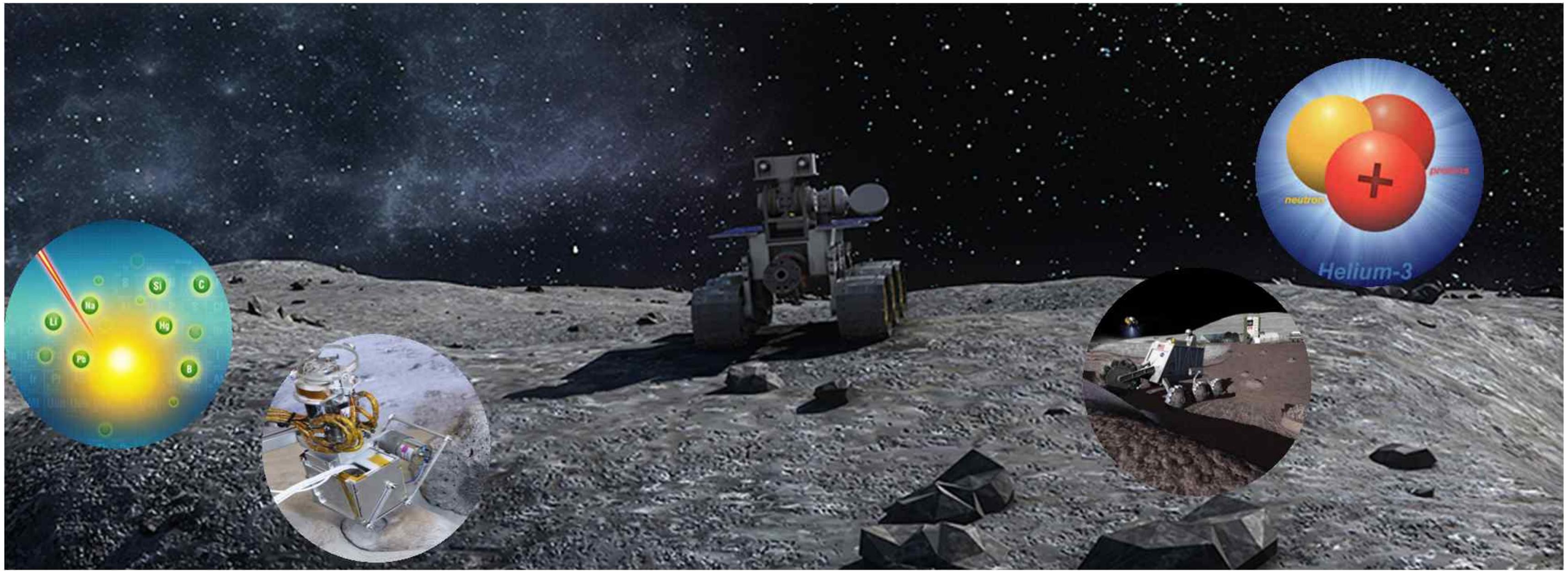
우주자원개발 계획 및 원자력 활용을 위한 정책과제

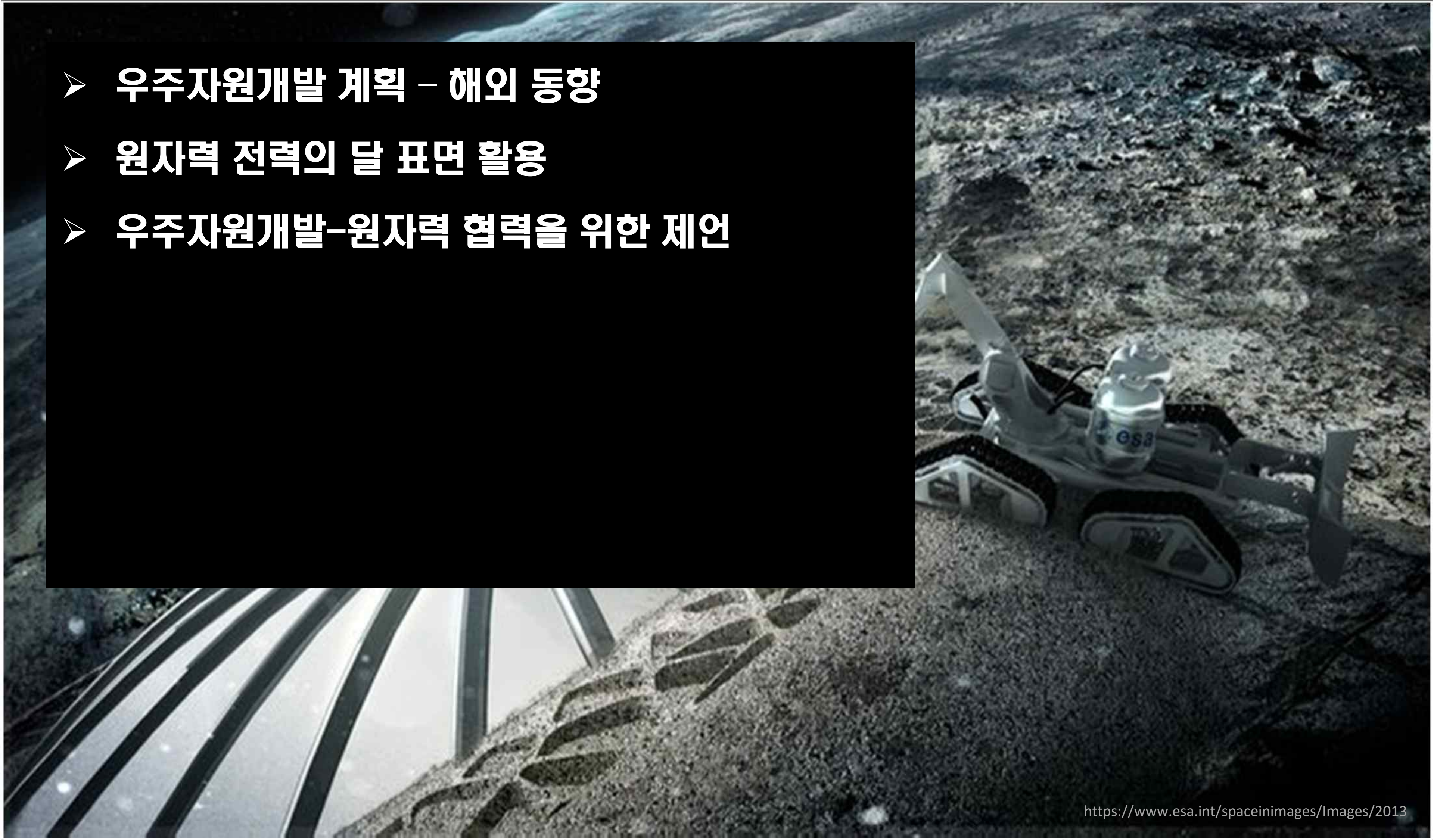


김경자
우주자원개발센터장/국토우주지질연구본부
한국지질자원연구원

발표 순서

KIGAM

- 우주자원개발 계획 – 해외 동향
- 원자력 전력의 달 표면 활용
- 우주자원개발-원자력 협력을 위한 제언



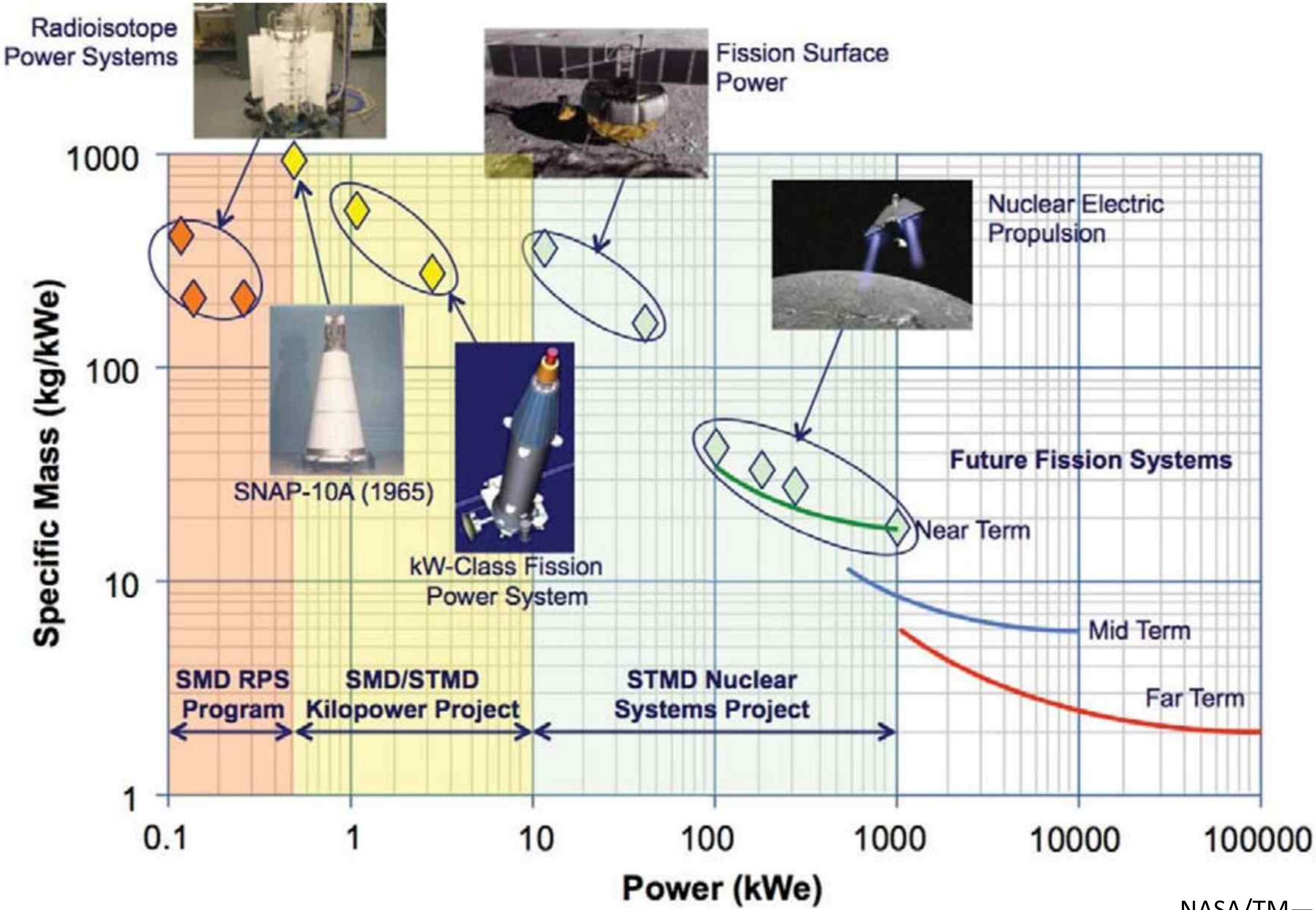
https://www.esa.int/spaceinimages/Images/2013

