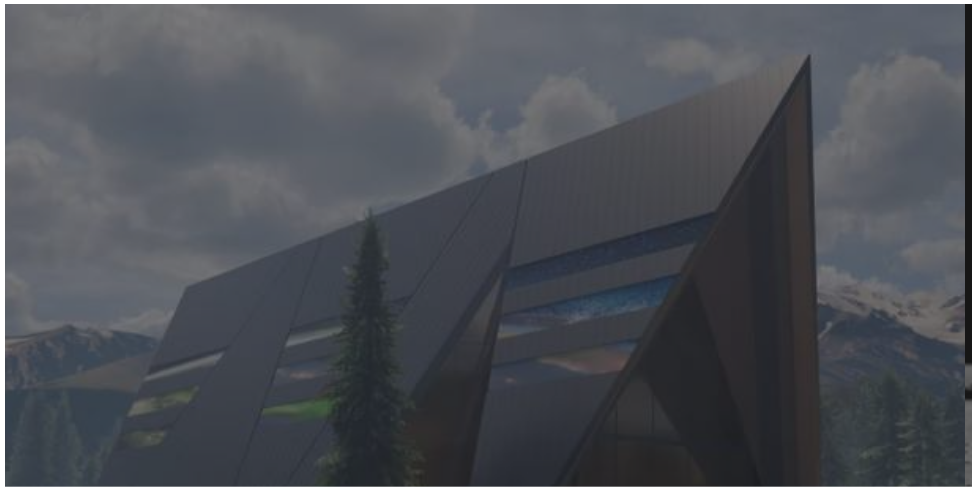
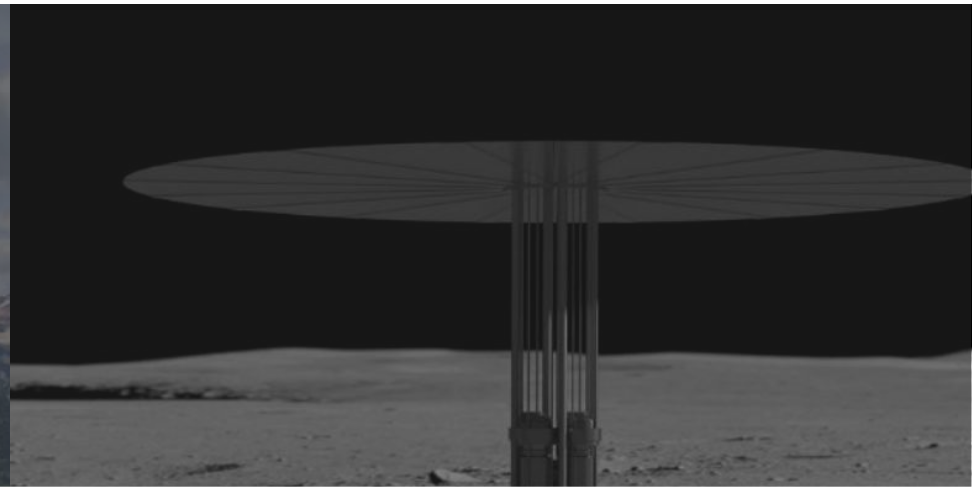
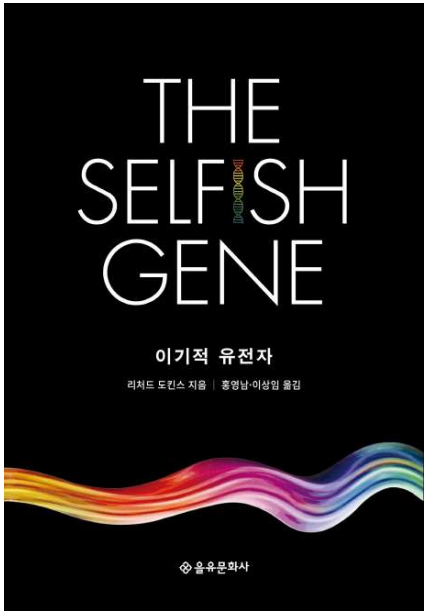



원자력 활용을 위한 히트파이프 열수력 연구개발 동향

방인철

Department of Nuclear Engineering
Ulsan National Institute of Science and Technology (UNIST)

