가 더 잘 할 수도 있음.**
- **우리나라가 미국의 종이 원자로 유행을 따라가는 것을 지양 해야함.**
  차세대 원자로 개발을 위해서는 진정성 있는 핵연료 조사/PIE 연구 시설 정상화에 이어 기초 물성 확보를 위한 노력이 중요함.

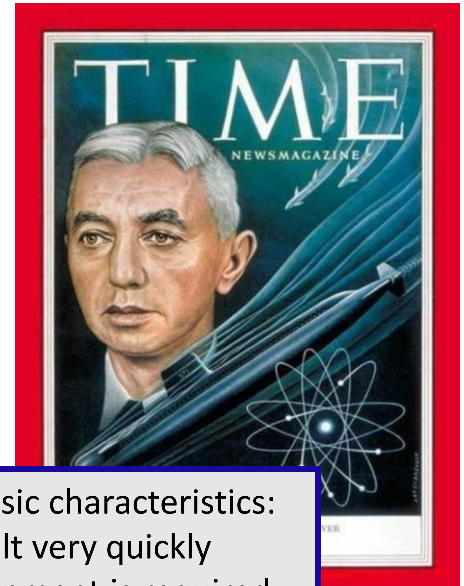
Admiral Rickover's (Father of Nuclear Navy) letter on academic reactor and practical reactor

June 5, 1953

Important decisions about the future development of atomic power must frequently be made by people who do not necessarily have an intimate knowledge of the technical aspects of reactors. These people are, none-theless, interested in what a reactor plant will do, how much it will cost, how long it will take to build and how long and how well it will

"I believe that this confusion stems from a failure to distinguish between the academic and the practical."

between the academic and the practical. These apparent conflicts can usually be explained only when the various aspects of the issue are resolved into their academic and practical components. To aid in this resolution, it is possible to define in a general way those character-istics which distinguish the one from the other.



An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly (6) It is very flexible in purpose ("omnibus reactor") (7) Very little development is required

On the other hand, a practical reactor plant can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It is requiring an immense amount of development on apparently trivial items. Corrosion, in particular, is a problem. (4) It is very expensive. (5) It takes a long time to build because of the engineering development problems. (6) It is large. (7) It is

"It is requiring an immense amount of development on apparently trivial items. **Corrosion**, in particular, is a problem

take around his neck; it cannot be erased. Everyone can see it.

The academic-reactor designer is a dilettante. He any real responsibility in connection with his pr luxuriate in elegant ideas, the practical shortco relegated to the category of "mere technical deta reactor designer must live with these same techni recalcitrant and awkward, they must be solved and until tomorrow. Their solutions require manpower,

Unfortunately for those who must make far-reachin benefit of an intimate knowledge of reactor techn for the interested public, it is much easier to ge an issue than the practical side. For a large part those involved with the academic reactors have more inclination and time to present their

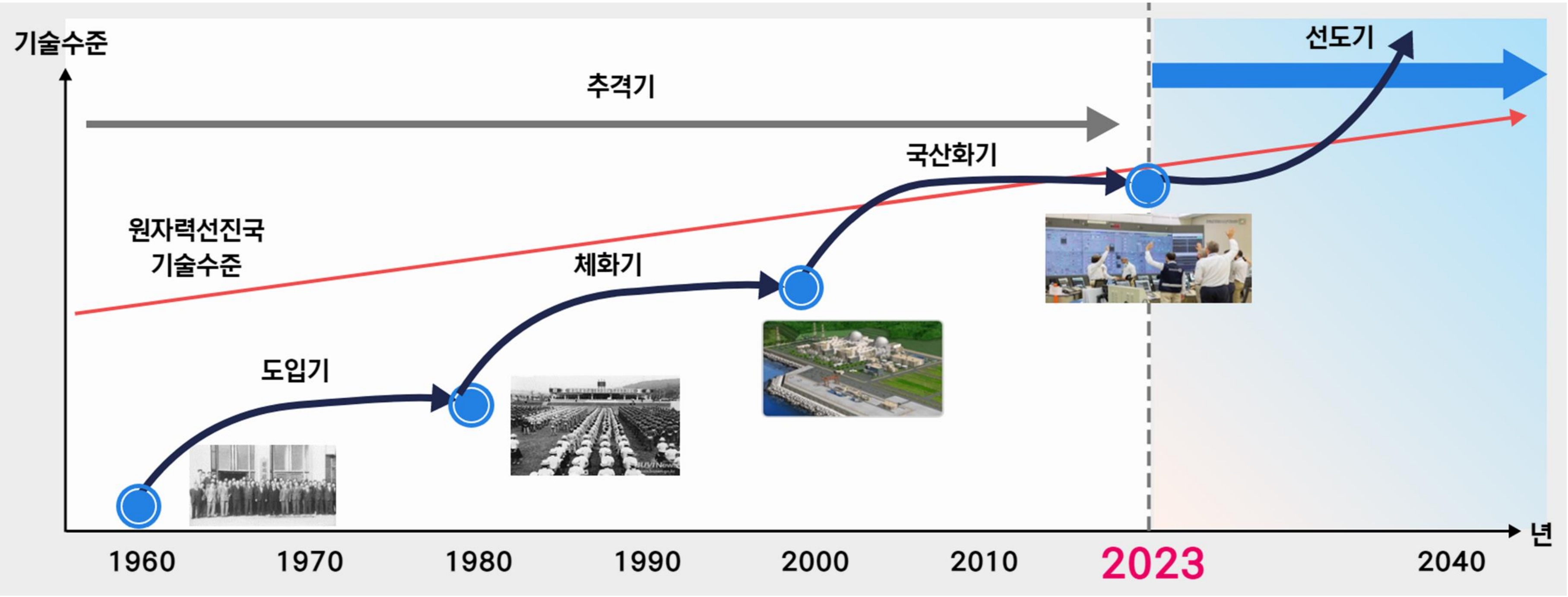
ideas in reports and orally to those who will listen. Since they are innocently unaware of the real but hidden difficulties of their plans, They speak with great facility and confidence. Those involved with practical reactors, humbled by their experiences, speak less and worry more.

t it is incumbent on those in high places to make wise decisions, and is reasonable and important that the public be correctly informed. is consequently incumbent on all of us to state the facts as forth-ghtly as possible. Although it is probably impossible to have reactor ideas labelled as "practical" or "academic" by the authors, it is worth while for both the authors and the audience to bear in mind this

"…those involved with the academic reactors have more inclination and time to present their ideas in reports and orally to those who will listen. Since they are innocently unaware of the real but hidden difficulties of their plans, they speak with great facility and confidence. **Those involved with Practical reactors, humbled by their experiences, speak less and worry more**.."