우주탐사와 전력 관련 NASA의 투자 현황

KIGAM

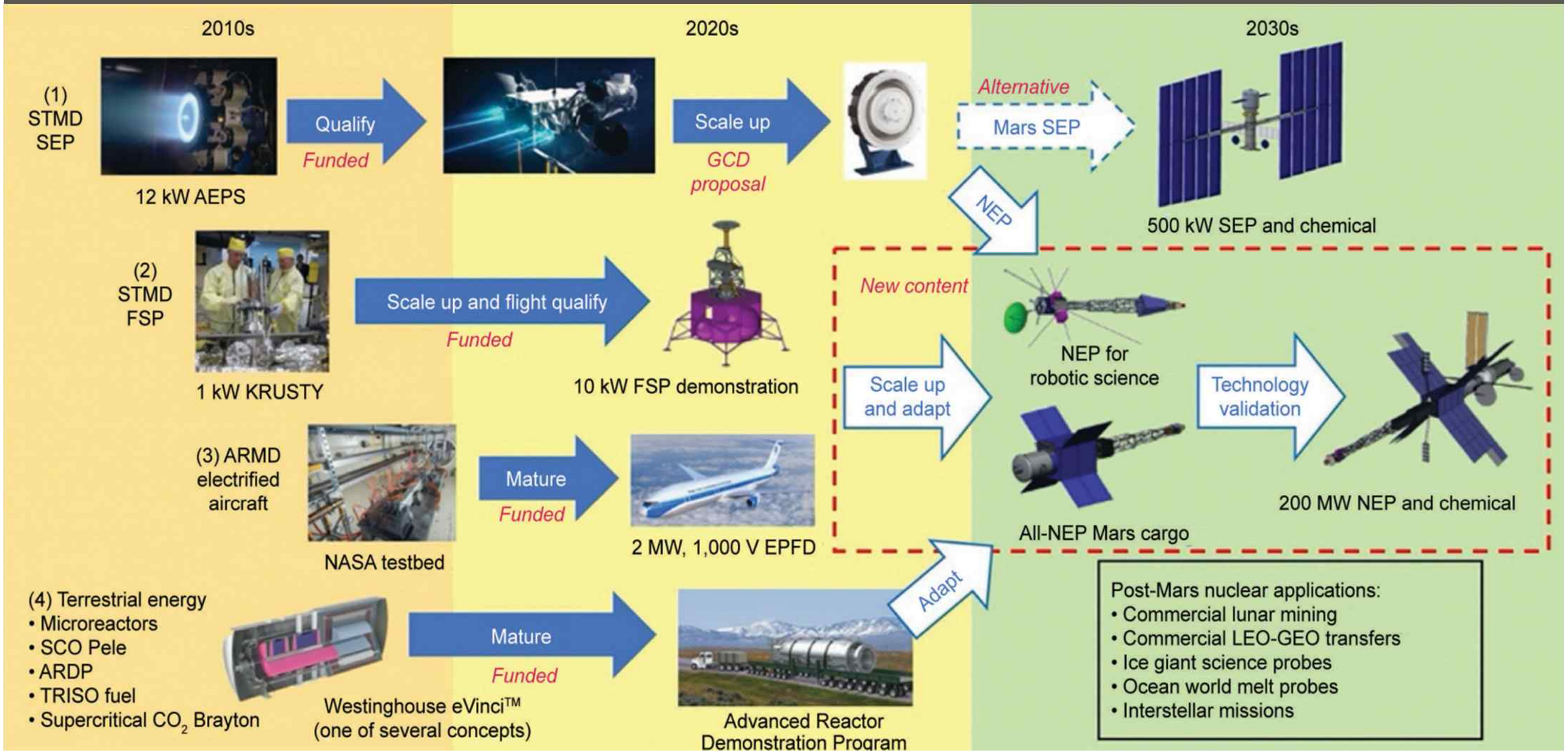
- **Space Technology Mission Directorate (STMD) – Game Changing Investments**
  - ✓ Nuclear Systems – Krusty/Kilopower (2012 – present)
  - ✓ Regenerative Fuel Cell Project (2018 – present)
  - ✓ Extreme Environment Solar Power Project (2015 – present)
  - ✓ Lunar Lander Fuel Cells ACO & Tipping Point [Blue Origin] (2020 – TBD)
  - ✓ Flexible Solar Arrays qual Protocols ACO [Maxar] (2020 – TBD)
  - ✓ Adaptable Lunar Lander Solar Array Systems Study (2019 – 2020)
  - ✓ Solar Arrays With Storage Seedling Study (2017)
  - ✓ Advanced Space Power Systems (2012-2015)
  - ✓ Solar Electric Propulsion Solar Array Systems [MegaFlex, ROSA] (2012-2015)
- **Space Technology Science Mission Directorate (SMD) Investments**
  - NextGen RTGs
  - Dynamic RPS
- **Human Exploration and Operations Mission Directorate (HEOMD) Investments**
  - Advanced Modular Power Systems
  - Autonomous Power Control
  - Non-Flow-Thru Fuel Cell Advancement

우주 원자력 전력 성능



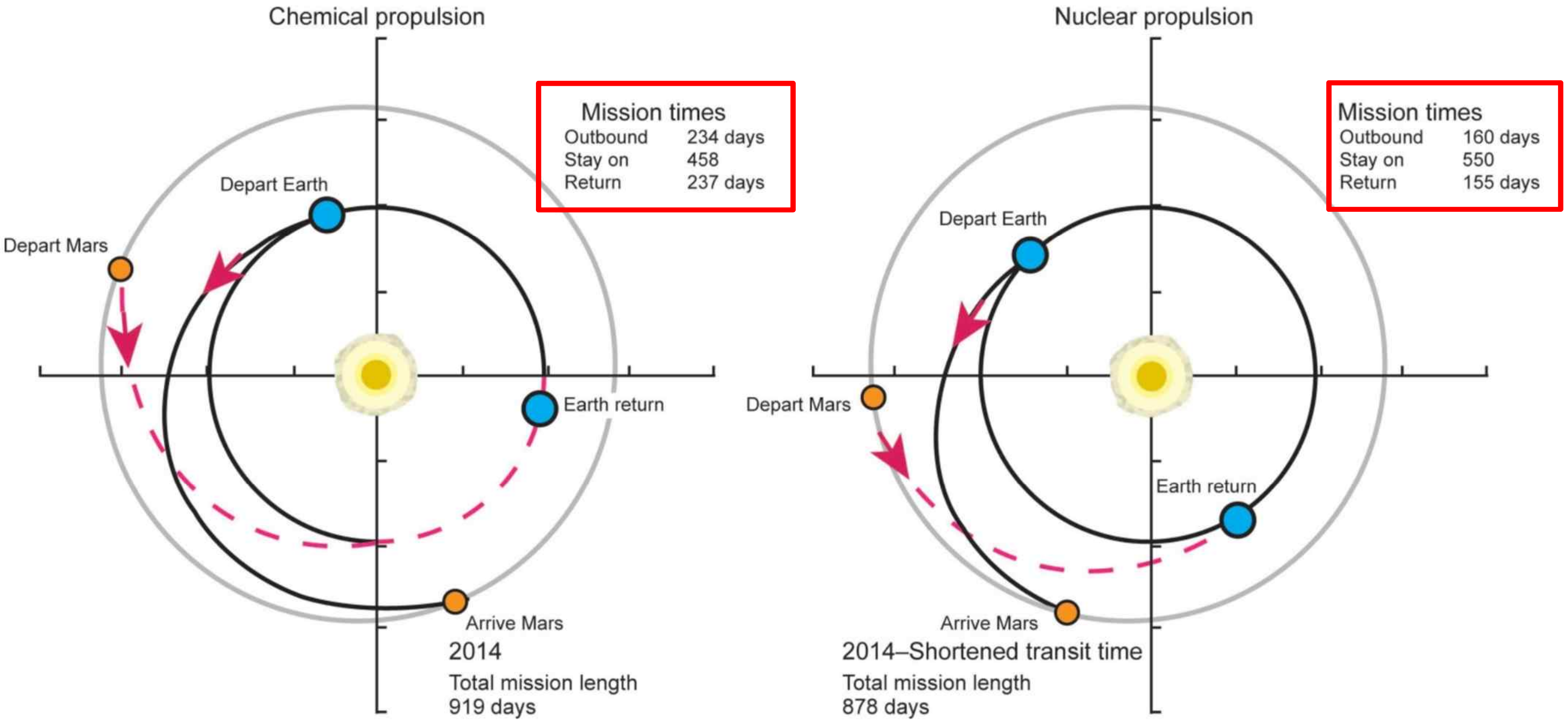
NASA/TM—2013-216541

원자력전기추진(NEP) 기술 로드맵



(1) Advanced Electric Propulsion System (AEPS) development by Space Technology Mission Directorate (STMD) for solar electric propulsion (SEP) applications. PPE is power and propulsion element and GCD is Game Changing Development. (2) STMD Fission Surface Power (FSP) project; KRUSTY is Kilopower Reactor Using Stirling Technology. (3) Aeronautics Research Mission Directorate (ARMD) Electrified Powertrain Flight Demonstration (EPFD) project. (4) Department of Energy and Department of Defense terrestrial activities. SCO Pele refers to Strategic Capabilities Office Project Pele, ARDP is Advanced Reactor Demonstration Program, and TRISO is tristructural isotropic.