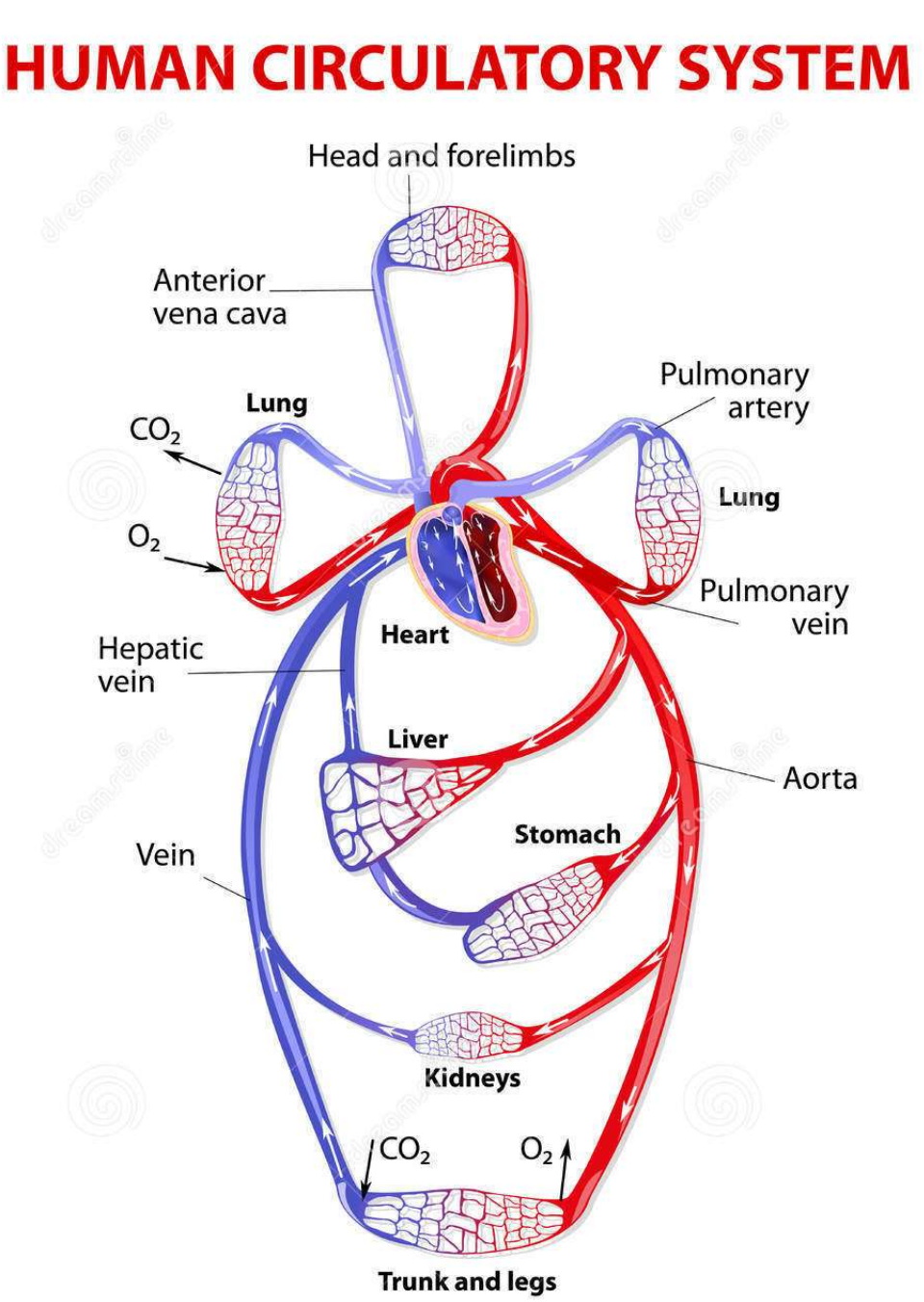
진화론:
이기적인 유전자



생체모방 원자로

진화하는 원자로

이기적인 원자로



1. 히트파이프 냉각 원자로 연구개발 현황

(초)소형 원자로 연구개발 현황

- 전세계적으로 70기 이상의 SMR 개념 설계가 다양한 활용 목적 하에 개발 중
- 2030년 ~ 2050년 사이에 운영 시작 예정

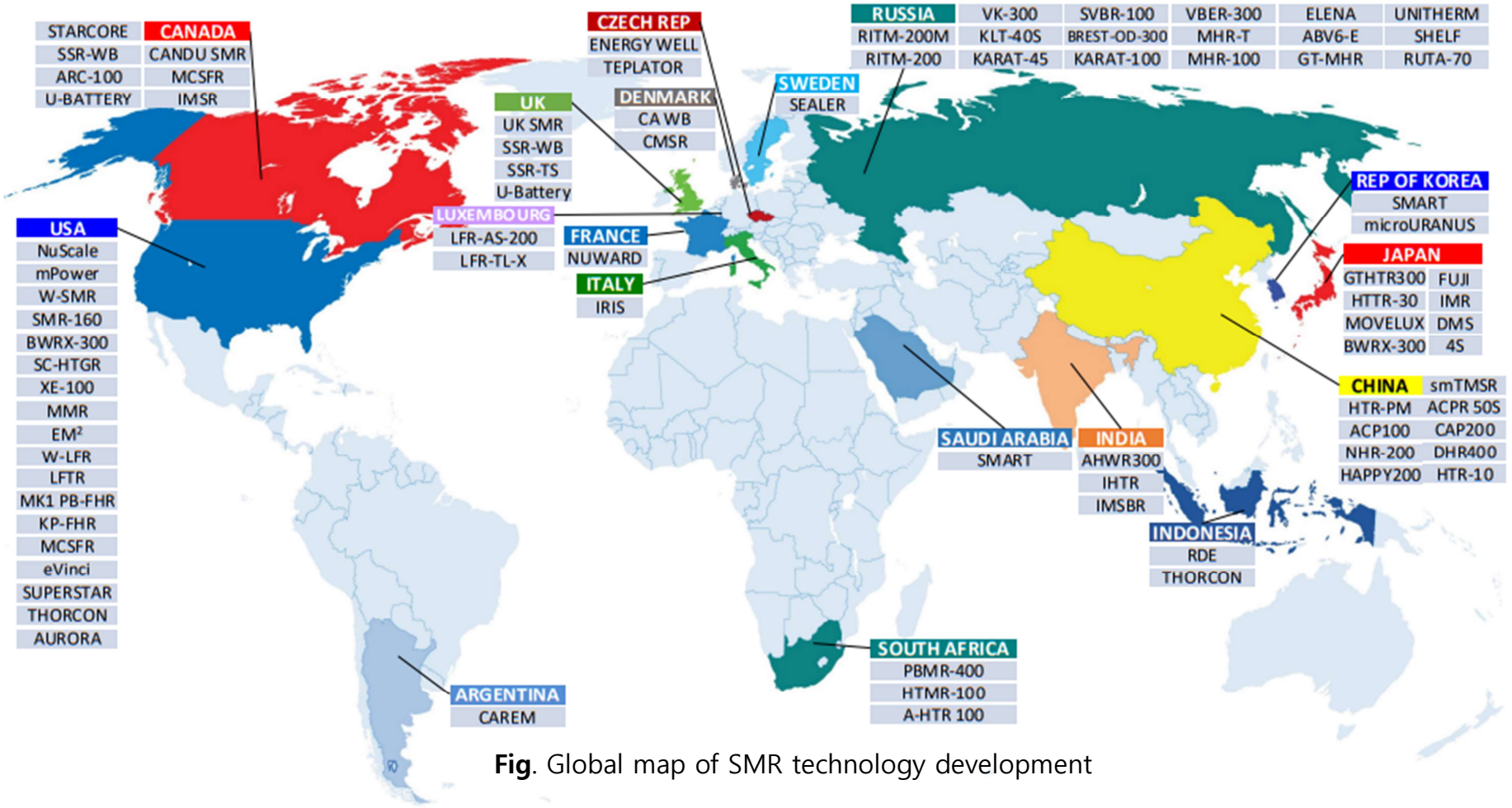


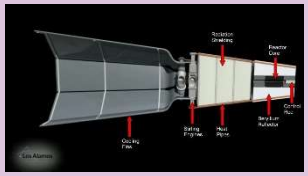
Fig. Global map of SMR technology development

IAEA Nuclear Energy Series, "Technology Roadmap for Small Modular Reactor Deployment", No. NR-T-1.18 (2021)

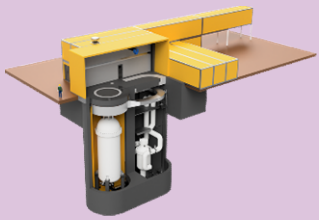
1. 히트파이프 냉각 원자로 연구개발 현황

[초]소형 원자로 연구개발 현황

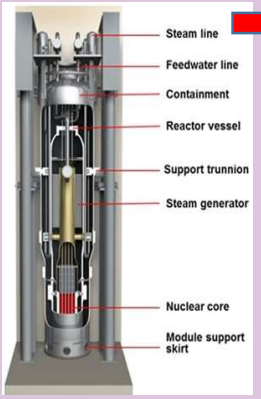
500 W ~ 10 MW
(Deep space power, Military, transportable)



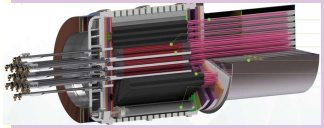
KiloPower(NASA)



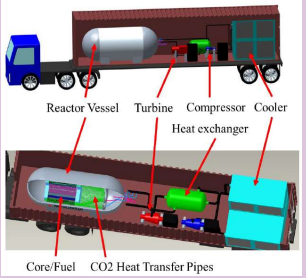
MMR(USNC)



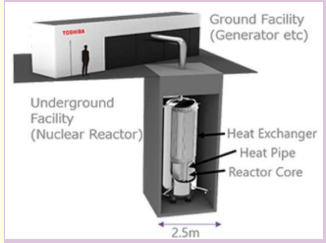
NuScale



eVinci(Westinghouse)



(Mitsubishi Heavy Industries)
MMR(USNC)



MoveluX(Toshiba Co.)

U-Battery(Urenco)

Xe-100(X Energy)

Aurora(Oklo)

10 MW to 50 MW Reactor

Non-LWR

Power to Grid; Military bases; Process heat

50 MW to 300 MW Reactor

LWR and Non LWR

Power to Grid; Small cities, Burning of actinides

1000 MW Commercial Reactor

LWR Focus

Power to Grid

10^4 10^5 10^6

Power Level in Kilo-Watts Electric

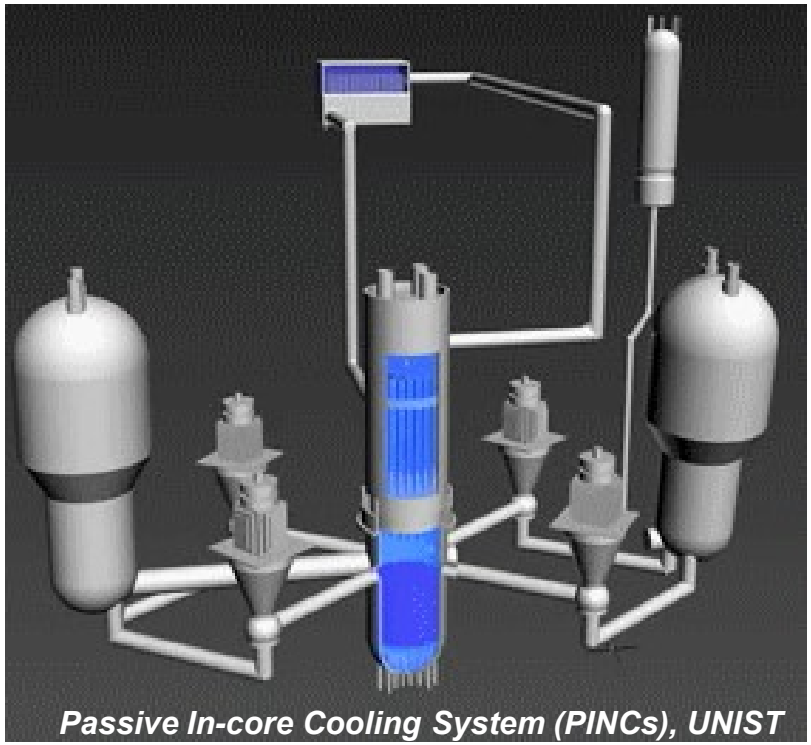
P. R. Mcclure, "Design of Megawatt Power Level Heat Pipe Reactors", LA-UR-15-28840 (2015)

히트파이프 작동 원리

INDEFINITE COOLING (전도, 대류, 복사)

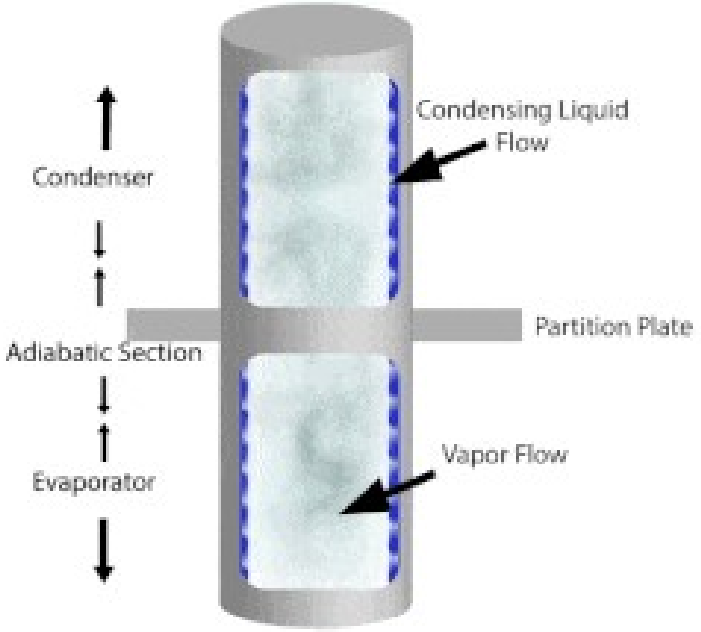
- 대형원전 → 소형화 → **완전/부분 피동화**
- 강제순환(펌프) → **자연순환(+상변화)** → 열전도도 → 열복사

히트파이프
(상변화 열전도관)



Passive In-core Cooling System (PINCs), UNIST

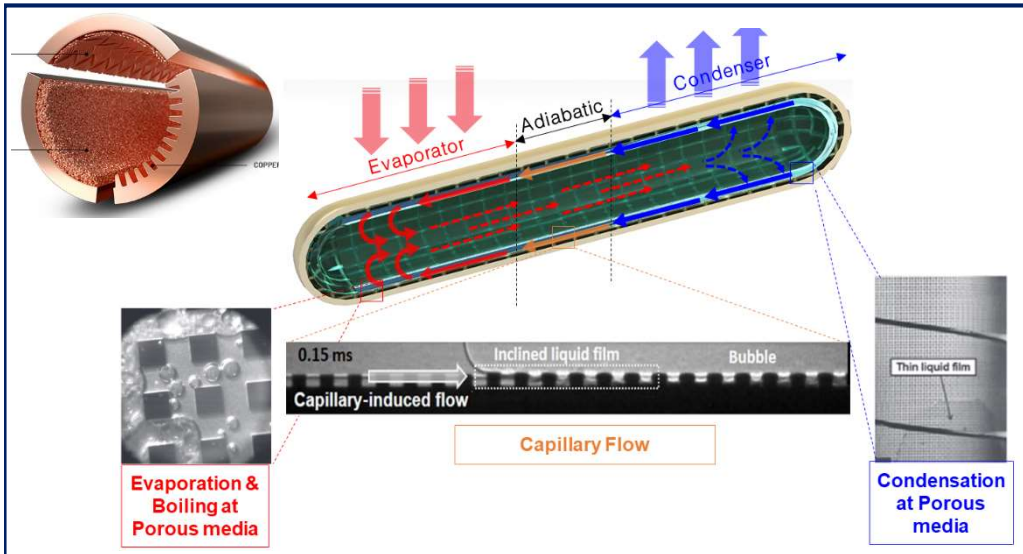
"cut away illustration of a thermosyphon heat pipe in operation"



1. 히트파이프 냉각 원자로 연구개발 현황

히트파이프 작동 원리

➢ 히트파이프를 원자력에 활용하는 이유?