결언 7: 차세대 핵연료 안전규제기준 자체 개발 중요

- **선도형 R&D = 안전규제기준 개발과 실증연구**



- **기술 종주국이 만든 규제기준을 잘 준용하며 원전을 누구보다 잘 만들고 운영하는 대한민국.**

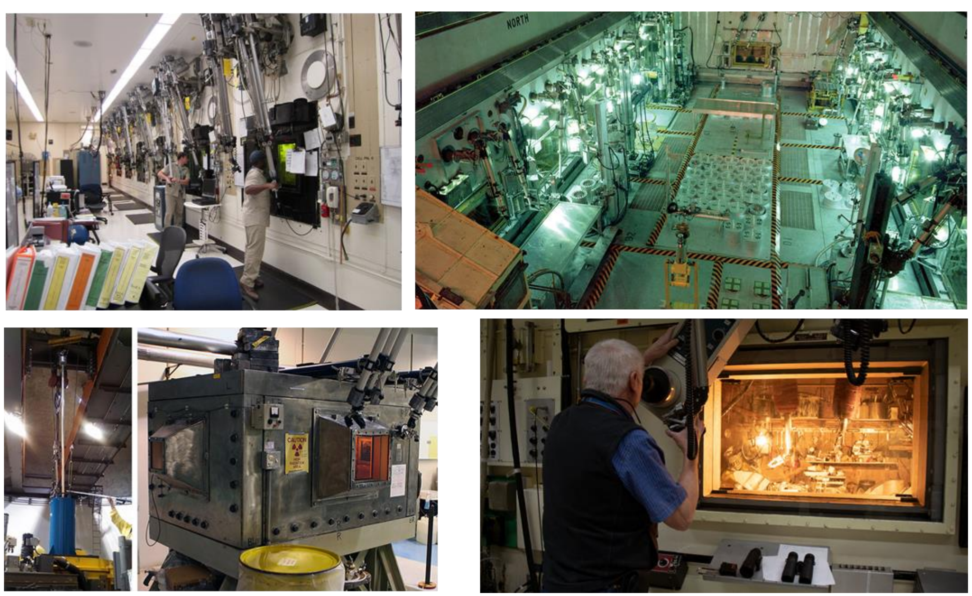
- **세계 원자력 기술개발을 선도하기위해선 스스로 안전규제 기준을 만들 수 있어야 함.**
  - 관성, 그리고 구조의 문제.
  - 원자력 발전소의 핵심 안전규제 기준은 핵연료 안전기준.
  - 실물 핵연료 실증 연구 필수.