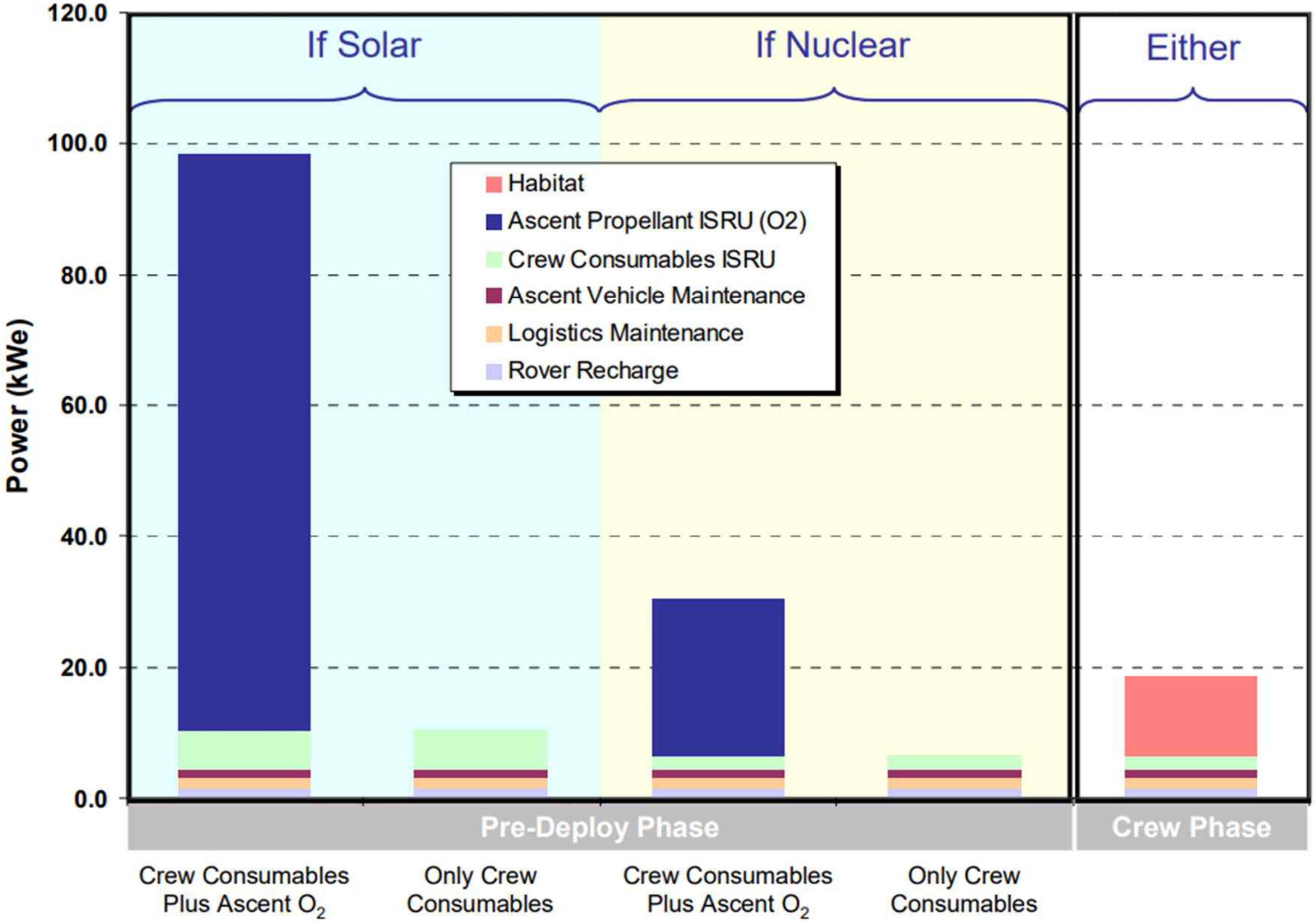
화학 대비 원자력 추진 시스템



Campbell et al. 2013

태양(Solar) 대비 원자력(Nuclear) 전력 옵션

소모 전력 예측

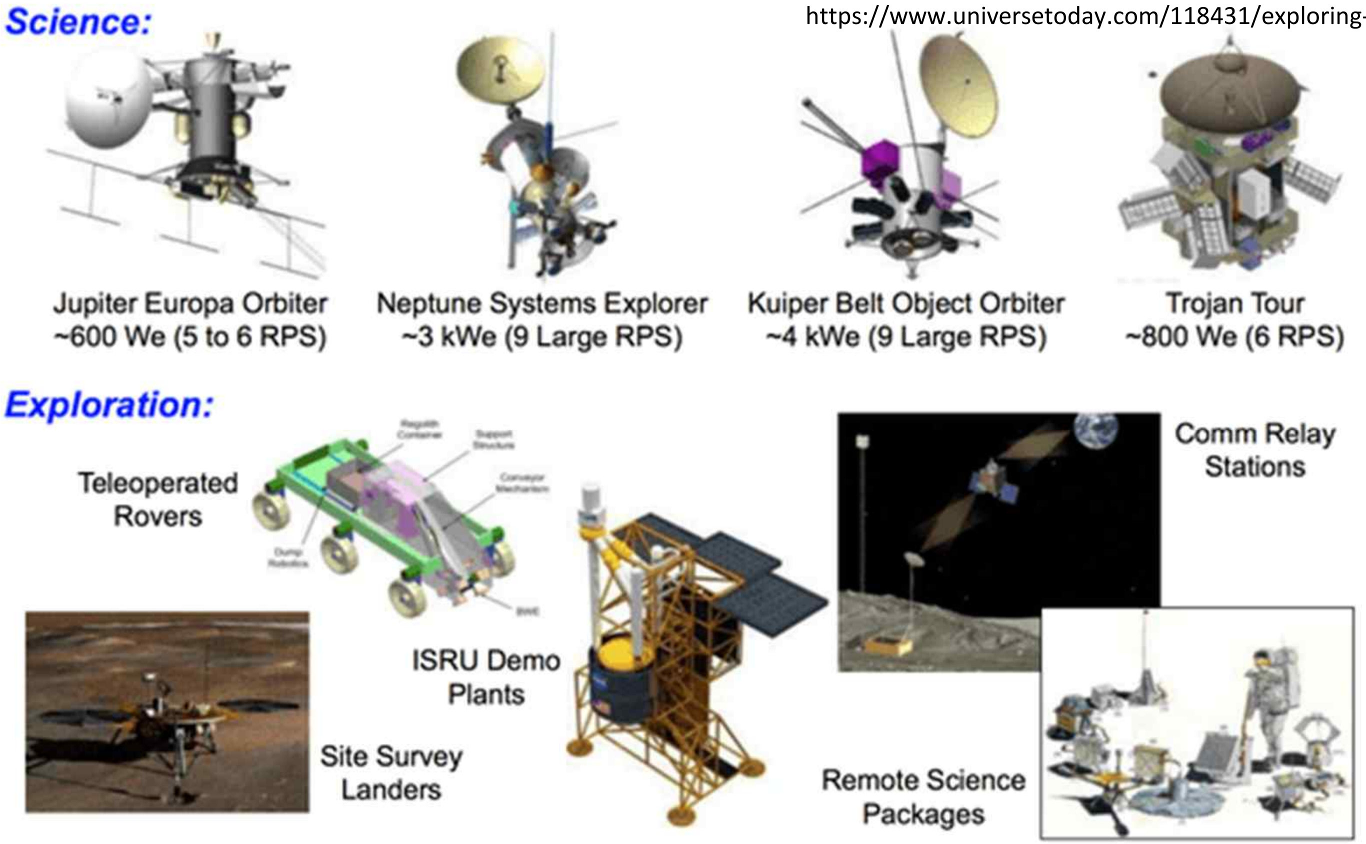


NASA 제안들 : 원자력 전력탐사

KIGAM

https://www.universetoday.com/118431/exploring-the-universe-with-nuclear-power/

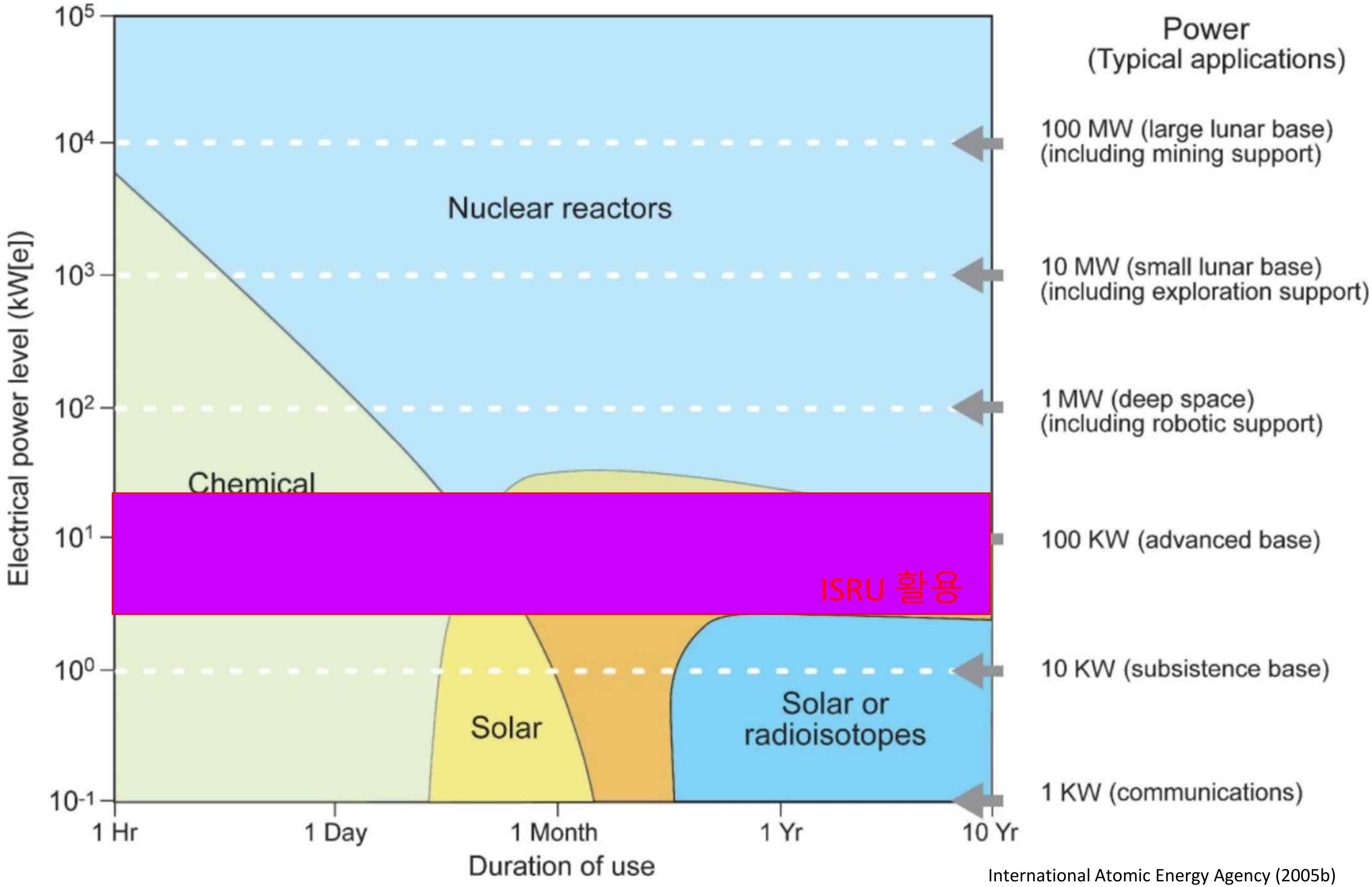
Credit: NASA



- **Concept for a "bimodal" rocket** : chemical propellants to achieve orbit & nuclear-thermal engine for propulsion
- NASA's plans to explore Mars by allowing for **the reliable delivery of high-mass automated payloads in advance of manned missions.**