히트파이프 특징

- 고용량 열이송
- 피동 상변화 열전달
- 윅구조물을 통한 모세관력 구동
- 대기압 이하 압력 조건
- 다양한 범위의 작동 온도 및 출력

히트파이프 냉각 원자로

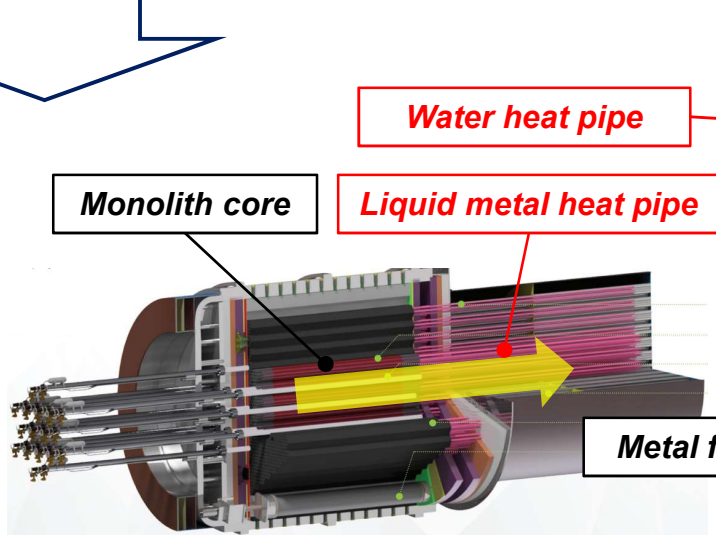
➢ *외부 전력 공급 X*

➢ *펌프 및 파이프 제거*

➢ ***기존 중대사고 배제 (LOCA, SBO)***

➢ ***무중력 작동 가능***

➢ ***높은 설계 자유도 및 단순한 구조***

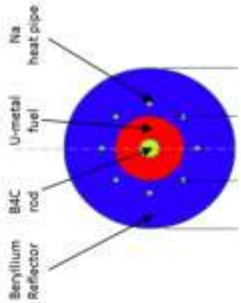


eVinci (Westinghouse)

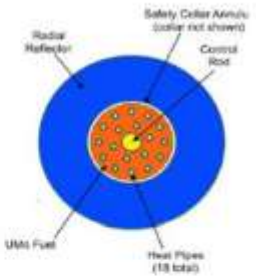
Kilopower (NASA)

히트파이프 연구의 필요성

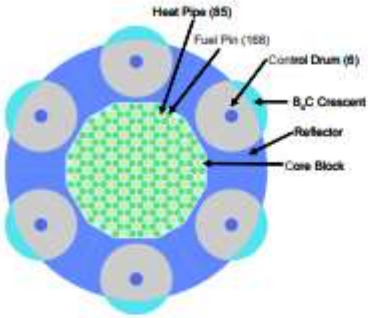
Characteristics of LEU Fueled Heat Pipe Reactors of Increasing Size



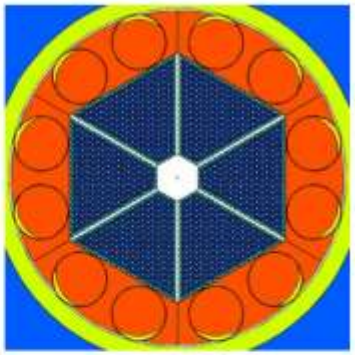
- **4 kWt**
- **1 kWe**
- Metal fuel
- 280 Kg fuel
- 660 Kg Rx Mass
- 40 cm Rx Dia
- 50 cm Rx Length
- 8 Heat Pipes



- **40 kWt**
- **10 kWe**
- Metal fuel
- 350 Kg fuel
- 800 Kg Rx Mass
- 50 cm Rx Dia
- 70 Rx Length
- 20 Heat Pipes



- **500 kWt**
- **200 kWe**
- Oxide fuel
- 600 Kg fuel
- 3000 Kg Rx Mass
- 65 cm Rx Dia
- 100 cm Rx Length
- 200 Heat Pipes



- **5 MWt**
- **2 MWe**
- Oxide fuel
- 5100 Kg fuel
- 22000 Kg Rx Mass
- 150 cm Rx Dia
- 200 cm Rx Length
- 2112 Heat Pipes

Increasing Reactor Power

Los Alamos NATIONAL LABORATORY

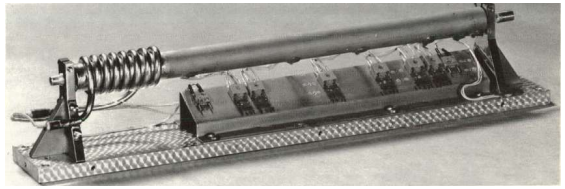
Increasing number / length of Heat Pipes

LANL, "Design and Testing of Small Nuclear Reactors for Defense and Space Applications", LA-UR-13-27054 (2013)

히트파이프 연구의 필요성

"원자력 활용을 위한 대형 히트파이프 길이/직경 별 성능 DB 필요"

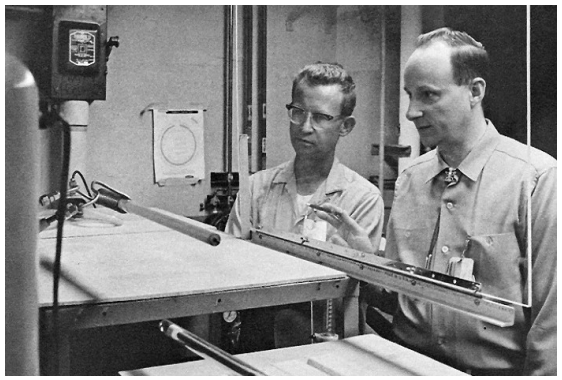
히트파이프 적용 분야 – 우주용 원자로



LANL, "Orbital Heat Pipe Experiment" (1967)

❖ History of Heat pipe

- 1960s, George Erickson
- LANL에서 우주용 원자로 연구의 일환으로 개발됨

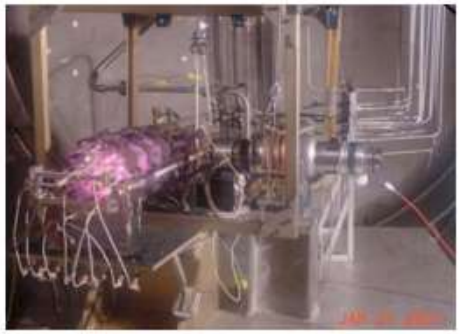


George Erickson and Ed Keddy at LANL

❖ History of Heat pipe reactor - Space

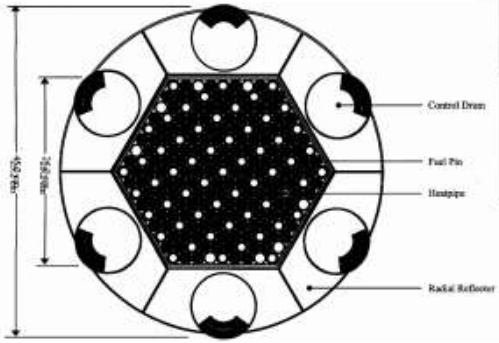
➢ SAFE (Safe Affordable Fission Engine)

- 100kWe, TEG, Sodium HP
- Reactor never built, but electrically-heated demonstration conducted



➢ HOMER (Heatpipe-Operated Mars Exploration Reactor)

- >20kWe, Lithium HP
- Heat pipes tested



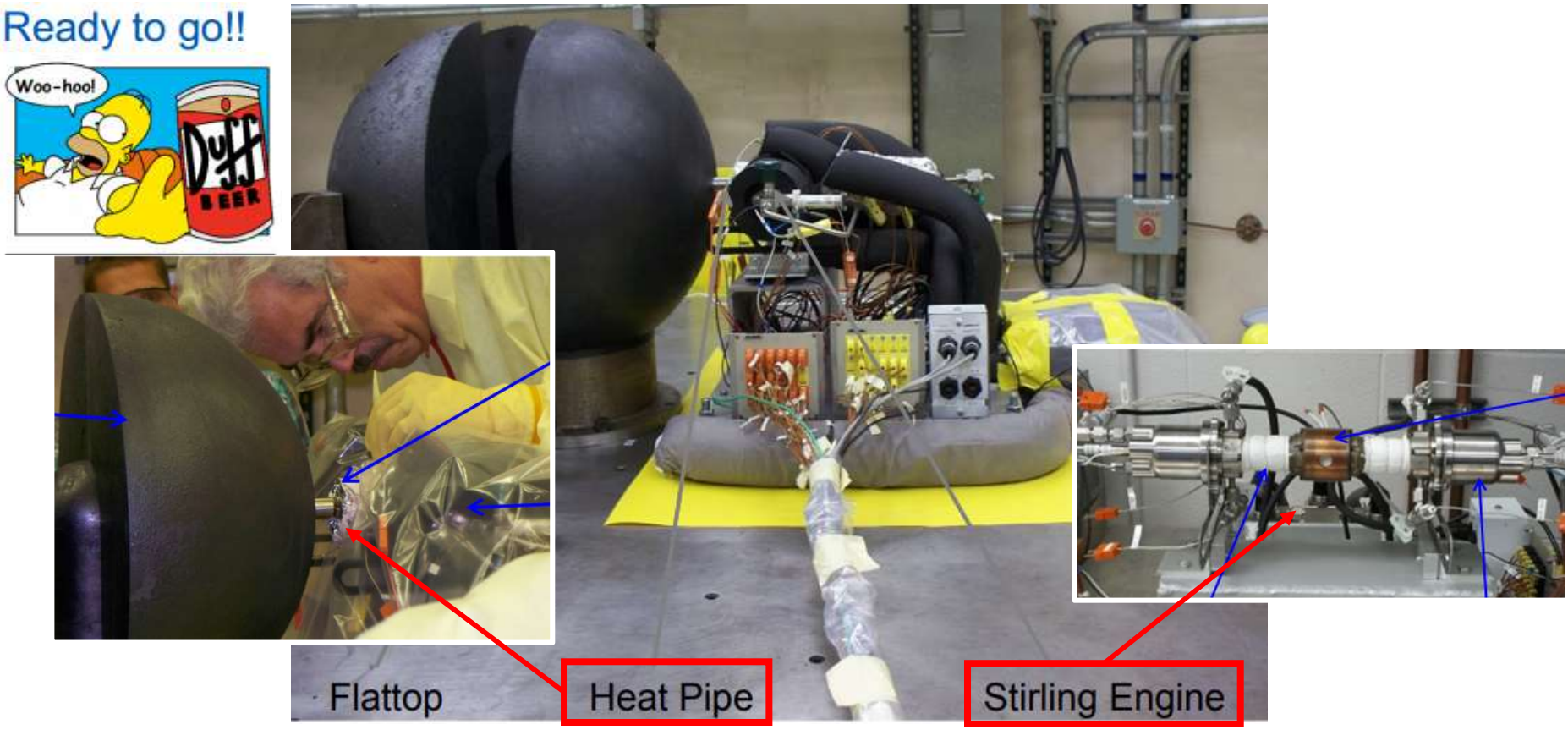
LANL, "Orbital Heat Pipe Experiment", LA-3714 (1967)

LANL, "Design and Testing of Small Nuclear Reactors for Defense ai

히트파이프 냉각 원자로 개발 역사

❖ DUFF (Demonstration Using Flattop Fissions) – LANL, NASA

- ✓ First-ever heat pipe cooled fission experiment
- ✓ First-ever Stirling engine operation with fission energy
- ✓ First nuclear-powered demonstration of a potential space reactor



LANL, "Design and Testing of Small Nuclear Reactors for Defense and Space Applications", LA-UR-13-27054 (2013)