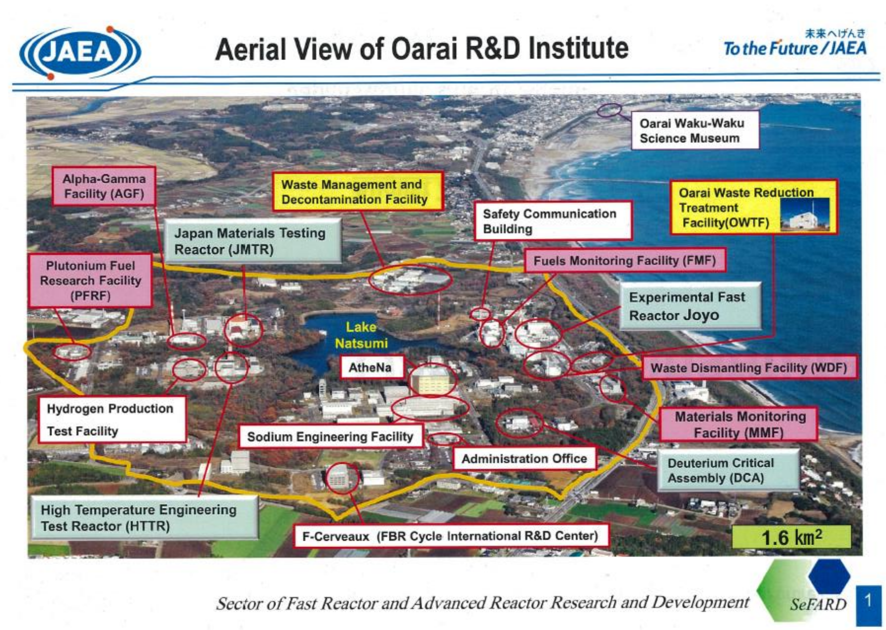
이 모든 것의 시작: 눈에 보이는 시설, 손에 잡히는 실물 핵연료 연구

- 핵연료 연구 정상화의 시급 과제

  ① 국내 핵연료 PIE 설비 구축 및 제도정비

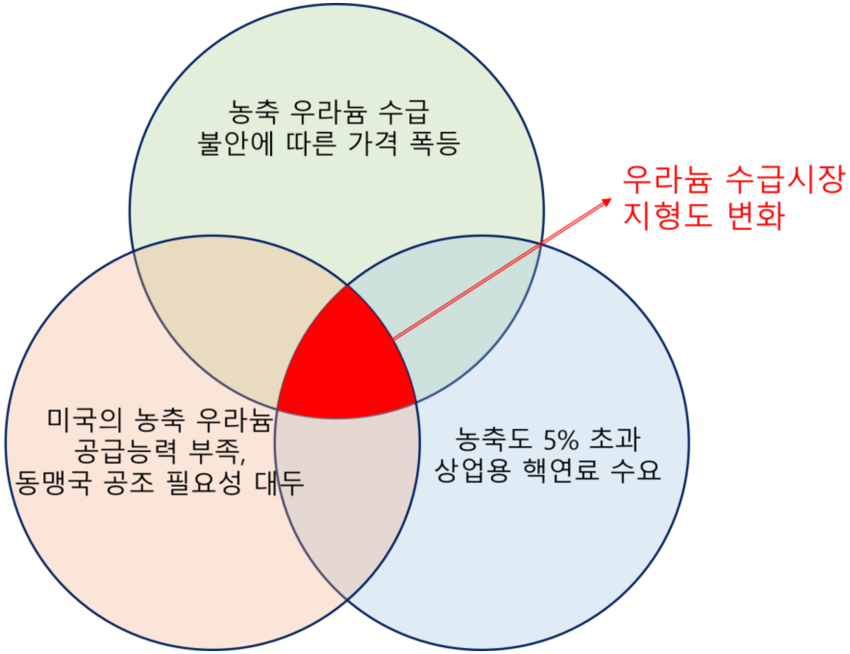
  ② 인허가 데이터 생산이 가능하도록 연구로 핵연료 조사시험 설비 강화 / 신규 구축





경청해 주셔서 감사합니다.

결언 5: 핵연료 공급 역량 강화



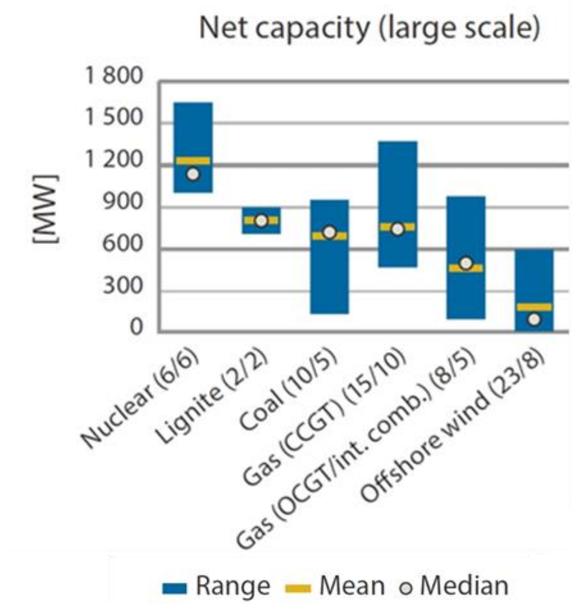
- 수급 불안에 따른 농축가격 폭등』,『취약한 미국의 농축우라늄 공급능력과 이에 따른 동맹국 공조 필요성 대두』,『농축도 5% 초과 핵연료 장전 상업용 원자로심 개발』이 동시에 펼쳐지고 있는 작금의 상황은 우리나라가 한미원자력협정 (2035)에서 농축 권한에 대한 실효성을 높이기 위한 주장을 효과적으로 펼칠 수 있는 토양을 제공함. 우리에겐 기회인 상황임.

-비확산을 중시하는 국무부에 눌렸던 에너지부의 농축관련 입김이 커지는 양상.

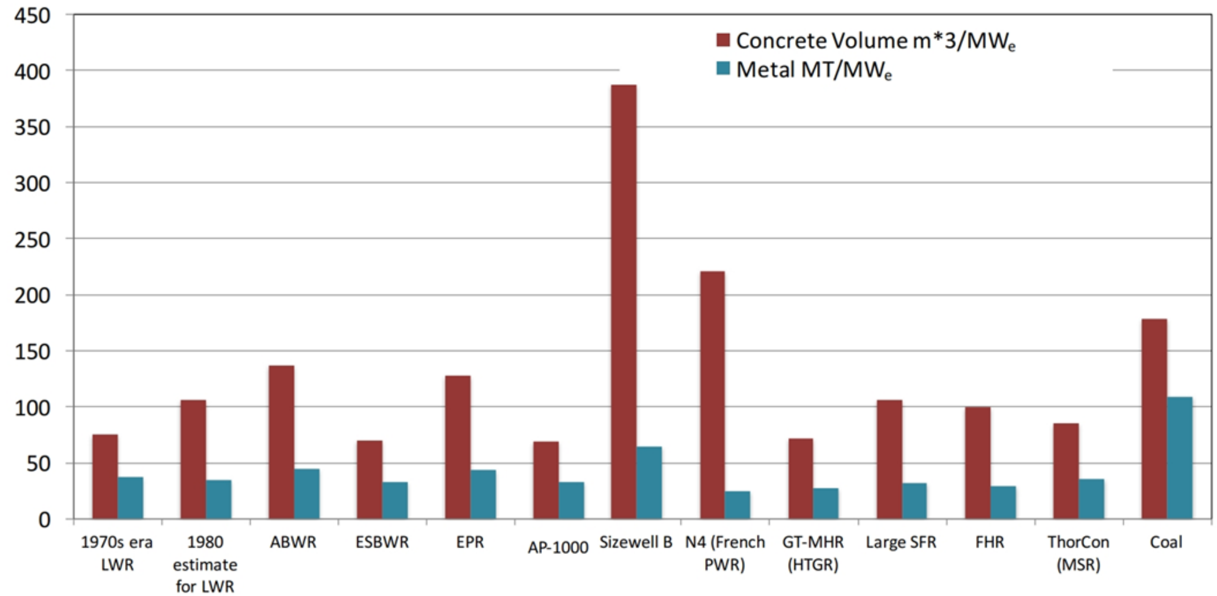
- 한·미 원자력 협상 테이블에서 5% 초과 농축도를 활용하는 신형원자로 및 핵연료 기술에 대한 진정성을 피력할 근거가 필요함. 이를 위해서는 관련 기술을 가지고 있어야 함. **5% 초과 농축도를 필요로 하는 원자로 & 핵연료 기술개발을 추진하고 농축우라늄 수급 불안을 전략적으로 쟁점화시킬 필요** 있음.