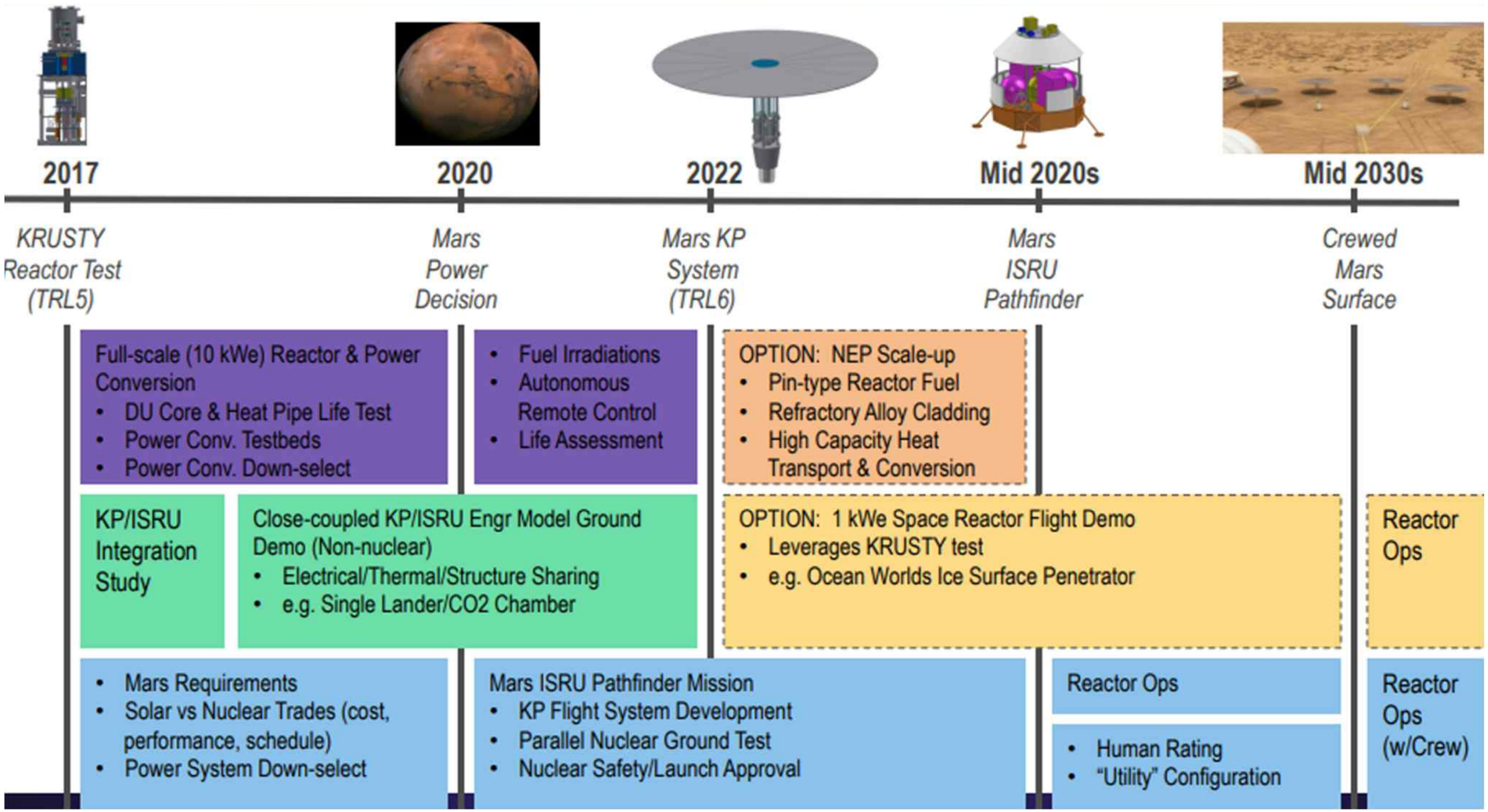
우주미션의 전력 공급원 비교

KIGAM



International Atomic Energy Agency (2005b)

NASA의 ISRU 활용 목표 원자로 개발 로드맵



Mcclure, Patrick Ray @LANL

원자력 추진체, 달-화성표면 ISRU 표면 전력 공급

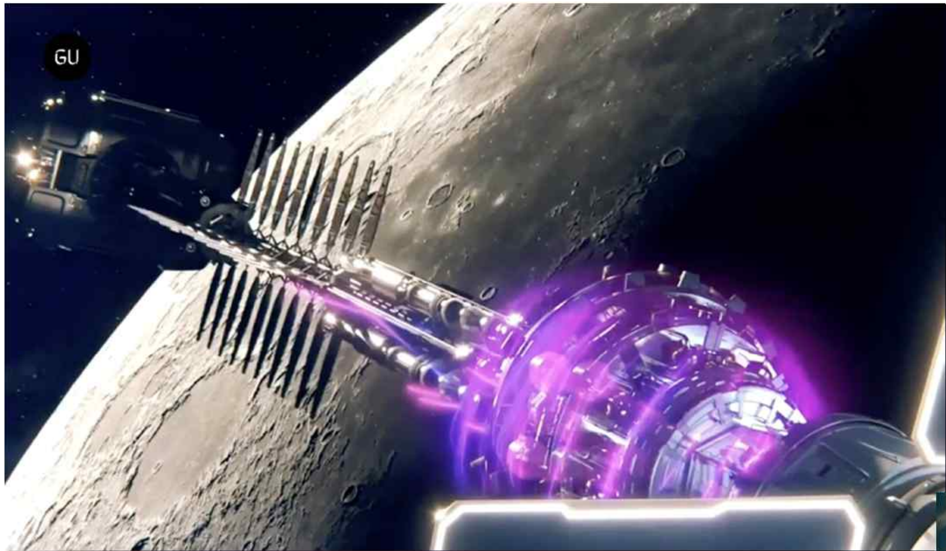
달 ISRU 표면활동(부지 특성·자원조사 준비) KIGAM

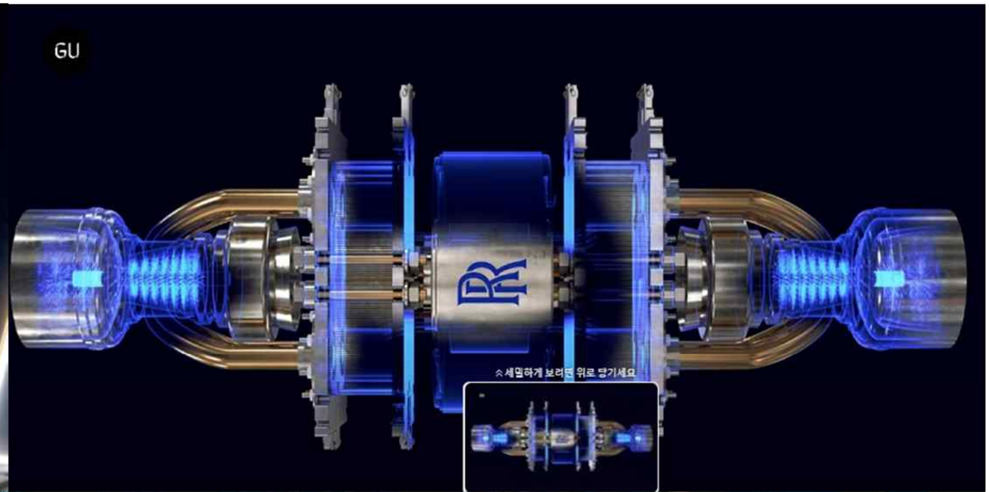
https://youtu.be/_Gx2jcpRiik?list=TLGGLZoICiGZ3UMwOTEwMjAyMw