1. 히트파이프 냉각 원자로 연구개발 현황
Publicly Available Designs of Heat Pipe Reactors

참조문헌	형상 정보			작동 환경			설계 용량		Purpose
	용기	윅	작동 유체	핵연료 타입	냉각부	반응도 조절	단일 용량 [kW]	개수	
Kilopower(LANL) (2018)	Haynes-230 H=1.3m(0.35:0.86:0.09) D=14.48mm	SS 316 Screen wick	Na	UMO	Stirling engine	Shutdown rod, Control drum	0.38	8	Space
Mega power(LANL) (2017)	Stainless 316 H=4.0m(1.5:0:2.5) D=15.75mm	SS316 Screen wick	K	UO_2 HALEU(Fast)	CO2 Brayton	Shutdown rod, Control drum	4.1	1224	Transportable
eVinci (Westinghouse) (2021)	FeCrAl H=4.0m(2.8:0:1.2) D=N/A	FeCrAl N/A	Na	TRISO(Thermal)	Open-air or sCO2 Brayton	Shutdown rod, Control drum	17.12	876	Transportable
Aurora(Oklo) (2021)	SS316L H=N/A D=N/A	SS316L Screen wick	K	U-10Zr HALEU(Fast)	sCO2 Brayton	Shutdown rod, Control drum	35.08	114	Stationary
NuScale-micro	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
INL-Design-A (2017)	SS316L H=4m(1.5:0.4:2.1) D=18mm	SS316L Screen wick	K	UO_2 HALEU(Fast)	Open-air Brayton	Shutdown rod, Control drum	4.41	1134	Transportable
INL-Design-B (2017)	SS316L H=4m(1.5:0.4:2.1) D=18mm	SS316L Screen wick	K	UO_2 HALEU(Fast)	Open-air Brayton	Shutdown rod, Control drum	4.08	1224	Transportable

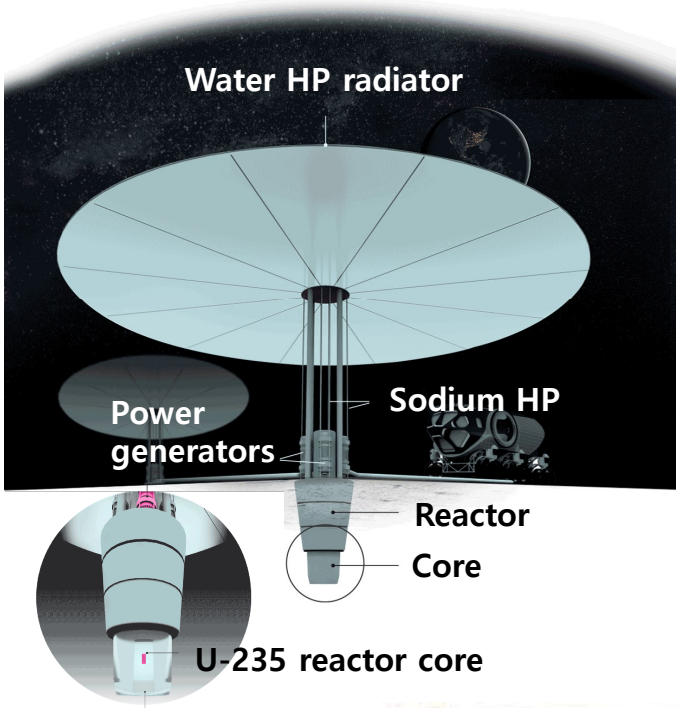
1. 히트파이프 냉각 원자로 연구개발 현황

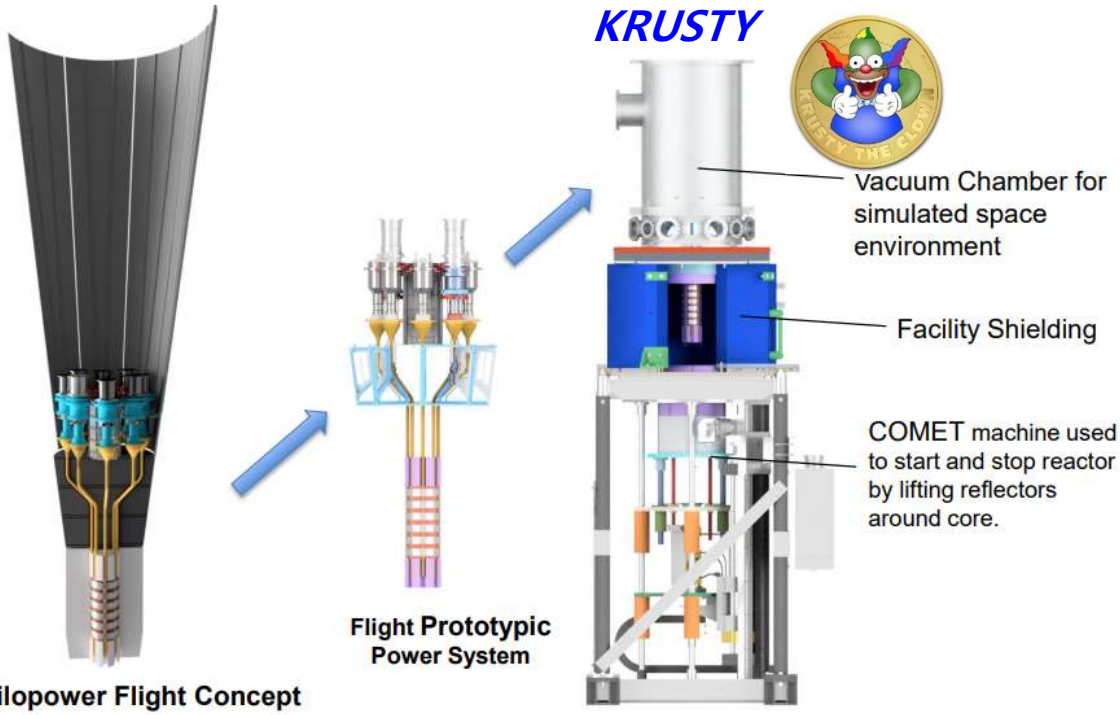
NASA, LANL – KiloPower, KRUSTY

❖ KiloPower (NASA, since 2015)

- Deep space / Mars surface fission system
- 1~10kWe, Stirling converters
- Sodium heat pipe / water radiator heat pipe
- First U.S space reactor built and tested
- Test reactor (1kWe) built and operated (2017~2018)