- 동력을 잃어가고 있는 **한·미 원자력 협력의 새로운 동력**이 될 것 으로 기대함. 이를 시작으로 선행 핵주기 핵연료 수급 분야의 전략적 파트너로써 대한민국의 국제적 위상이 격상될 토대를 마련할 수 있음.

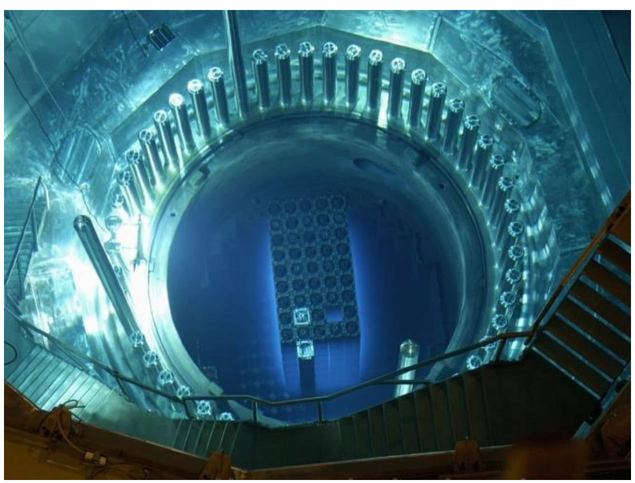
가동원전 경제성 확보 문법 1: 높은 출력 밀도

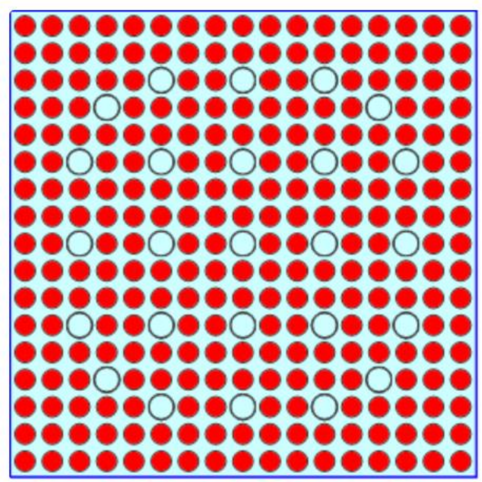


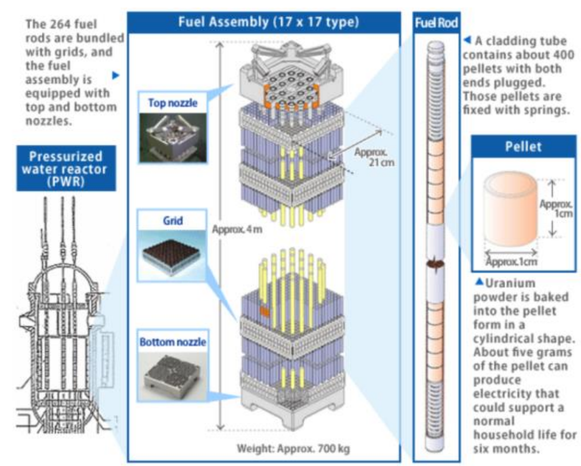
발전원별 설비용량



설비용량당 필요한 원자재 양 (콘크리트 및 금속재료)



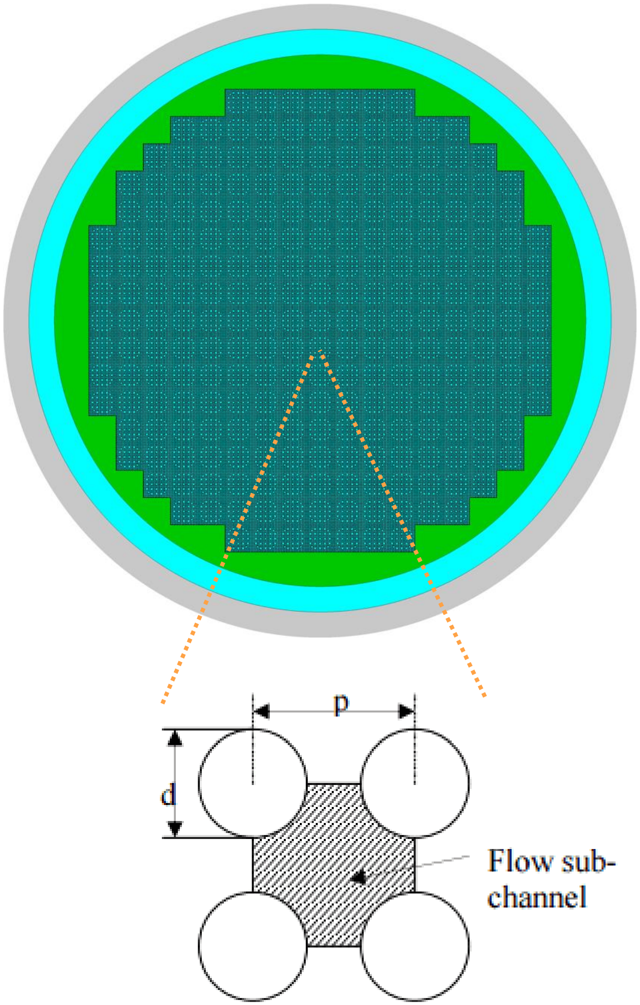




높은 출력밀도 구현을 위한 원자로 설계

가동원전 경제성 확보 문법 1: 높은 출력 밀도

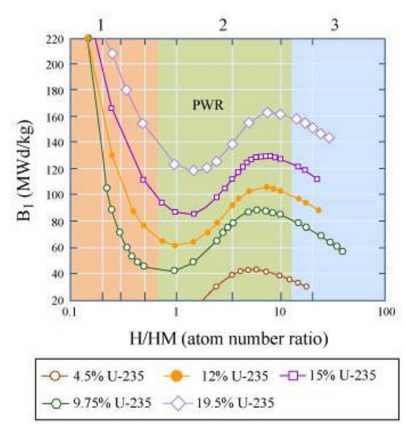
- 원자력 공학의 정수: 높은 출력 밀도 (w/cm^3) 구현을 위한 원자로 설계