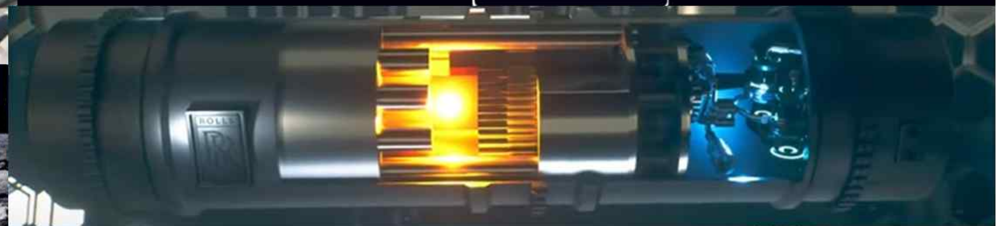
Rolls Royce : 달 원자로 설치 계획 및 기술개발

Rolls-Royce : ‘29 원자로 설치, UK SA

‘30 마이크로 반응로





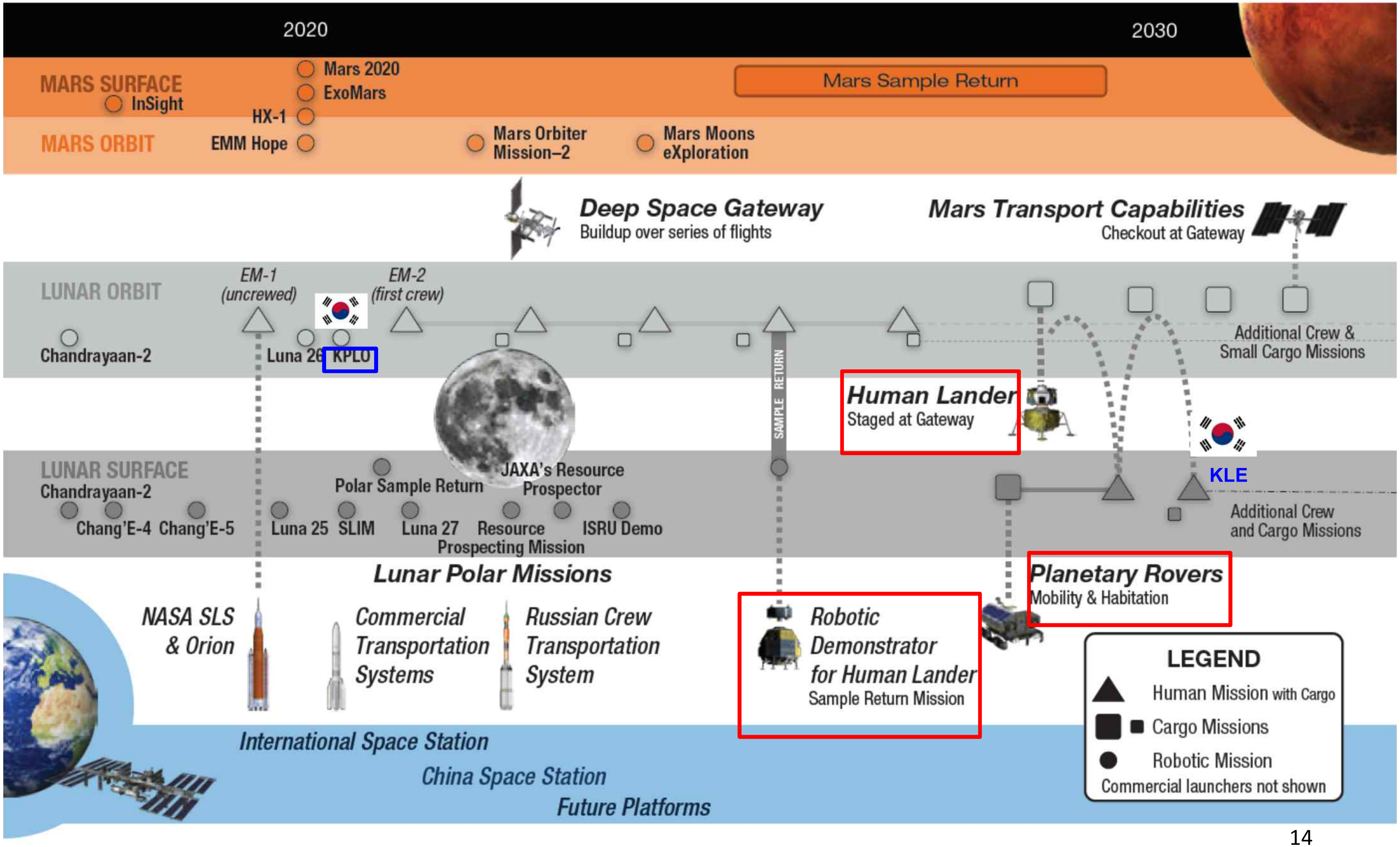


https://www.youtube.com/watch?v=EiP4wocRp3g

ISECG (국제우주탐사협의체) 미션 시나리오

KIGAM

ISECG Mission Scenario

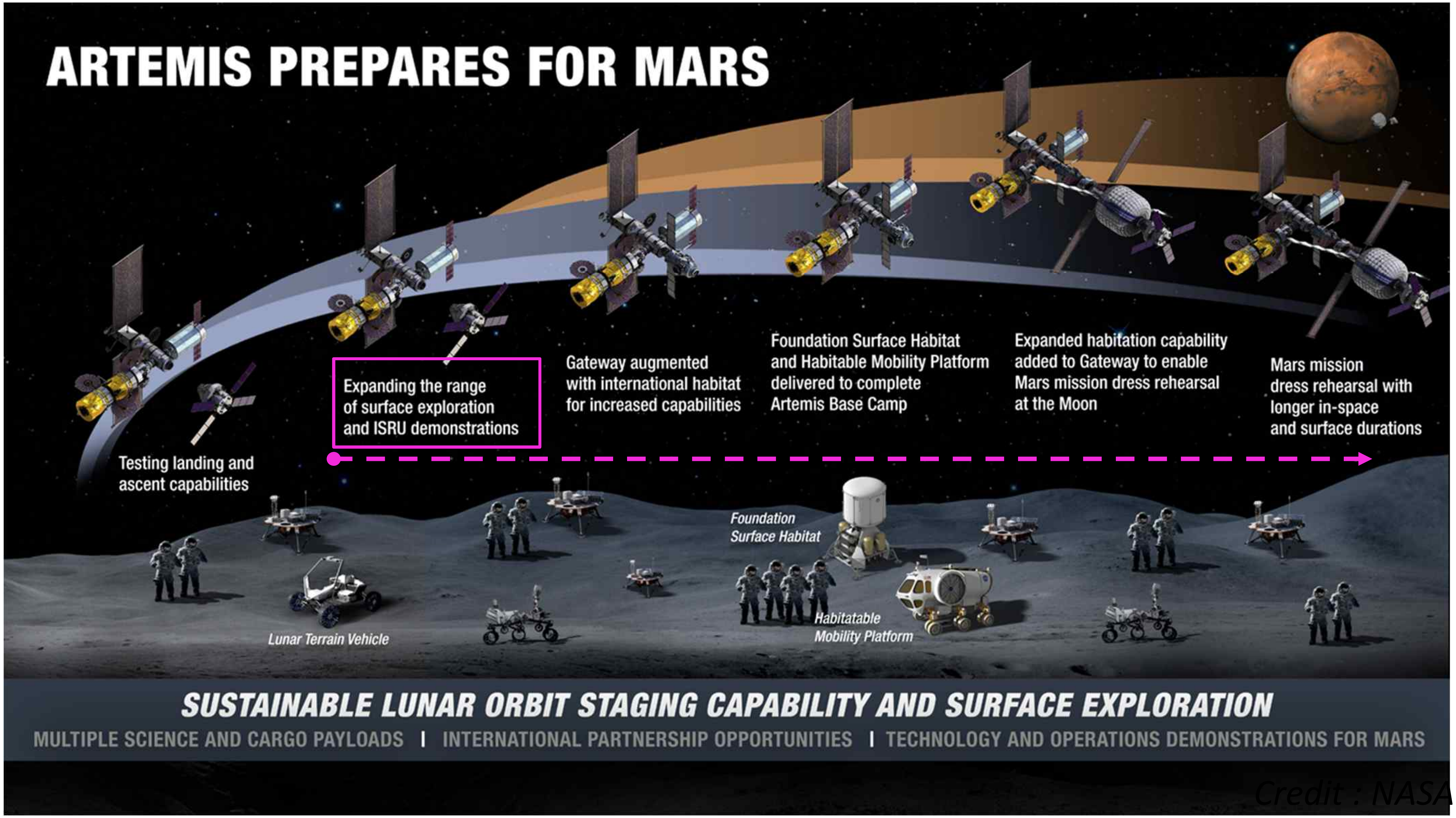


14

14

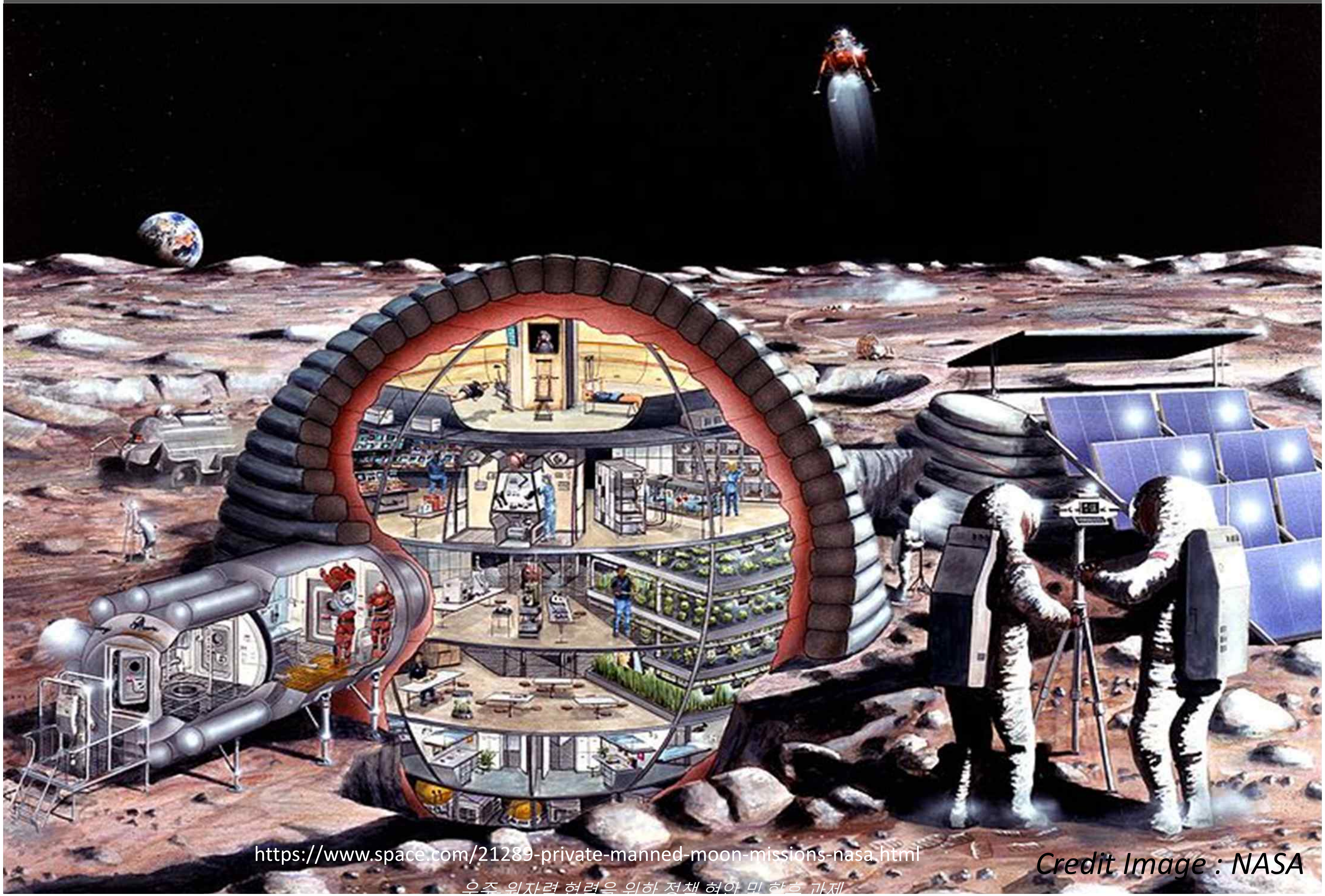
아르테미스 계획은 화성 진출 준비

KIGAM



Credit : NASA

달 기지 개념도



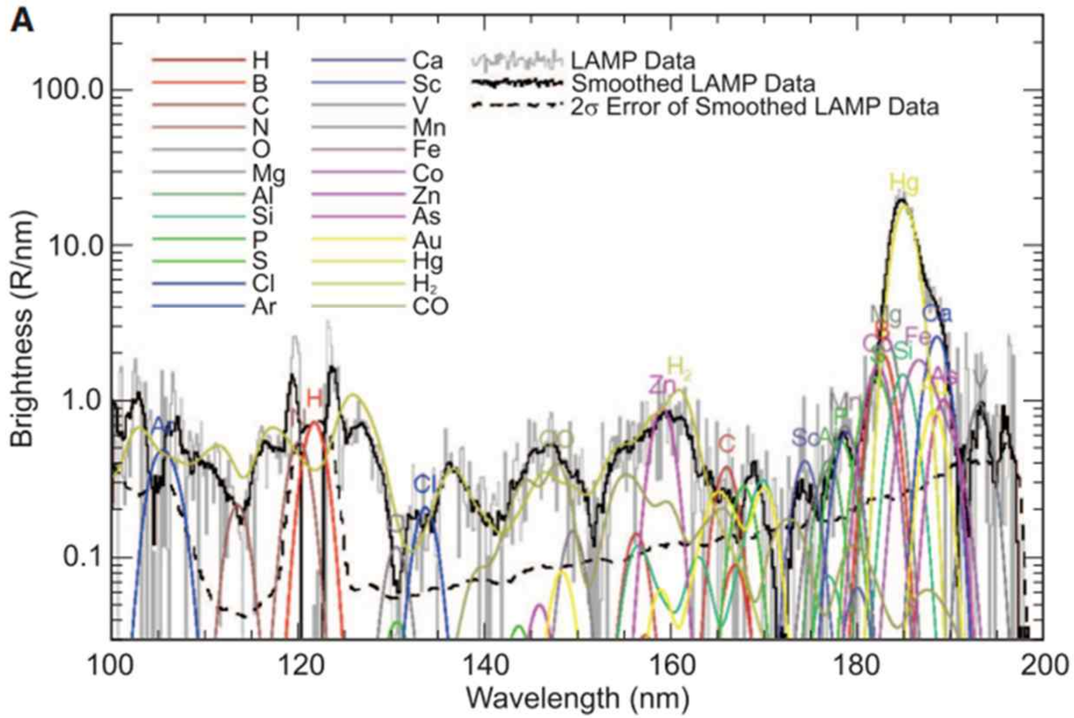
https://www.space.com/21289-private-manned-moon-missions-nasa.html

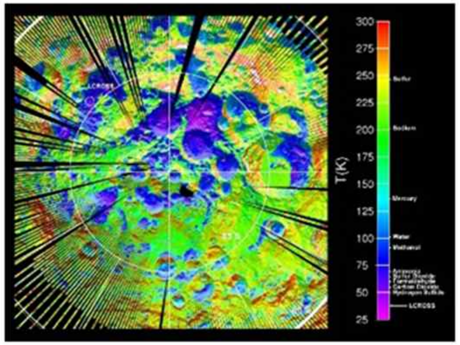
Credit Image : NASA

달 극지 자원

KIGAM

LCROSS /LRO (LAMP)





DIVINER

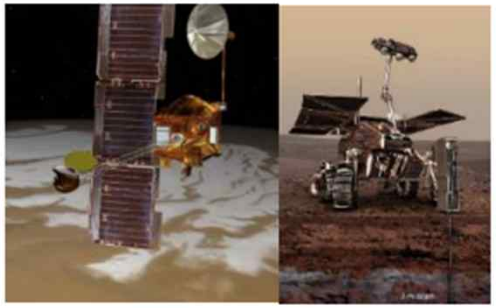
Compound	% Relative to $H_2O(g)$
H_2O	100 %
H_2S	16.75 %
NH_3	6.03 %
SO_2	3.19 %
C_2H_4	3.12 %
CO_2	2.17 %
CH_3OH	1.55 %
CH_4	0.65 %
OH	0.03 %