  → Transient scenario testing including HP failure





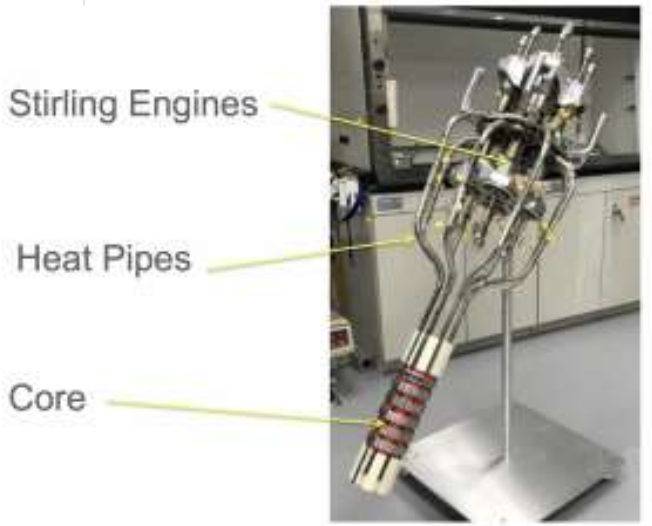


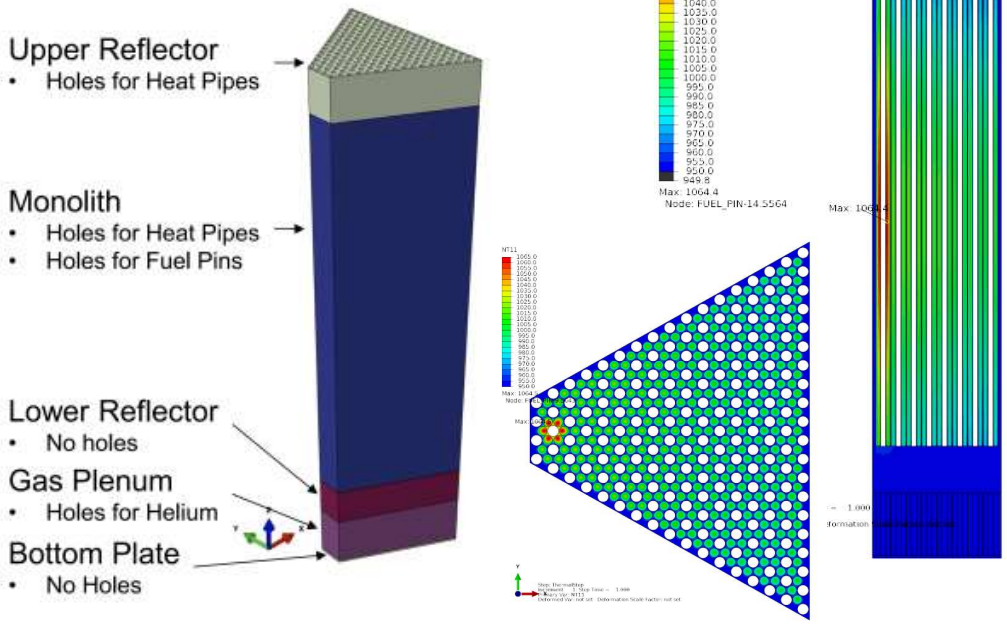
Fig. Mockup of assembled power system

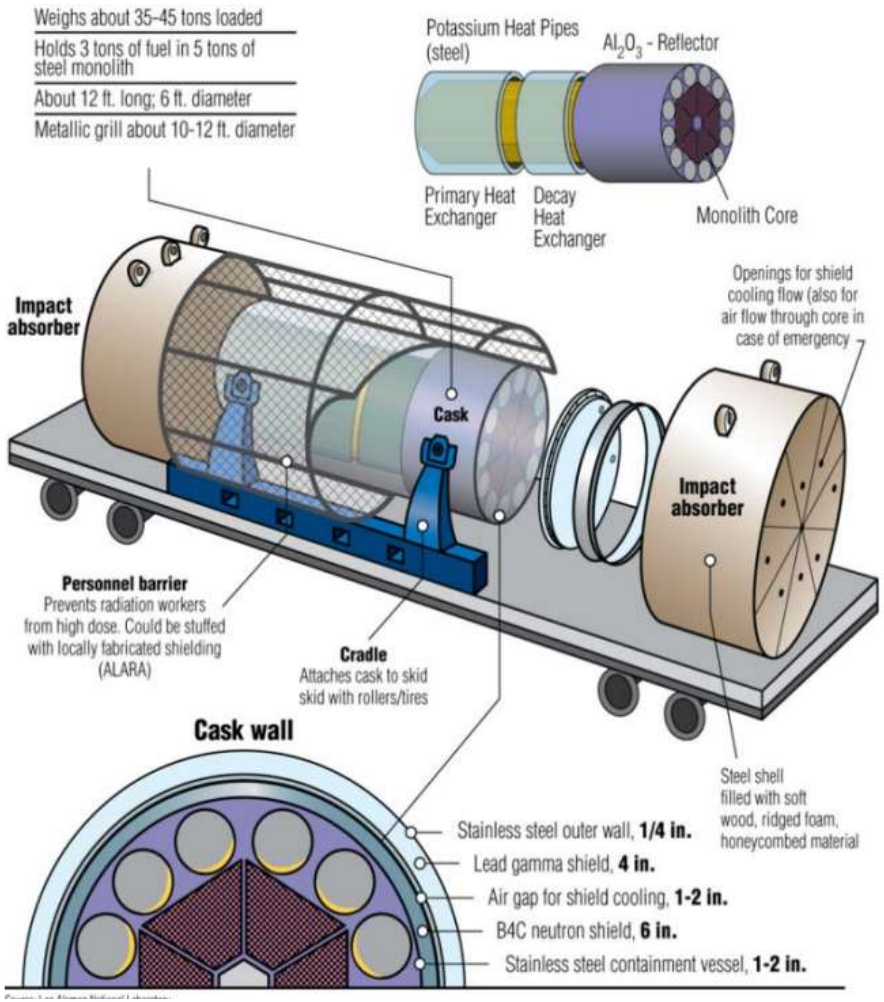
https://www.wsj.com/articles/mini-nuclear-reactors-offer-promise-of-cheaper-clean-power-11613055608

LANL – MegaPower

❖ MegaPower, LANL

- 5 MW_{th} / 2 Mw_e 히트파이프 냉각 초소형 원자로
- Horizontal type(Transportable), Fast spectrum
- Maximum allowable temperature; 825°C for fuel





MegaPower

Single HP failure analysis

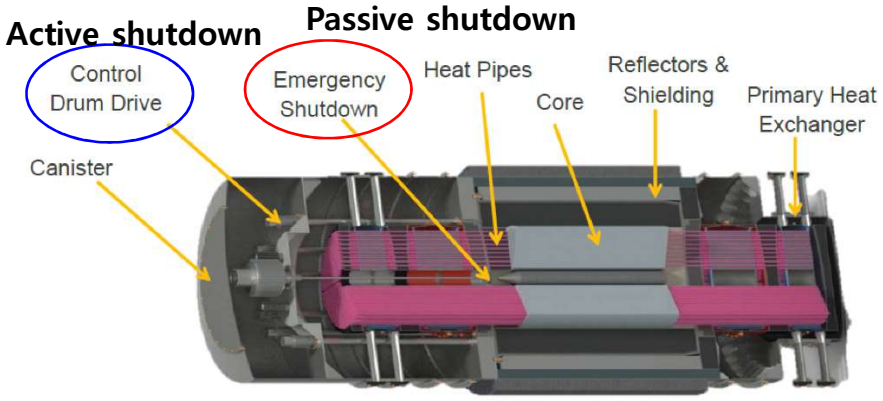
INL, "Special Purpose Nuclear Reactor (5MW) for Reliable Power at Remote Sites Assessment Report" (2017)

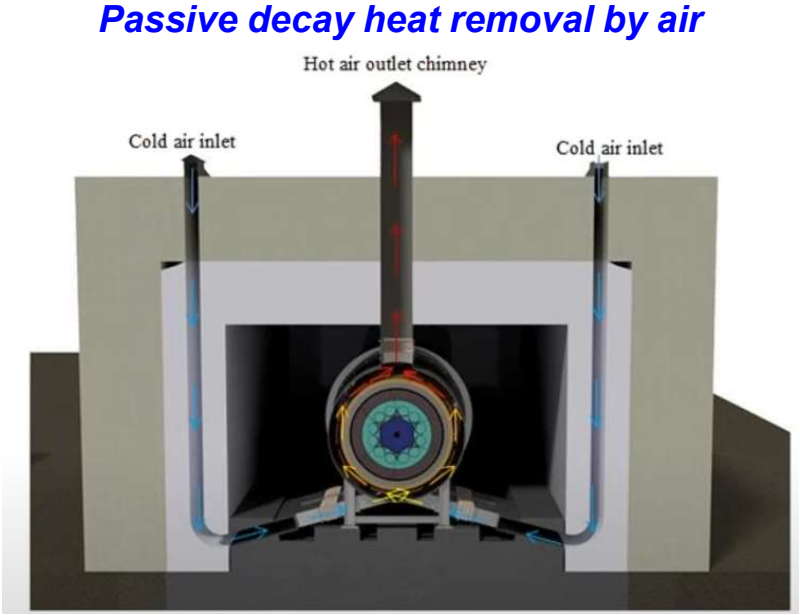
1. 히트파이프 냉각 원자로 연구개발 현황

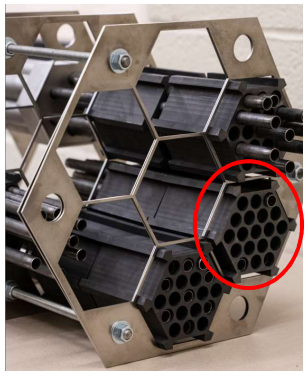
Westinghouse – eVinci Micro Reactor

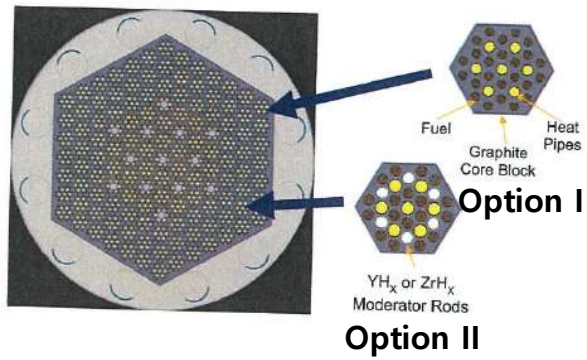
❖ eVinci Micro Reactor, Westinghouse

- 14 MW_{th} / 5 Mw_e 히트파이프 냉각 초소형 원자로
- Horizontal type(Transportable), Thermal spectrum
- 상업운전 2027년 계획, 미국/캐나다 인허가 기관이 설계 검토 중









Swartz, Matt M., et al. "Westinghouse eVinci™ Heat Pipe Micro Reactor Technology Development." International Conference on Nuclear Engineering, (2021)

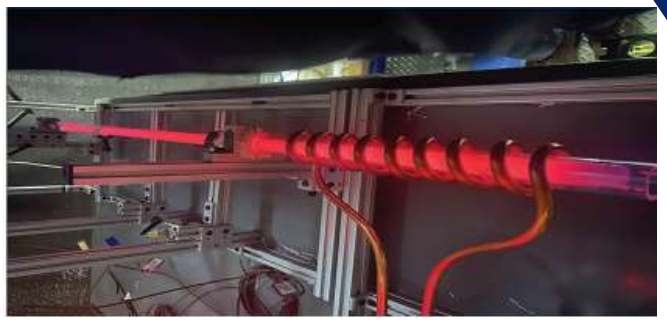
Westinghouse, "ENS webinar Micro reactor technology applications Westinghouse Electric Company" *(2019)*

1. 히트파이프 냉각 원자로 연구개발 현황

Westinghouse – eVinci Micro Reactor

❖ eVinci Micro Reactor, Westinghouse

- **FeCrAl alloys** → High operating temperature(~850°C)
- Manufacturing studies → Long alkali metal heat pipes up to 4m.
- **Cellular design of core** → Symmetric, Simplify demonstration
- **Start up and endurance test** (2850 hours)



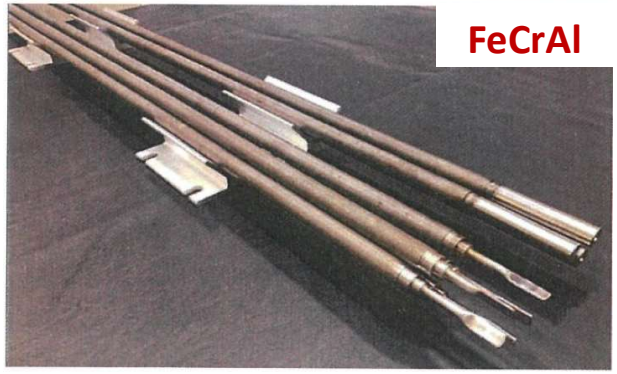
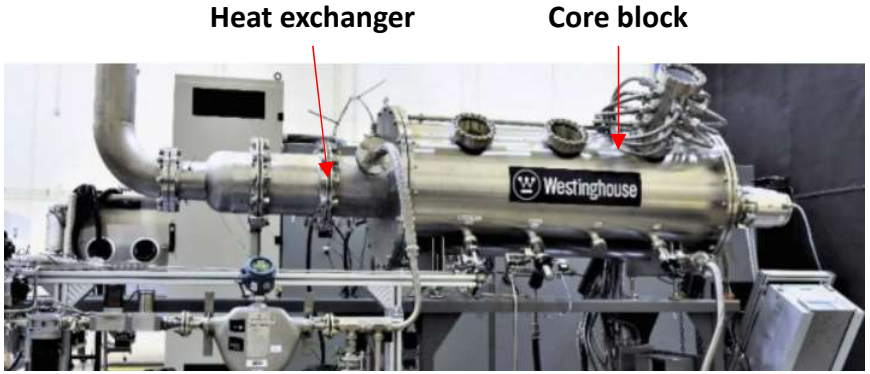


Fig. FeCrAl alkali metal heat pipe for high operating temperature



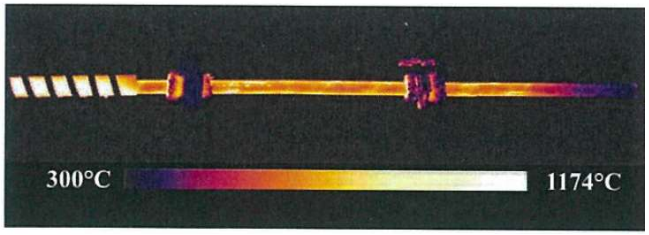


Fig. Thermal image **of** FeCrAl alkali metal heat pipe operated at 800°C (1.2m)