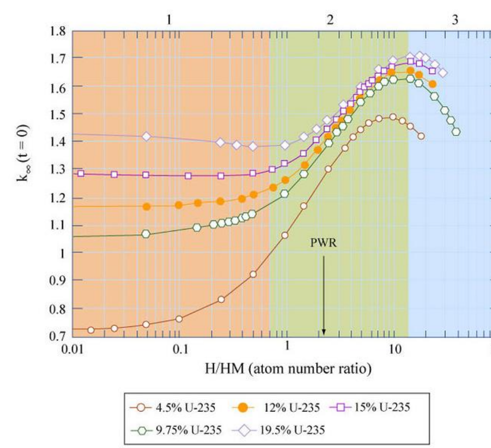


- **원자로 물리**
  - Lattice 설계 (P/D): 핵연료(HM)와 감속재 (H)의 적정 비율 유지
  - 임계, 음의 안전계수 유지

- **핵연료 재료**
  - 고온 핵연료재료기술
  - 공학적으로 구현 가능한 핵연료 형상

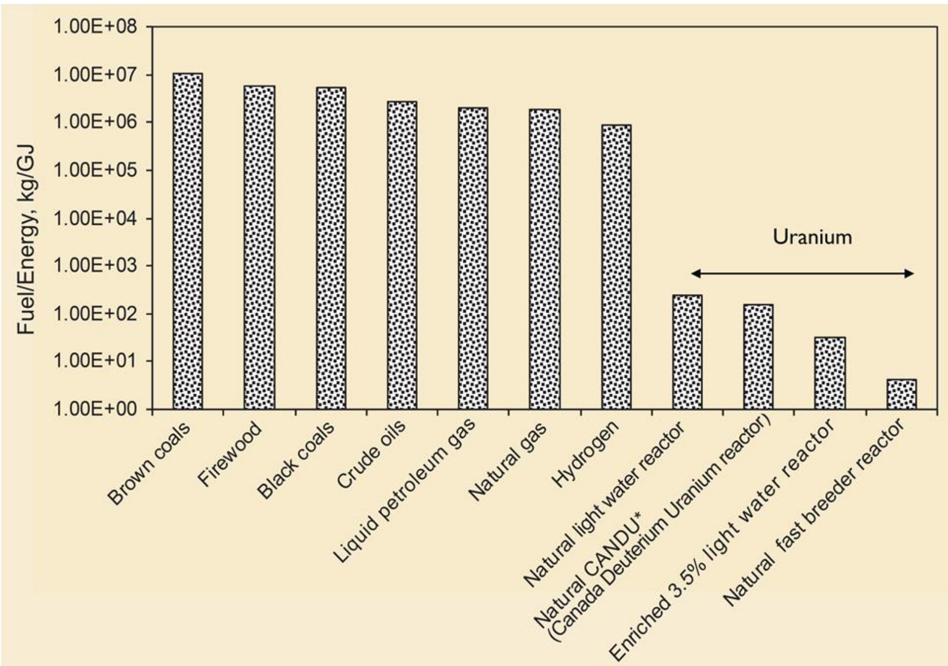
- **열수력**
  - 표면 열전달 면적 비약적 증진 (14x14→17x17)
  - 연료당 표면 열유석 저하 및 노심 유속 증진에 의한 임계열유속 억제
  - 압력강화 심화. 대용량 펌프 필요





가동원전 경제성 확보 문법 2: 높은 에너지 밀도

- **높은 에너지 밀도에 기인하는 값 싼 핵연료**
  - 핵에너지에 기인한 높은 연소도 (60 MWd/kgU)



<연료별 에너지 밀도 차이>

[Power Density and the Nuclear Opportunity, Jesse H. Ausubel]