달 현지자원활용 연구 영역

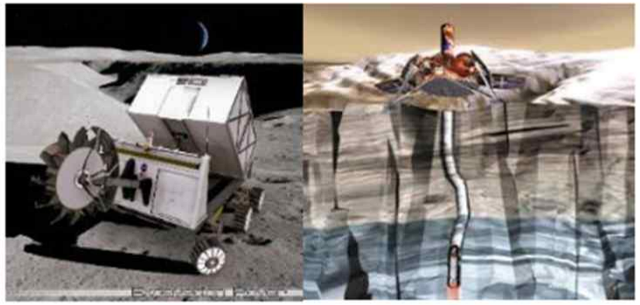
KIGAM

- NASA가 규정하는 달 현지 자원 활용의 6 가지 연구 범위 -

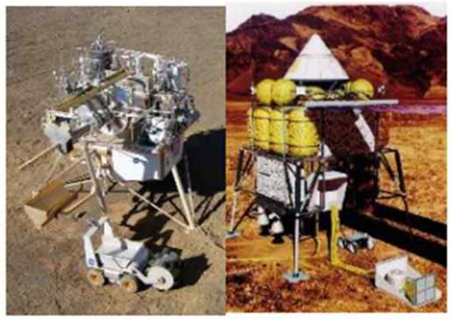
(1) 자원 조사 (Prospecting)



(2) 자원 획득



(3) 자원 처리/ 소모품 생산



(4) 현지 물질 생산

(5) 현지 건설

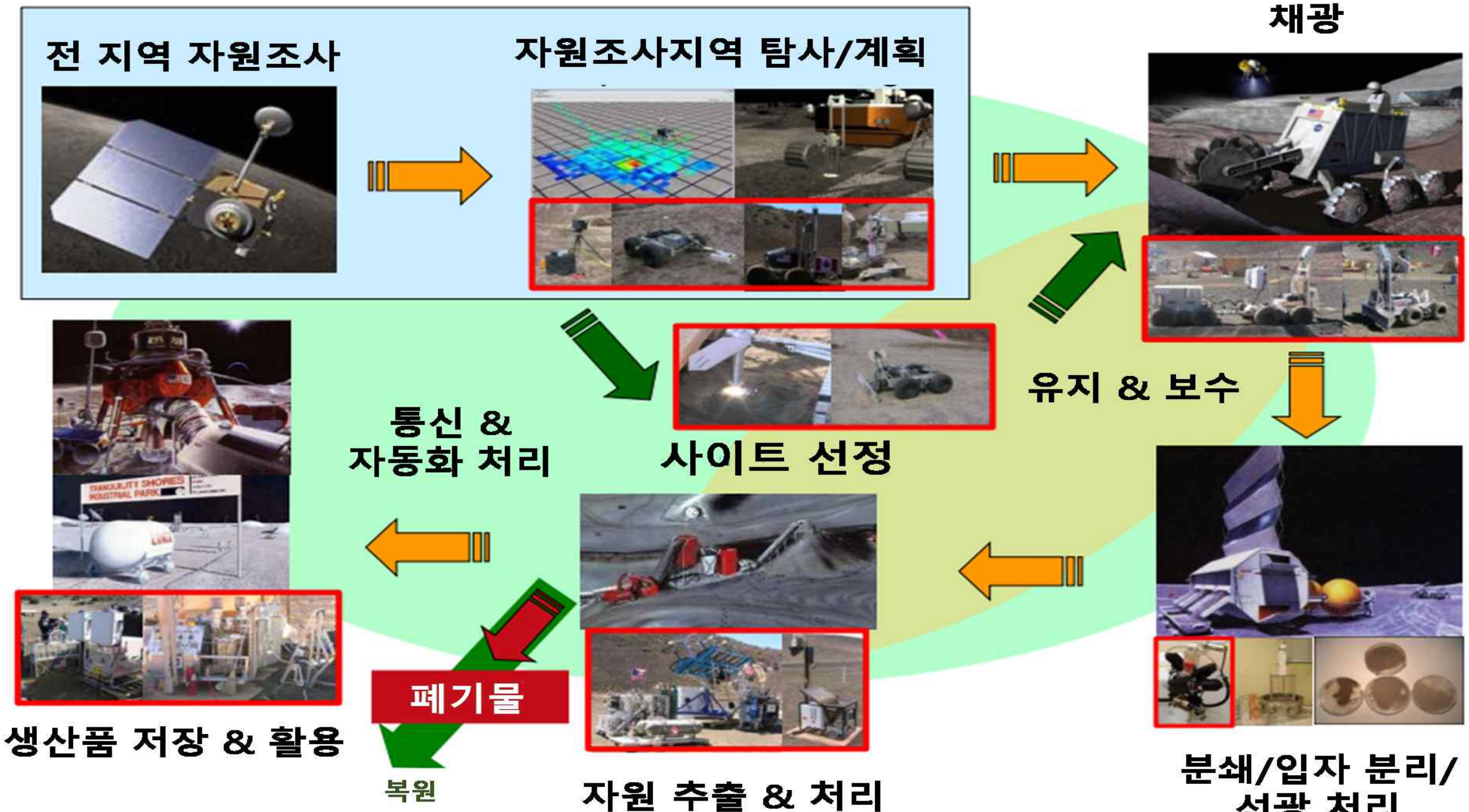
(6) 현지 에너지

Gerald B. Sanders, NASA gerald.b.sanders@nasa.gov

우주 자원 채광 주기: 조사에서 생산까지

KIGAM

우주 현지자원활용 '채광' 사이클



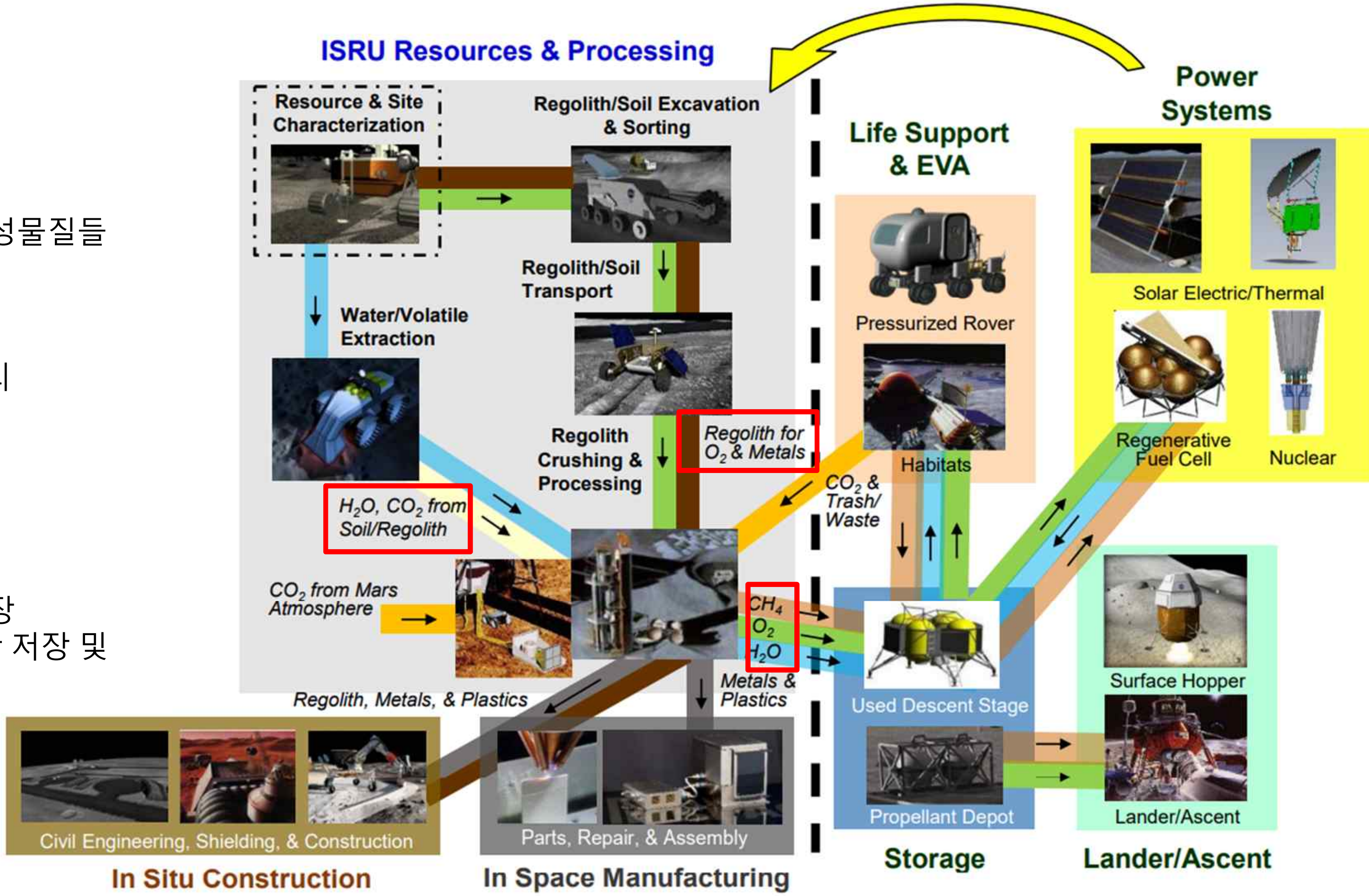
© G. Sanders/JSC, Gerald b.sanders@nasa.gov

달 표면 자원 추출과 관련된 요소 및 활동

KIGAM

- ❖ **ISRU 기능과 요소**
  - ➢ 자원 조사/매핑
  - ➢ 채광
  - ➢ 표토 이송
  - ➢ 표토 처리
    - ✓ 물/휘발성물질들
    - ✓ 산소
    - ➢ 금속
  - ➢ 대기 포집
  - ➢ 이산화탄소 처리
  - ➢ 물 처리
  - ➢ 물질 생산
  - ➢ 건설기술