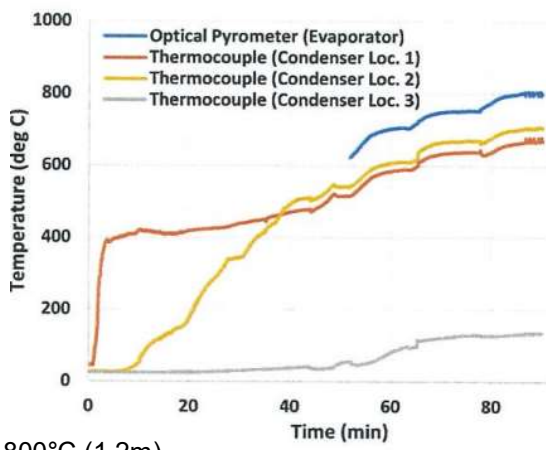


Fig. Startup performance of Heat pipe

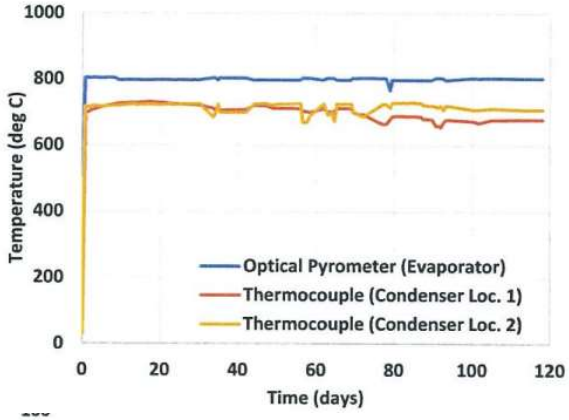


Fig. Duration test of Heat Pipe (2850 hours)

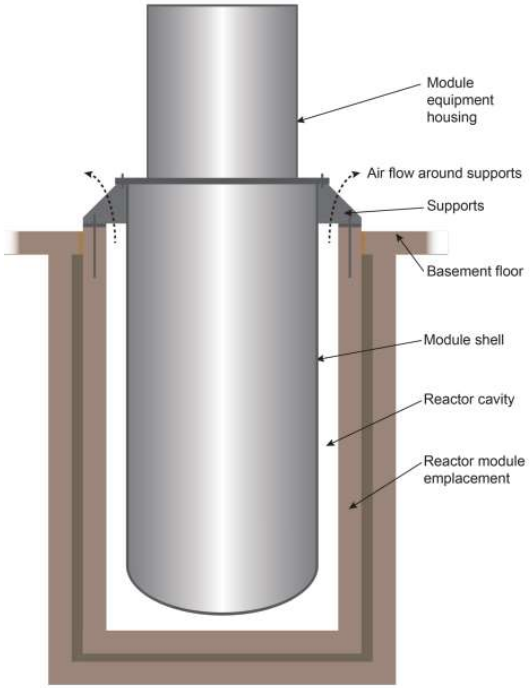
Swartz, Matt M., et al. "Westinghouse eVinci™ Heat Pipe Micro Reactor Technology Development." International Conference on Nuclear Engineering, (2021)

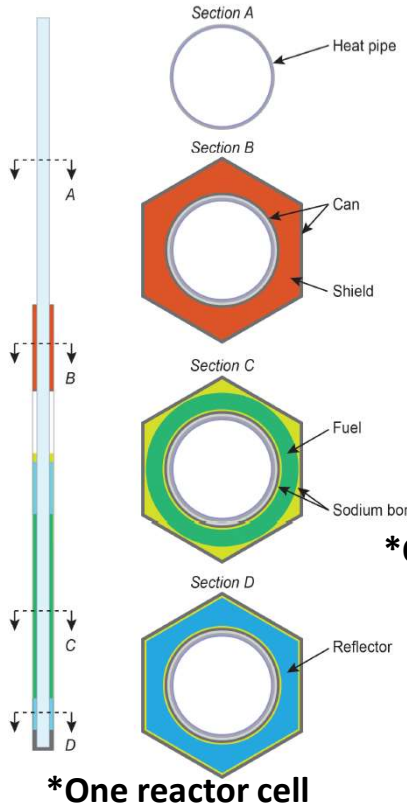
Westinghouse, "ENS webinar Micro reactor technology applications Westinghouse Electric Company" *(2019)*

Oklo- Aurora

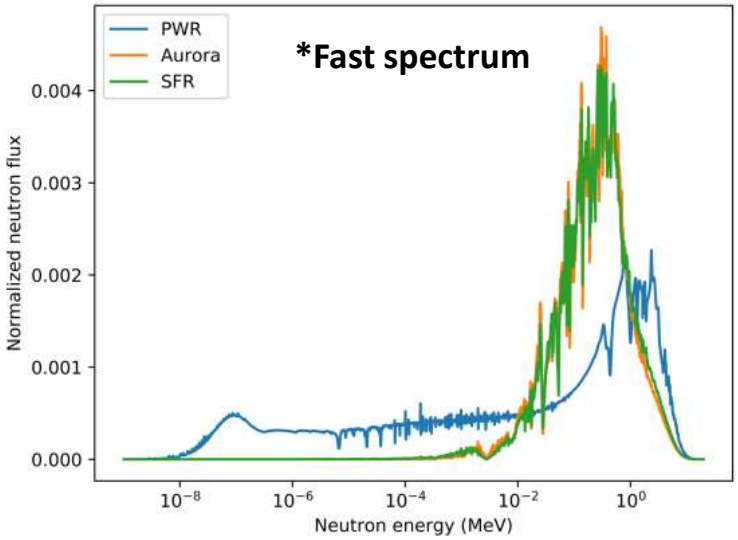
❖ Aurora powerhouse

- 4 MW_{th} / 1.5 Mw_e 히트파이프 냉각 초소형 원자로
- Vertical type(Stationary), Fast spectrum
- **Reactor cell type:** One heat pipe per one fuel can (total 114 heat pipes)





*One reactor cell



***Operating temperature range: 505-550°C (base: 540 °C)**

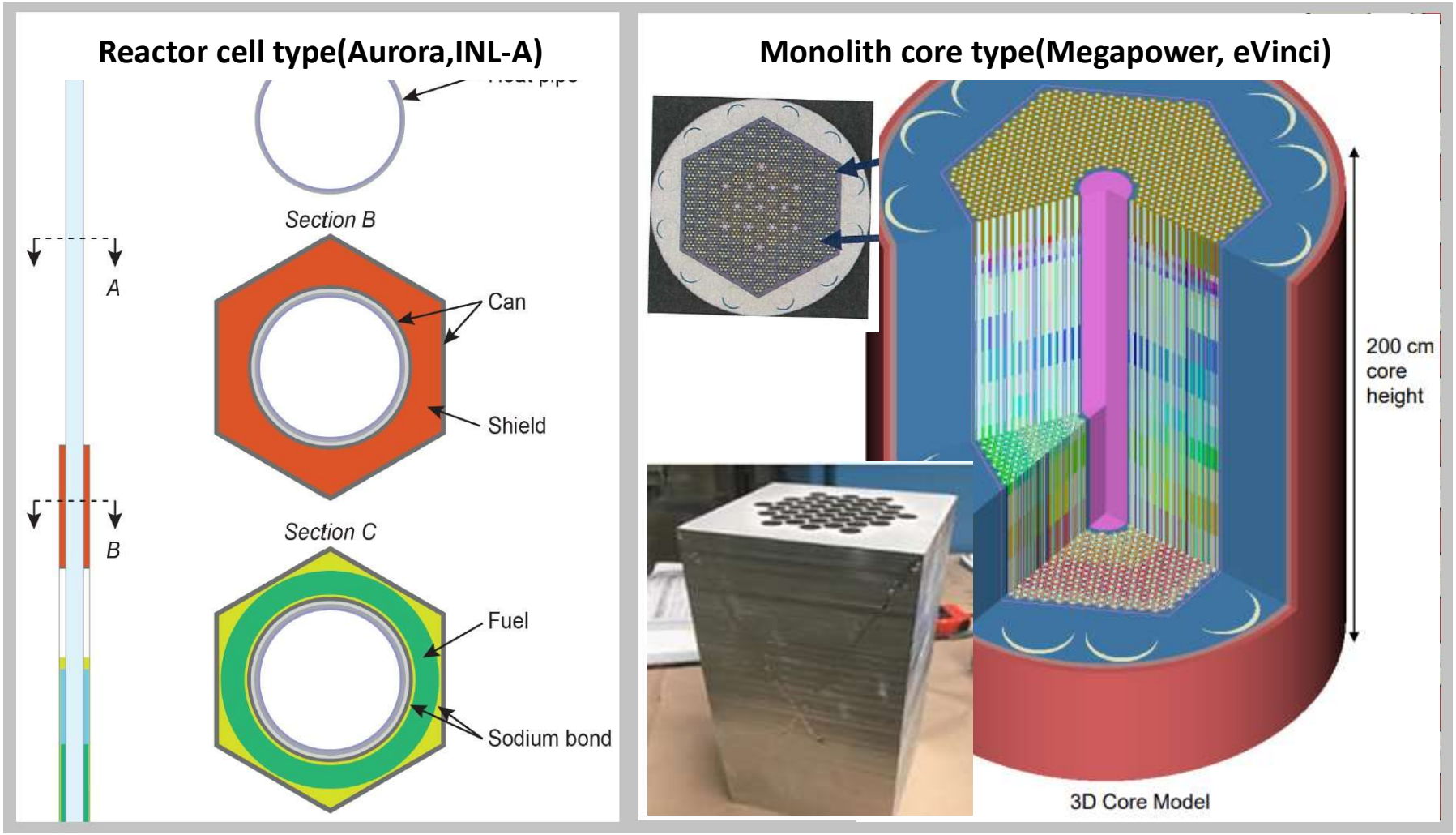
T_{fuel}=720°C (**operating limit)** due to eutectic formation.