원자력 균등화발전비용

설비 비용 (capital cost): ~48%

운영 및 관리 (O&M cost): ~37%

핵연료 비용: ~15%

Stephen P. Nesbit
president@ans.org

NuclearNewswire

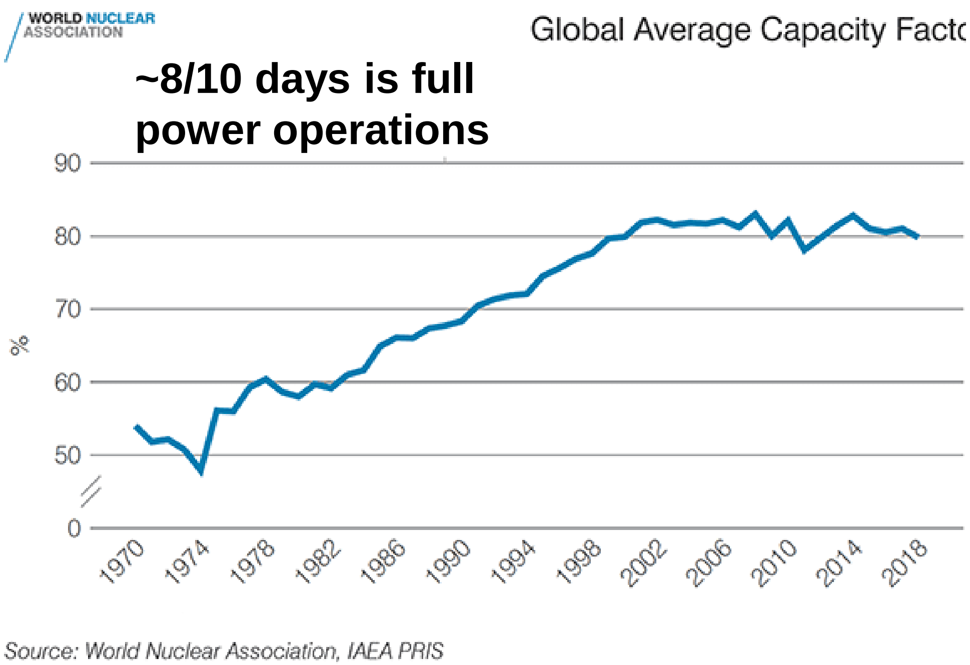
FUEL

Nuclear fuel: The foundation of nuclear power

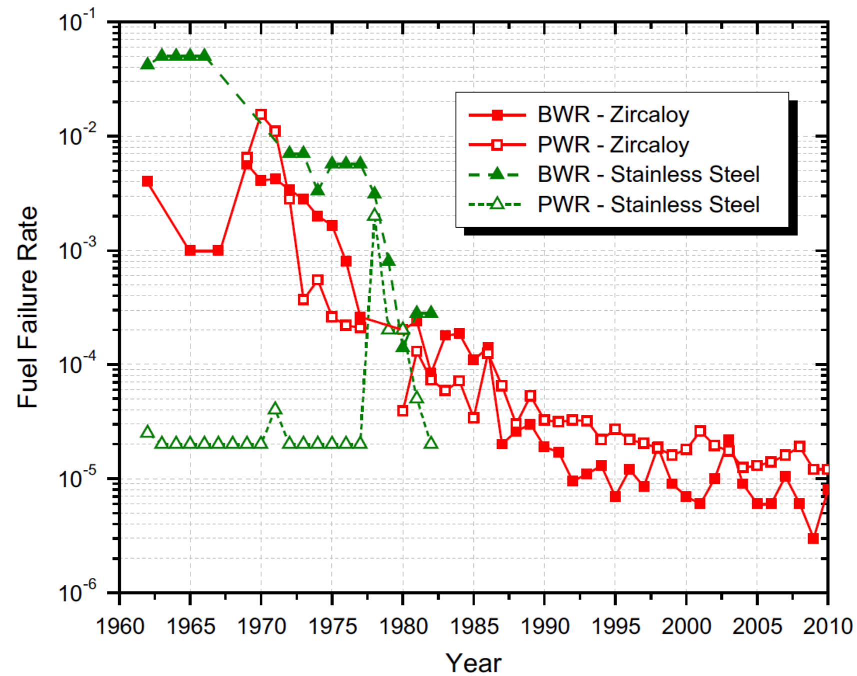
*"the **low cost of nuclear fuel compared to fossil fuel alternatives is the only reason nuclear power plants exist.** Everything else—up-front capital cost, operations and maintenance, regulation, and decommissioning—is more expensive with highly regulated nuclear technology"*

가동원전 경제성 확보 문법 3: 높은 가동률

- **높은 가동률**
  - 초기 건설비용 집약적 발전과 정해진 발전소 수명 → 높은 가동률 중요
  -핵연료 및 주요 부품 재료 내구성 향상을 통해 이룩한 오늘날의 경수로 가동률



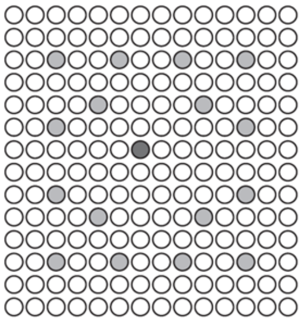
원자력 발전소 가동률 (국제 평균)



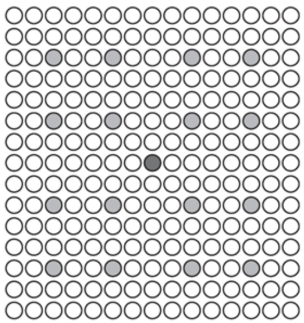
미국 경수로 핵연료 고장률 (failure rate)

오늘날의 가압 경수로: 출력 밀도

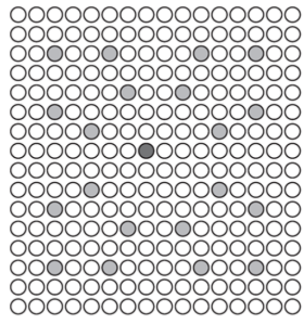
- **핵연료/집합체 설계를 통해 구현되는 높은 출력 밀도**



14x14

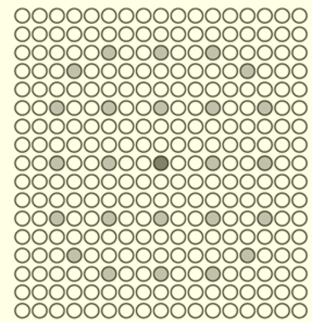


15x15

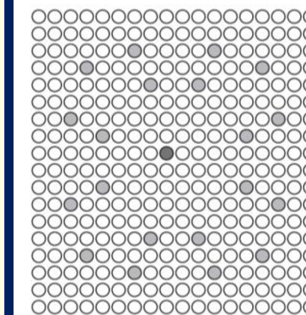


16x16

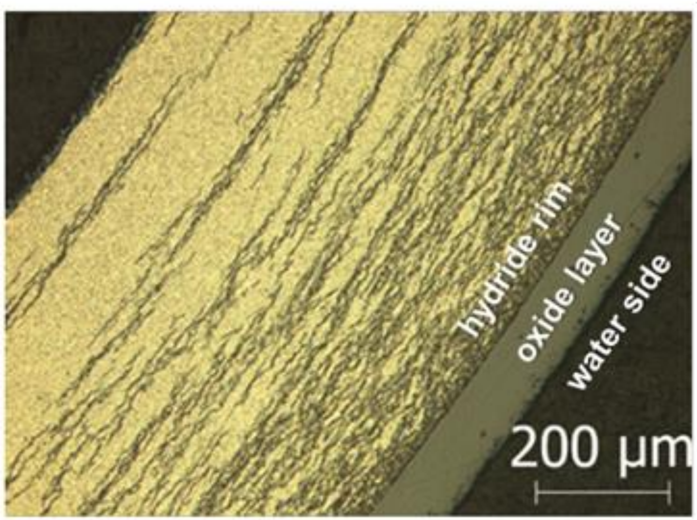
~100 w/cm^3



17x17 (Today)



>17x17with ATF?