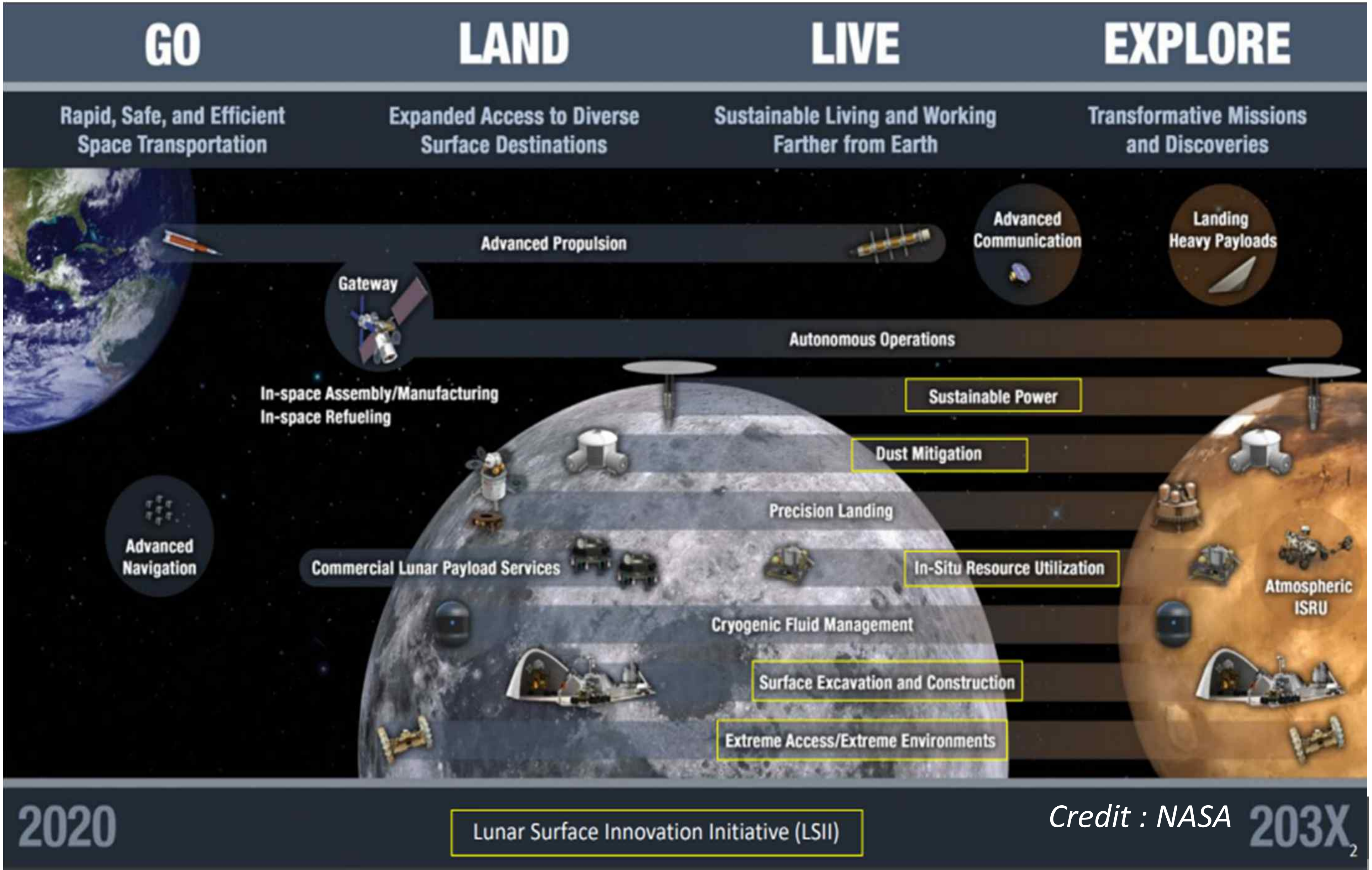
- ❖ **지원 기능과 요소들**
  - ➢ 전력 생산 & 저장
  - ➢ 산소, 수소, 메탄 저장 및 이송



NASA Lunar ISRU Strategy Gerald Sanders/NASA ISRU SCLT

아르테미스 유인 미션 : 달 현지 자원 활용 시스템 시험

지구를 떠나, 달에 정착 생존하고, 화성으로 진출

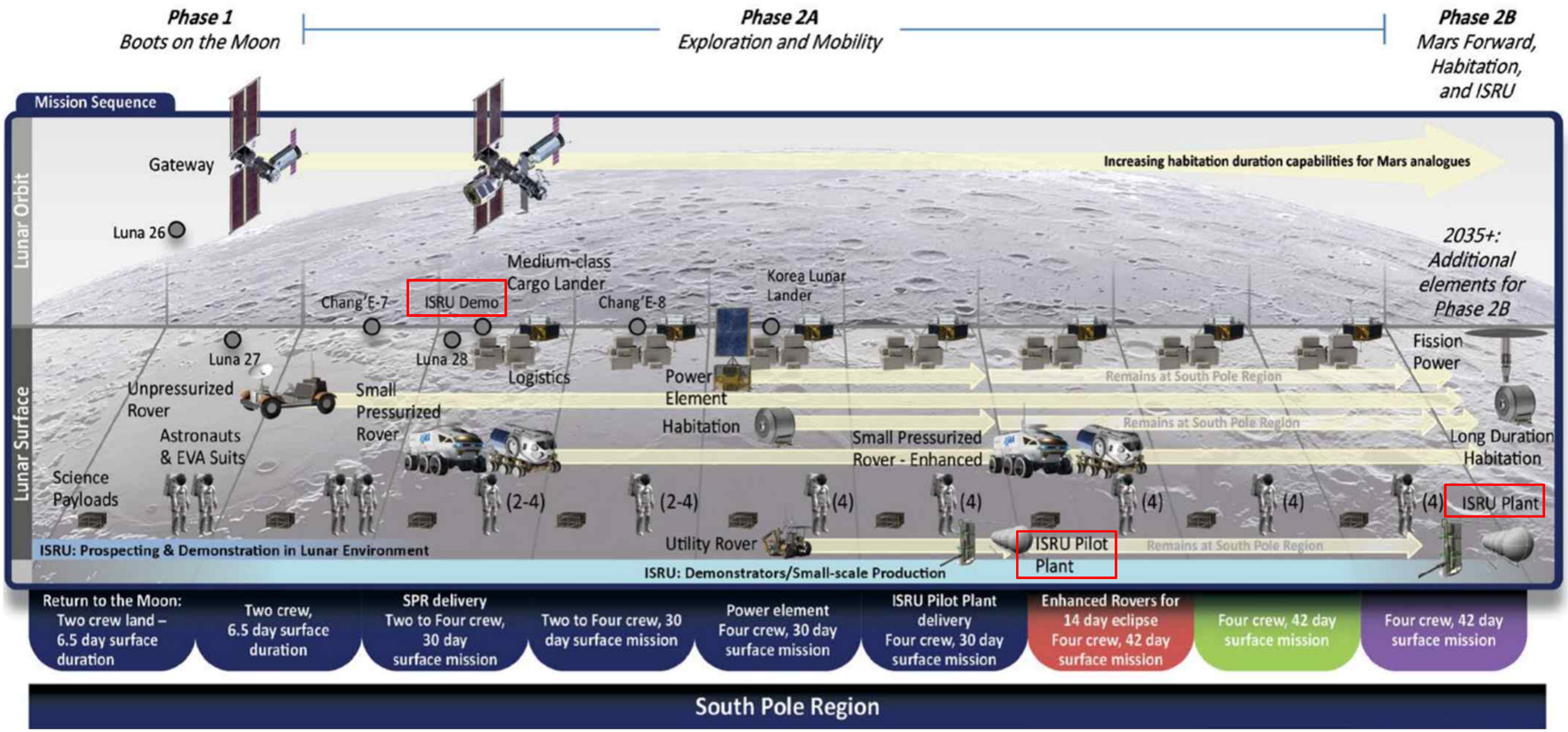


Credit : NASA

달 현지자원활용과 인간의 표면 활동 가속화

KIGAM

아르테미스 유인 달 탐사 프로그램 단계 1 ~ 2B



Credit : NASA

달 표면 전력 요구 레벨과 응용/수용력 (극지)

KIGAM

Location : Polar (near continuous light)

	Application / Capability	Power Level	Power Source Suitability and Readiness					
			Radioisotope Power	Fission Power	Photovoltaics	Batteries	Primary Fuel Cells	Regen Fuel Cells
Uncrewed	Lander, Small Robotic, NET 2020	<500W						
		500W – 1kW						
	Lander, Mid-size Robotic, NET 2022	1 – 3 kW						
	Lander, Large Robotic, NET 2026	3 – 7 kW						
	Mobile, Small Robotic Rover, NET 2022	< 500W	NextGen RPS			Lunar night survival		
		500W – 1kW	Dynamic RPS			Lunar night survival		
	Mobile, Large Robotic Rover, NET 2026	1 – 3 kW		Recharge Only		Lunar night survival		
	ISRU, NET 2027	3 – 7 kW				Lunar night survival		
		7 – 20 kW						
Crewed	Lander, Advanced Exploration, NET 2026	3 – 7 kW						
	Rover (unpressurized), NET 2023	1 – 3 kW						
	Rover (small pressurized)	3 – 5 kW		Recharge Only		Lunar night survival	ISRU Reactants	Station Recharge
	Rover (pressurized), NET 2026	7 – 20 kW		Recharge Only			ISRU Reactants	Station Recharge
	Ascent Stage, NET 2024	3 – 7 kW						
	Habitat, NET 2031	4 – 10 kW						

Color key: SOA adaptable | Funded Development | Dev started – more needed | Development needed | Not suitable/practical

Credit: NASA GRC, 2019

달 표면 전력 요구 레벨과 응용/수용력 (극지 외)

KIGAM

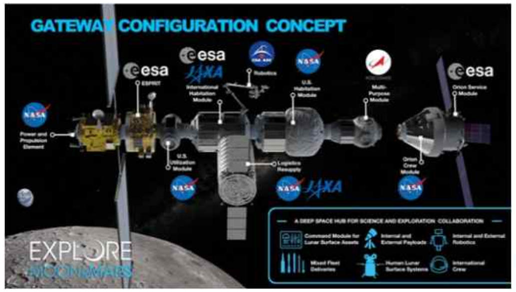
Location : Non-Polar (340 hrs sunlight, 340 hours darkness)

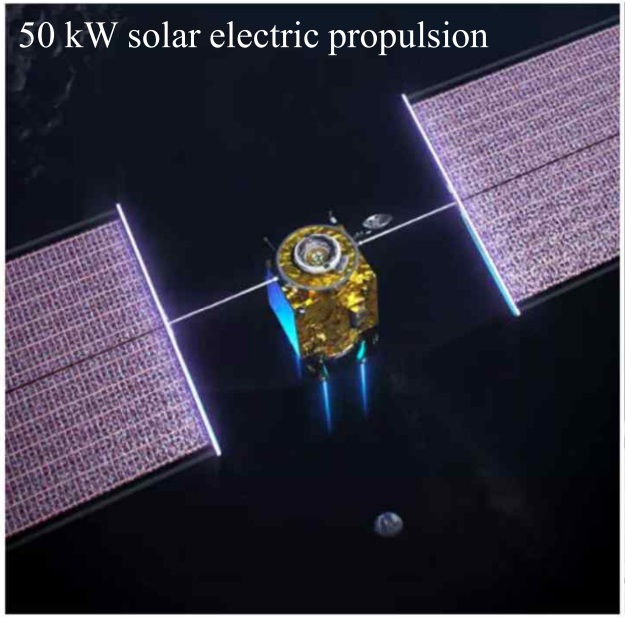
	Application / Capability	Power Level	Power Source Suitability and Readiness					
			Radioisotope Power	Fission Power	Photovoltaics	Batteries	Primary Fuel Cells	Regen Fuel Cells
Uncrewed	Lander, Small Robotic, NET 2020	<500W						
		500W – 1kW						
	Lander, Mid-size Robotic, NET 2022	1 – 3 kW						
	Lander, Large Robotic, NET 2026	3 – 7 kW						
	Mobile, Small Robotic Rover, NET 2022	< 500W	NextGen RPS			Lunar night survival		
		500W – 1kW	Dynamic RPS			Lunar night survival		
	Mobile, Large Robotic Rover, NET 2026	1 – 3 kW		Recharge Only				
	ISRU, NET 2027	3 – 7 kW						
		7 – 20 kW						
Crewed	Lander, Advanced Exploration, NET 2026	3 – 7 kW						
	Rover (unpressurized), NET 2023	1 – 3 kW						
	Rover (small pressurized)	3 – 5 kW		Recharge Only			ISRU Reactants	Station Recharge
	Rover (pressurized), NET 2026	7 – 20 kW		Recharge Only			ISRU Reactants	Station Recharge
	Ascent Stage, NET 2024	3 – 7 kW						
	Habitat, NET 2031	4 – 10 kW						