Channel	Setpoint type	Setpoint value	Number of channels monitored
Heat pipe temperature channel	upper limit (Δ from nominal)	+15 C	342
Heat pipe temperature channel	lower limit (Δ from nominal)	-35 C	342
Reactor thermal power	upper limit	4.2 MW	2
Reactor period	lower limit	5 s	2

OKLO POWER, "Part II: Final Safety Analysis Report," U.S. Nuclear Regulatory Commission (2020)

Oklo- Aurora

- **No Monolith core type**: Reduce thermal stress
- **Monolith core type**: Strong negative reactivity feedbacks



OKLO POWER, "Part II: Final Safety Analysis Report," U.S. Nuclear Regulatory Commission (2020)

원자력 히트파이프 인허가 연구의 필요성

➢ Reactor Accident and Normal Operations PIRT / Heat Pipe PIRT

Issue	Importance	Knowledge Level	Comments
HP performance due to neutron irradiation	H	M	>Potassium HP database under irradiation conditions does not exist
Reactor starts up from a cold state with HPs not functioning	M	L	**>Limited experience database**
HP performance over range of operating temperatures	M	M	**>Aspect ratio of HPs is a potential area for experimental verification** >HP test program would provide an operational database
Loss of 1 HP / 2 HPs / 3 HPs	L	M	>Increase local fuel temperature, HP cascading loss effect **>Limited experimental data**
Cascading HP failure	H	M	>The relationship between the failed HP and monolith needs to be better understood
Crack initiation and substantial crack growth (into HP)	H	M	>If HP fails, insufficient data exists to show the integrity of HP wall relative to the increase in temperature and stresses
Loss of fluid of HP	M	L	**>Performance of HP in nuclear systems needs to be addressed.**
Breach (Loss of strength/deformation)	M	M	**>Limited information is available for HP reactor design** >Additional modeling and testing are required to determined the effect of a failed HP on component performance
Oxide deposition	L	H	>Material aging and Effects of exposure of HP at operating temperature need to be evaluated

원자로 적용 히트파이프 실험적 DB 부족

INL, "Special Purpose Nuclear Reactor 95MW) for Reliable Power at Remote Sites Assessment Report" (2017)

2. 원자력 히트파이프 연구의 필요성

Oklo – Aurora (히트파이프 냉각 원자로 라이선스 신청)

- *원자로 안전성 관련 정보 제공 미흡*
- *원자로 설계 여유도 평가 방법 모호*

"Denial of the Aurora Combined operating License Application"

"...Oklo has repeatedly failed to provide substantive information... on the maximum credible accident(MCA) for the Aurora design, the safety classification of structures, systems, and components(SSC)..."

"...The topical reports are vague about how to determine and implement proper treatment of uncertainties, appropriate design margins, and adequate defense-in-depth..."

NRC, "OKLO INC. - DENIAL OF THE AURORA COMBINED OPERATING LICENSE APPLICATION FOR FAILURE TO SUPPLY INFORMATION (EPID L-2020- NEW-0004 AND EPID L-2020-NEW-0005)" (2022)

Oklo – Aurora (히트파이프 냉각 원자로 라이선스 신청)

2020.03.11 Oklo project 신청

*"...기존 신청 지침은 **대형 LWR**에 의거해 있지만, NRC는 이 신청서를 따르는 것을 요구하지는 않았다...."*

2020.07.31 Oklo → NRC에 긴급 청원 제출

NRC에서 안전 이슈에 대한 자세하고 추가적인 계산, 분석 요구

→ NRC에서는 Oklo가 제안한 원자로에 대한 안전 문제에 대한 표준이나 요구 사항이 아직 개발되지 않음

→ Oklo에 대한 maximum credible accident(MCA), classification of structures, systems and components(SSCs), Quality Assurance(QA) 등에 대한 기준이 설립되지 않음

→ Oklo는 첫번째 "advanced" 또는 non-LWR 원자로이다. Oklo의 절차는 추후 다른 SMR, HTGR, micro-reactor에도 영향을 미칠 것이기 때문에 검토가 필요하다.

➢ ***히트파이프 냉각 원자로에 대한 정확한 안전성 검토 기준 설립 필요***

Oklo Power, "UNITED STATES OF AMERICA NUCLEAR REGULATORY COMMISSION BEFORE THE COMMISSION, Emergency petition by beyond nuclear..", Docket No. 52—49-COL, July 31 (2020)

원자력 히트파이프 실험적 연구의 중요성 – 인허가 이슈

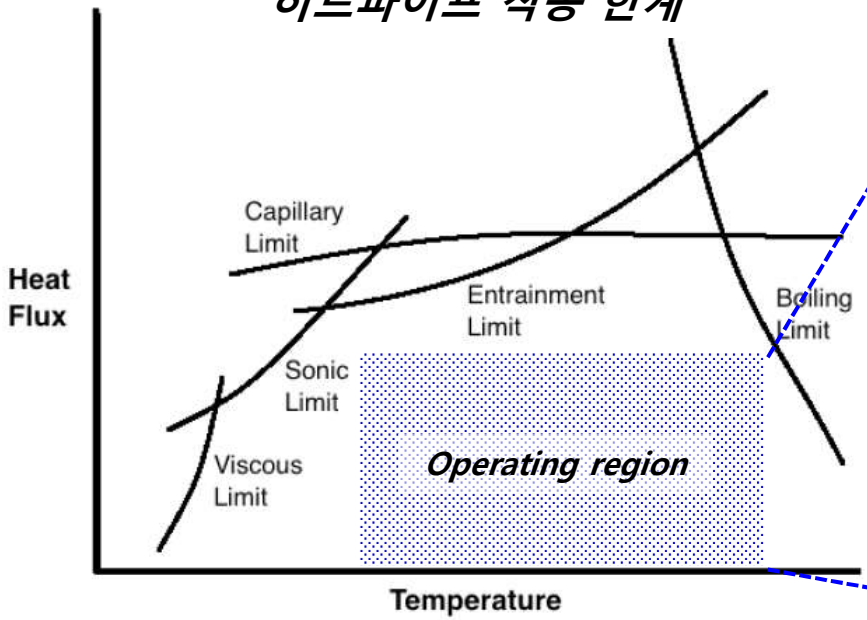
❖ 원자력 활용을 위한 히트파이프 기술 채택 활발 및 새로운 설계/인허가 문제 등장

➢ 정확한 히트파이프 열적 limit 예측

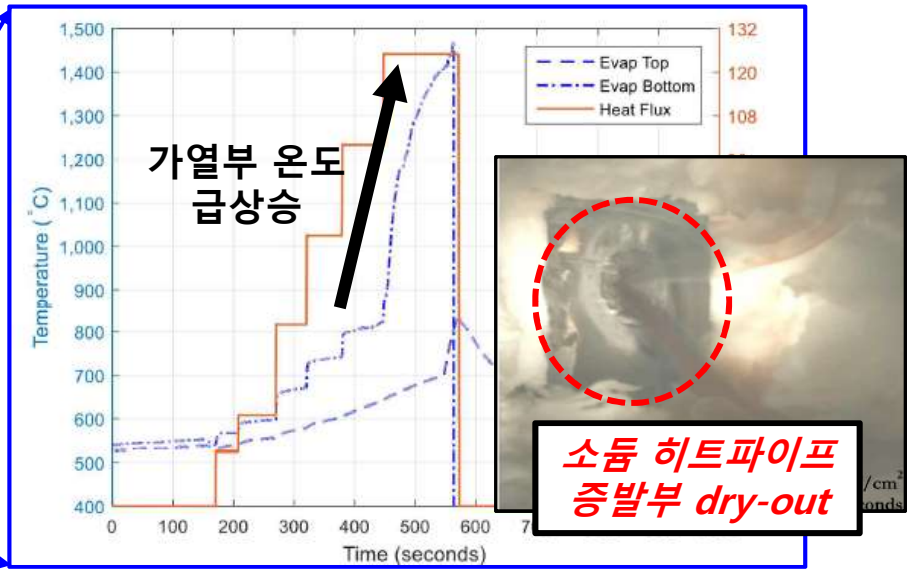
➢ 단일 히트파이프 성능 향상을 통한 열적 limit 증진

➢ 다양한 온도 범위 / 길이 스케일의 원자력 활용 Heat pipe DB 제공

히트파이프 작동 한계



소듐 히트파이프 작동 한계 초과



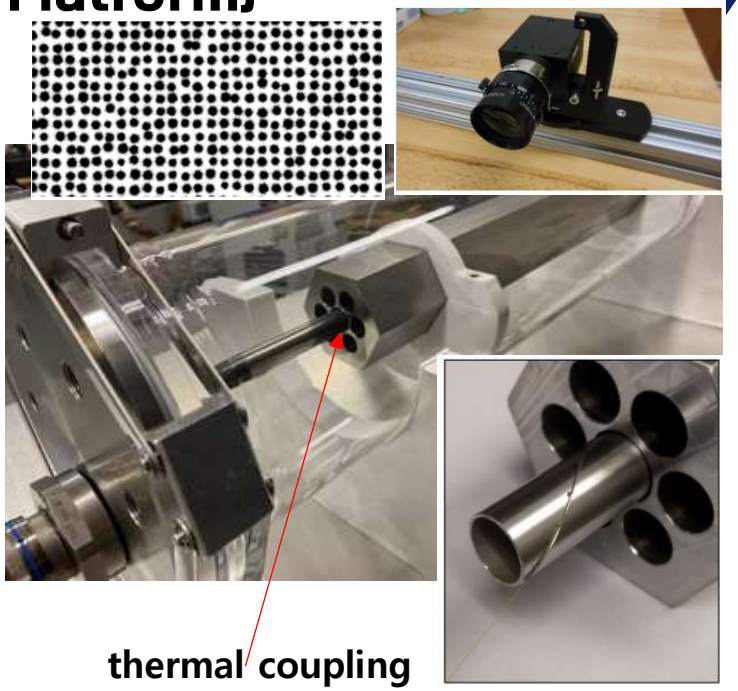
A. J. Clark, "Failures and Implications of Heat Pipe Systems", Sandia National Laboratories, SAND2019-11808 (2019)

INL – SPHERE, MAGNET (Non-Nuclear Test Platform)

❖ DOE Microreactor Program

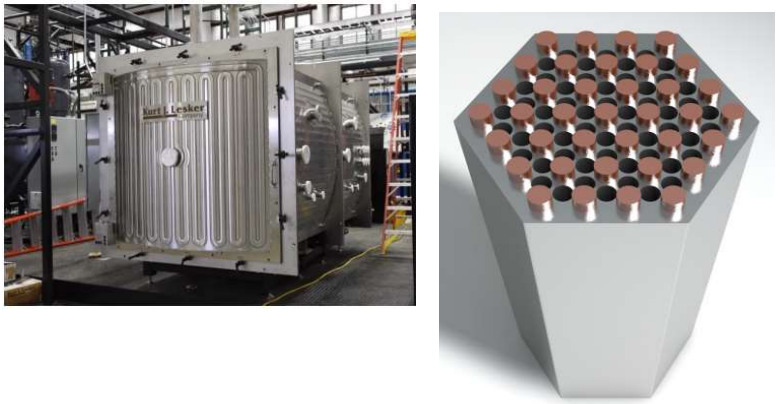
➢ SPHERE (Single Primary Heat Extraction and Removal Emulator)

- 단일 HP 성능 실험 (2kW electrical power)
- HP startup , transition operation
- HP 외벽과 노심 블록, 히터 간의 thermal coupling method 개발
- Validation of sensing technologies



➢ MAGNET (Microreactor Agile Non-Nuclear Experimental Test Bed)

- Integration test (interface with PCU, HX)
- Multiple heat pipes test (structural integrity)
- Demonstrate additive technology (sensor, 3D) printing)