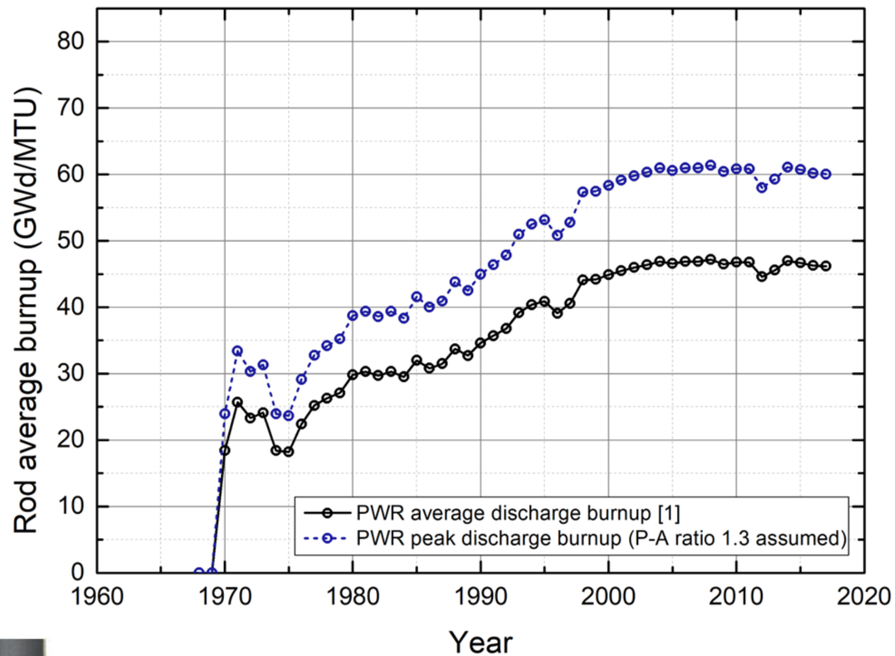
Zircaloy-4
67 GWd/MTU
$[H]_{average}$: 640 ± 140 wppm

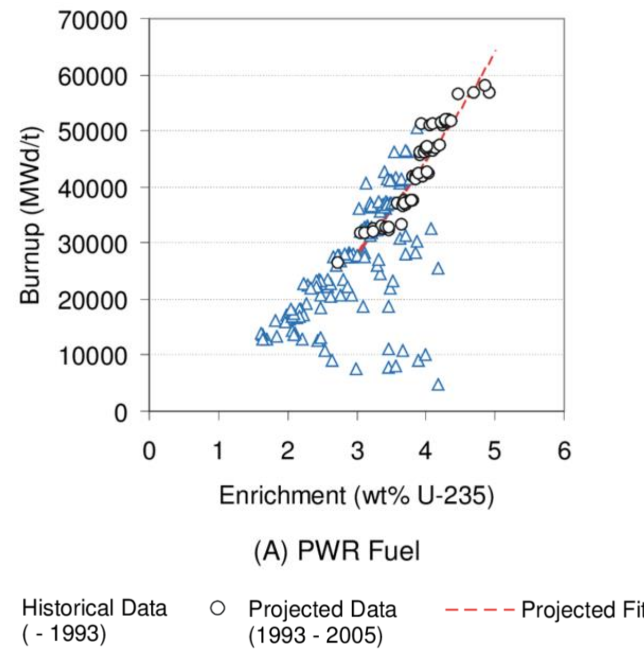
- **얇고 부식저항성이 향상된 핵연료 도입을 통한 집합체내 핵연료수 증가에 기반한 출력밀도 향상. (Zr-4 → Zirlo → Opt Zirlo, HANA-6, M5)**
  - 열전달: 열전달 면적 증가를 통한 열적 안전 여유도 유지
  - 원자로물리: H/HM 일정수준 유지
  - 핵연료: DBA 사고관련 열화 (ECCS Criteria) 기준 만족

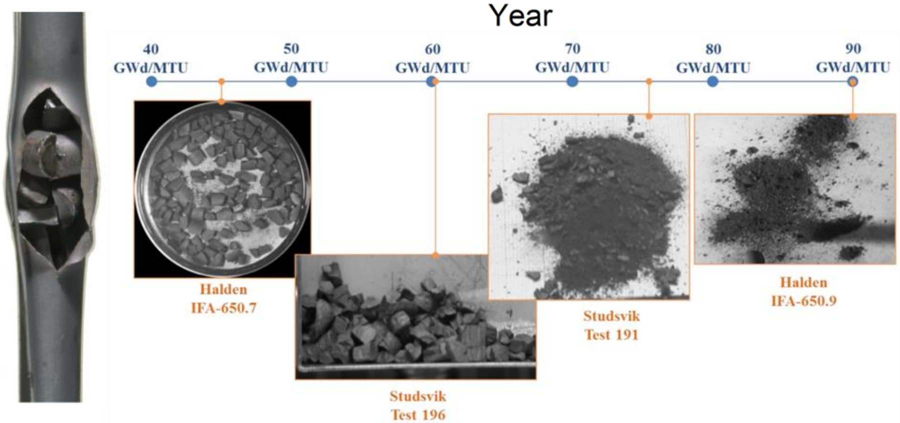
- **추가적인 출력밀도 향상을 위해서는 핵연료 열화 (부식 및 수소취화) 완화 필요.**