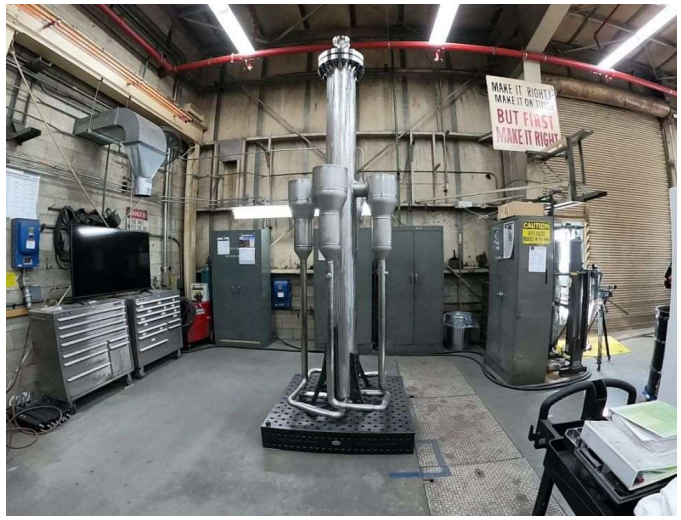
INL, "DOE Microreactor Program: Summary of Experimental Capabilities Development and Activities" INL/EXT-20-60441 *(2021)*

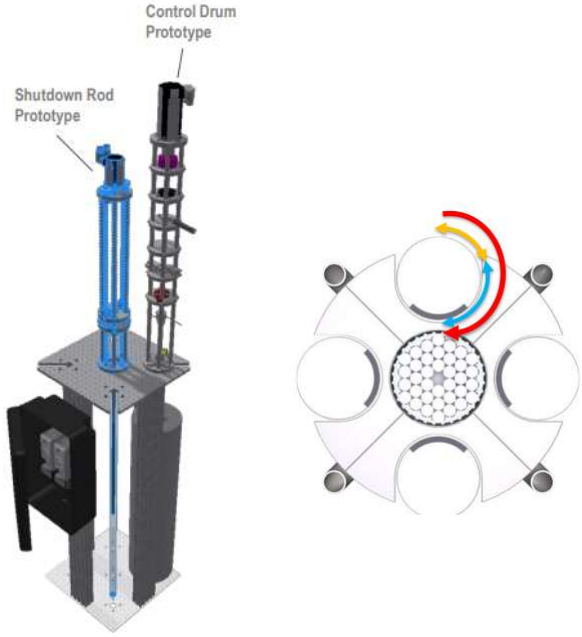
INL – MARVEL (Nuclear Test Platform)

❖ DOE Microreactor Program

➢ MARVEL (Microreactor Applications Research Validation and Evaluation)

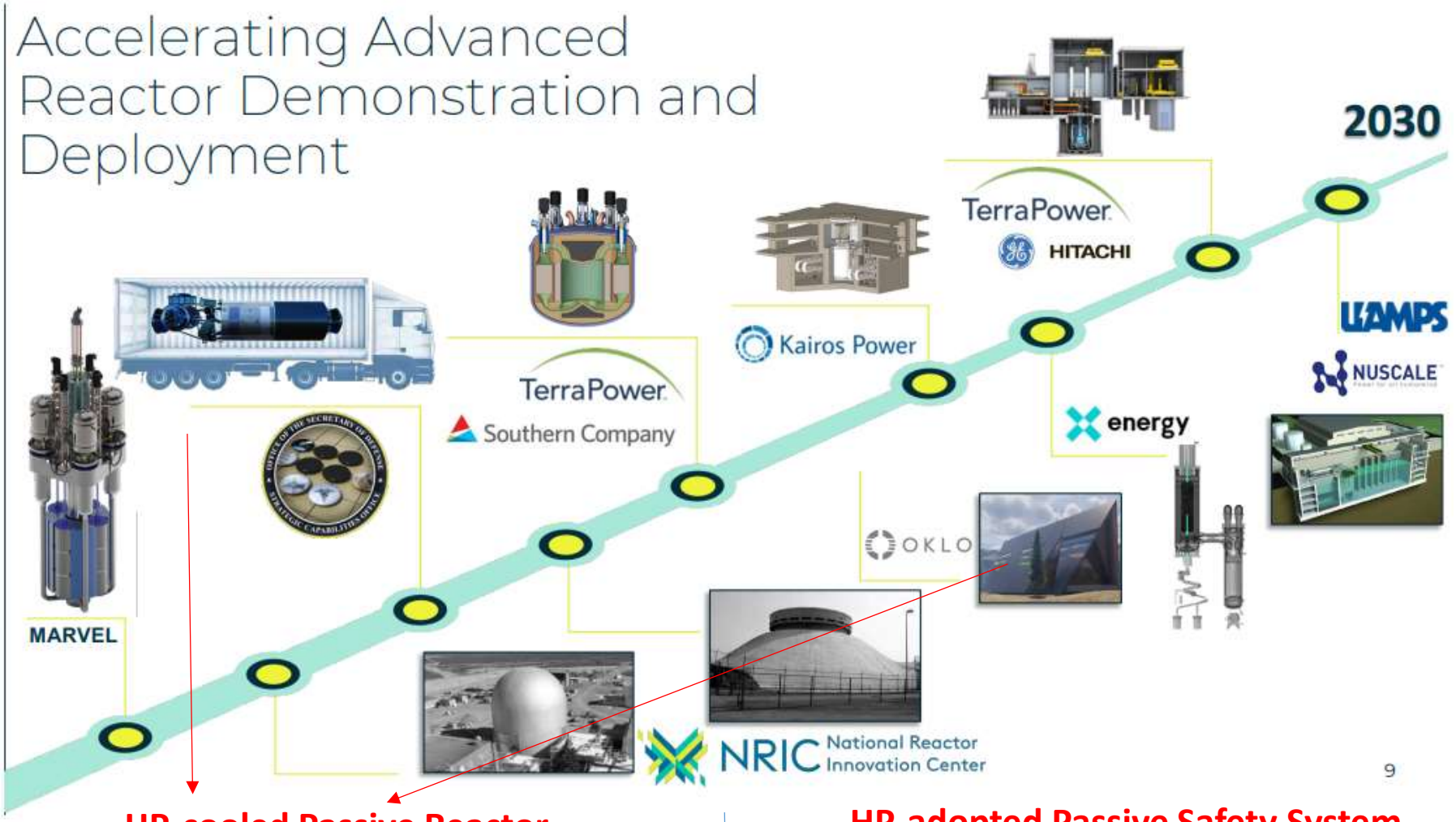
- Control systems manage test (Control drum, Shutdown rod)
- Investigate diverse electrical and thermal applications
- Evaluate autonomous technology





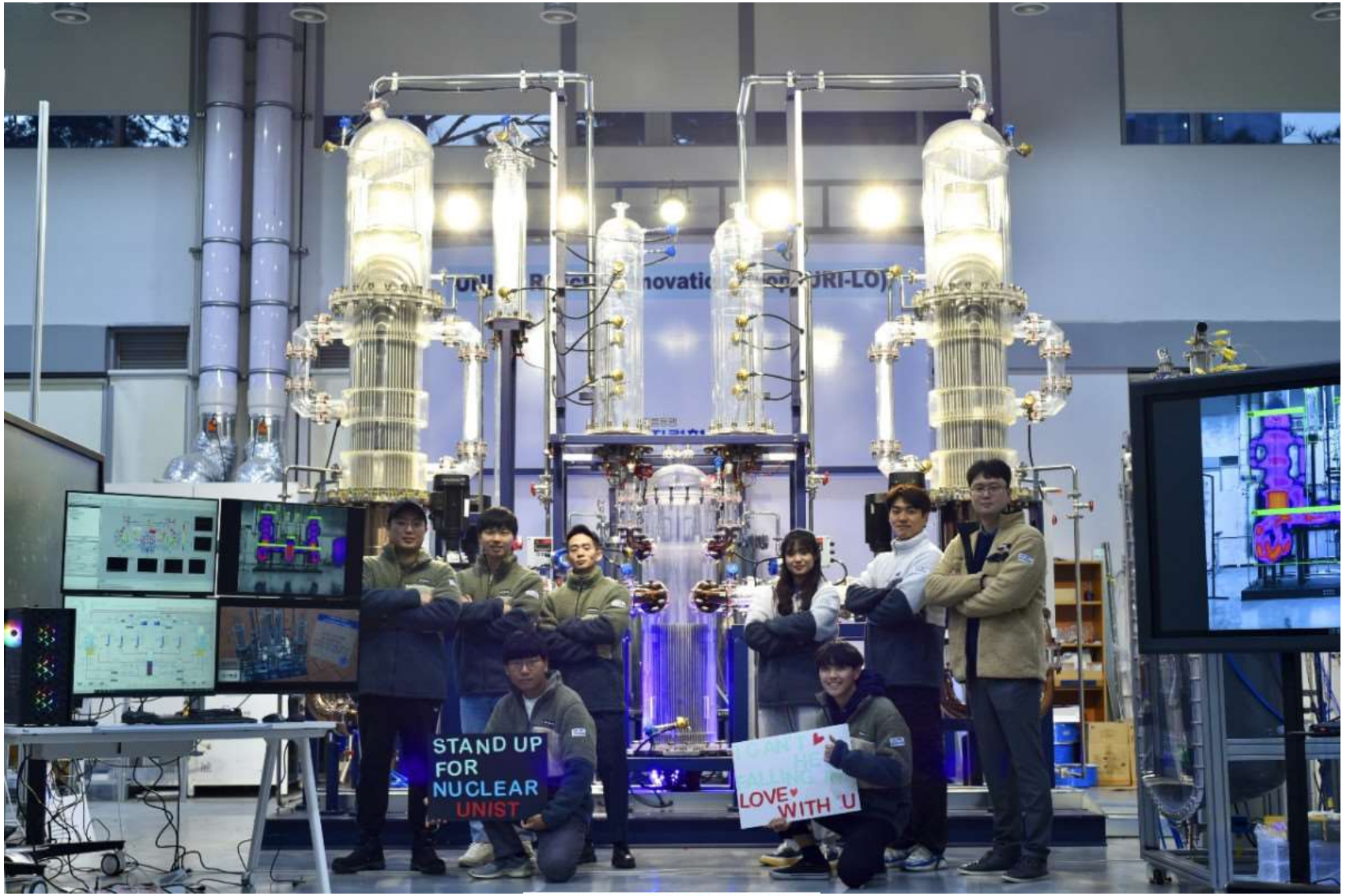
INL, "DOE Microreactor Program: Summary of Experimental Capabilities Development and Activities" INL/EXT-20-60441 *(2021)*

열유체분야가 혁신을 이끄는 진화하는 원자로:
HP-cooled Passive Reactor and HP-adopted Passive Safety System 채택



Modified from "What's on the Horizon – Overview of Advanced Nuclear National Governor's Association Learning Collaborative November 10, 2021 Ashley E. Finan, Ph.D., NRIC director"

경청해 주셔서 감사합니다.



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