오늘날의 가압 경수로: 에너지 밀도 (방출 연소도 Bu_d)

- **방출 연소도 증진 이력**







<Fuel pellet fragmentation & pulverization with burnup increase [5]>

- **미국 (62MWd/kgU), 한국 (60MWd/kgU)에 머물러 있는 방출 연소도**

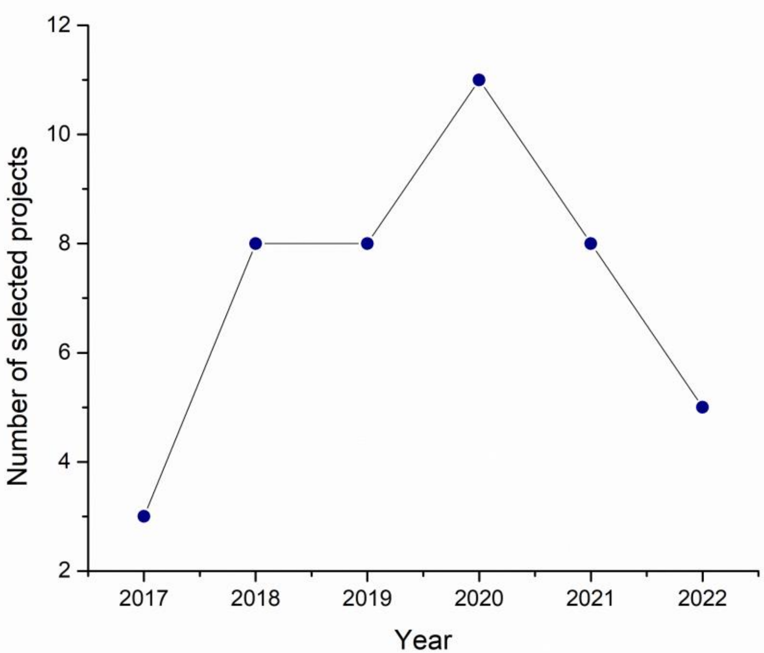
- **추가 연소도 증진을 위해선 다음의 현안해결 필요**
  ① 농축도 상향 (>5%)
  ② 내식성 향상 피복관
  (Modern Zircaloy 혹은 ATF)
  ③ FFRD 문제 해석/해결 방안 필요

[5] Sonnenburg, H., et al. "Report on fuel fragmentation, relocation and dispersal." NEA/CSNI/R (2016) 16. Organization for Economic Co-operation and Development, 2016.

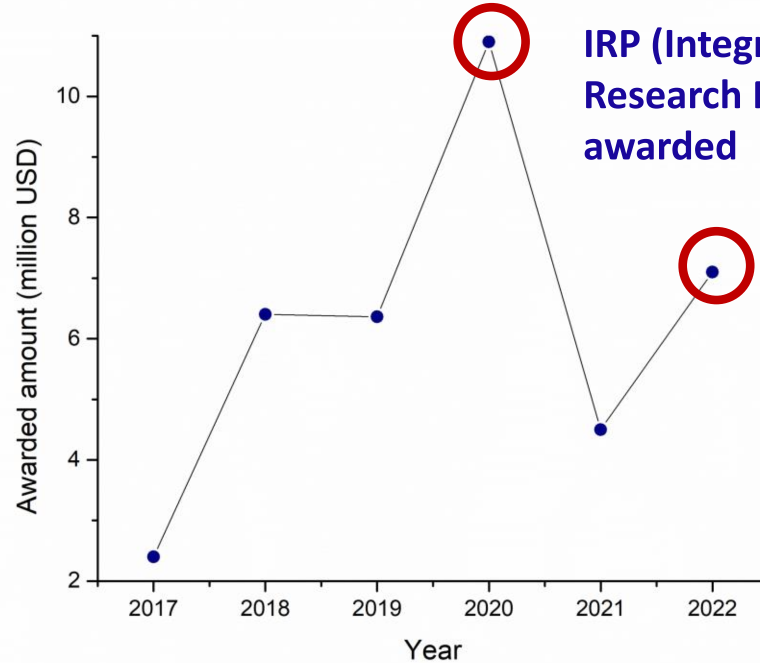
미국 에너지성 (DOE) NEUP (Nuclear Energy University Program) 분석

□ **NEUP 분석 (https://neup.inl.gov/),**
최근 6년간 (2017 – 2022)년간 선정된 44개 MSR 기술개발 과제 분석
과제당 3년간 400K – 800K (5억 - 10억)

<NEUP 선정과제 개수 추이>



<선정과제 총 연구비 추이>



IRP (Integrated Research Project) awarded

미국 에너지성 (DOE) NEUP (Nuclear Energy University Program) 분석

□ **IRP (Integrated Research Project) 분석 (https://neup.inl.gov/),**

최근 6년간 (2017 – 2022) MSR 관련 2건의 IRP 과제 선정

The project will develop along multiple tracks in order to complete a comprehensive assessment of the role of impurities and FPs within the limited timeframe and resources available. The experimental effort will focus on measurements of key properties identified together with the industrial partners both for clean salt (if needed) and salt with added solutes (fission products as well as impurities and

U.S. Department of Energy

activation products). Molecular dynamics simulations in combination with machine learning

5.0 million / 3 years

2020

U.S. Department of Energy

Molten Salt Reactor Test Bed with Neutron Irradiation

PI: Charles Forsberg
Massachusetts Institute of Technology (MIT)

Program: Reactor Concepts

Collaborators:
David M Carpenter—MIT
Ayman Hawari—North Carolina State University
Raluca O. Scarlat—University of California at Berkeley
Kevin Robb—Oak Ridge National Laboratory

4.8 million / 3 years