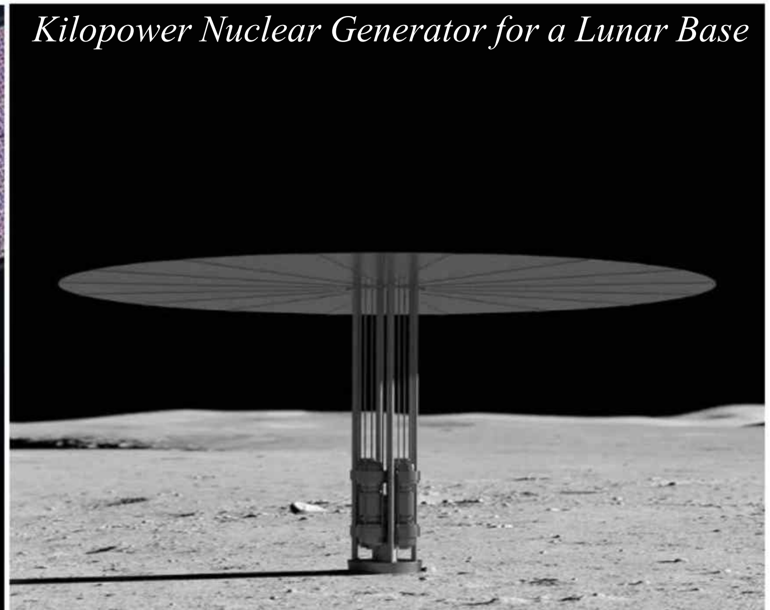
Color key: SOA adaptable | Funded Development | Dev started – more needed | Development needed | Not suitable/practical

Credit: NASA GRC, 2019

원자력 활용 – 달 게이트웨이 & 달 표면



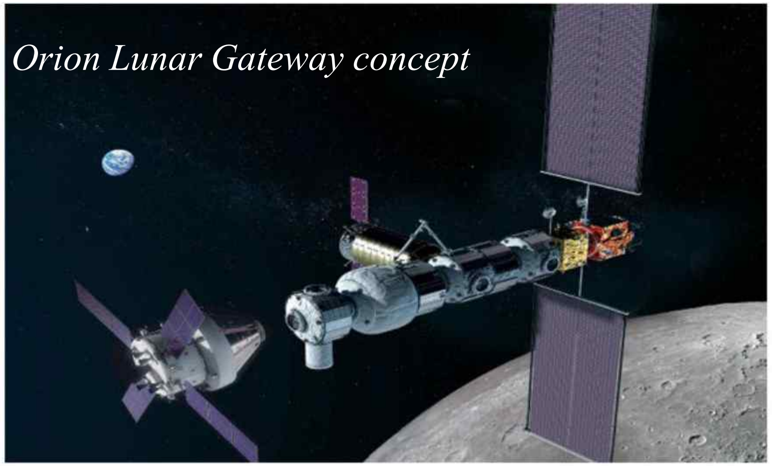

50 kW solar electric propulsion


Kilopower Nuclear Generator for a Lunar Base

https://www.popularmechanics.com/science/a38441853/nasa-moon-nuclear-reactor/


Lunar Base from Bigelow Aerospace


Blue Origin Lunar Lander

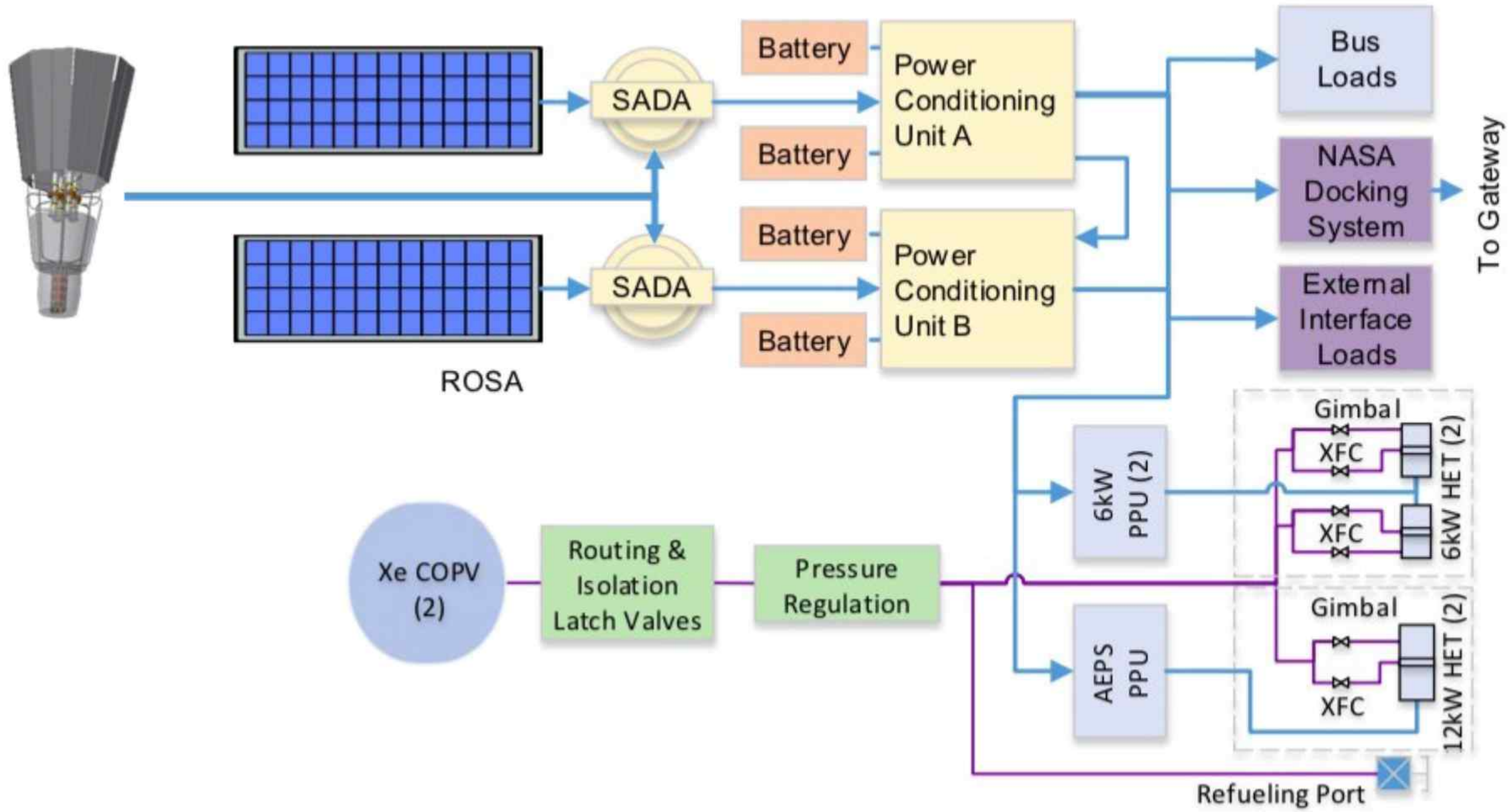

Orion Lunar Gateway concept


ISRU concept using robotic construction

Bueno et al. 2020

NASA의 개발된 원자력 전력 시스템, 발사 이전

KIGAM

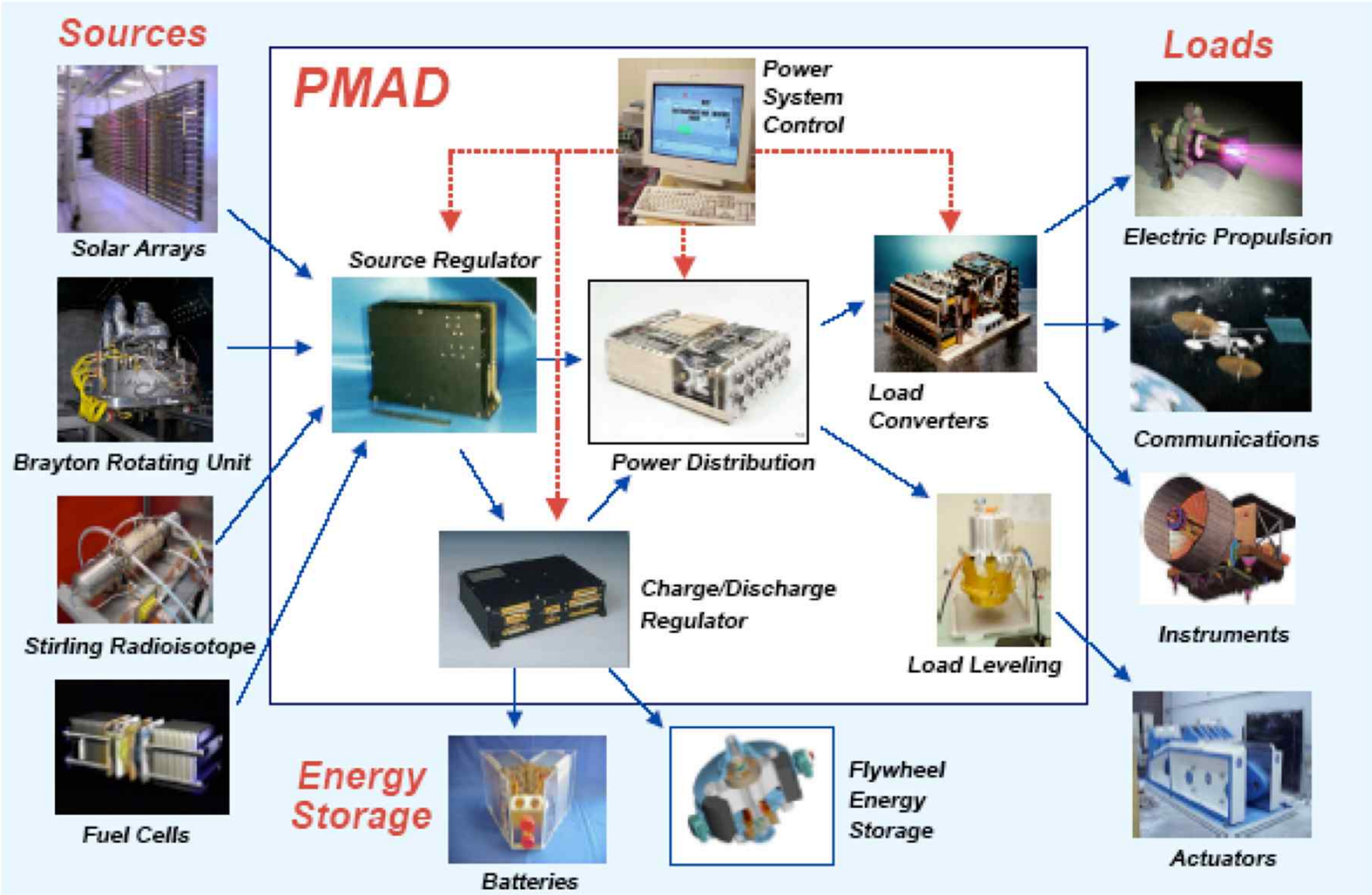


Modified PPE SEPP system to include Kilo power Nuclear Reactor for a Lunar Base

Bueno et al. 2020

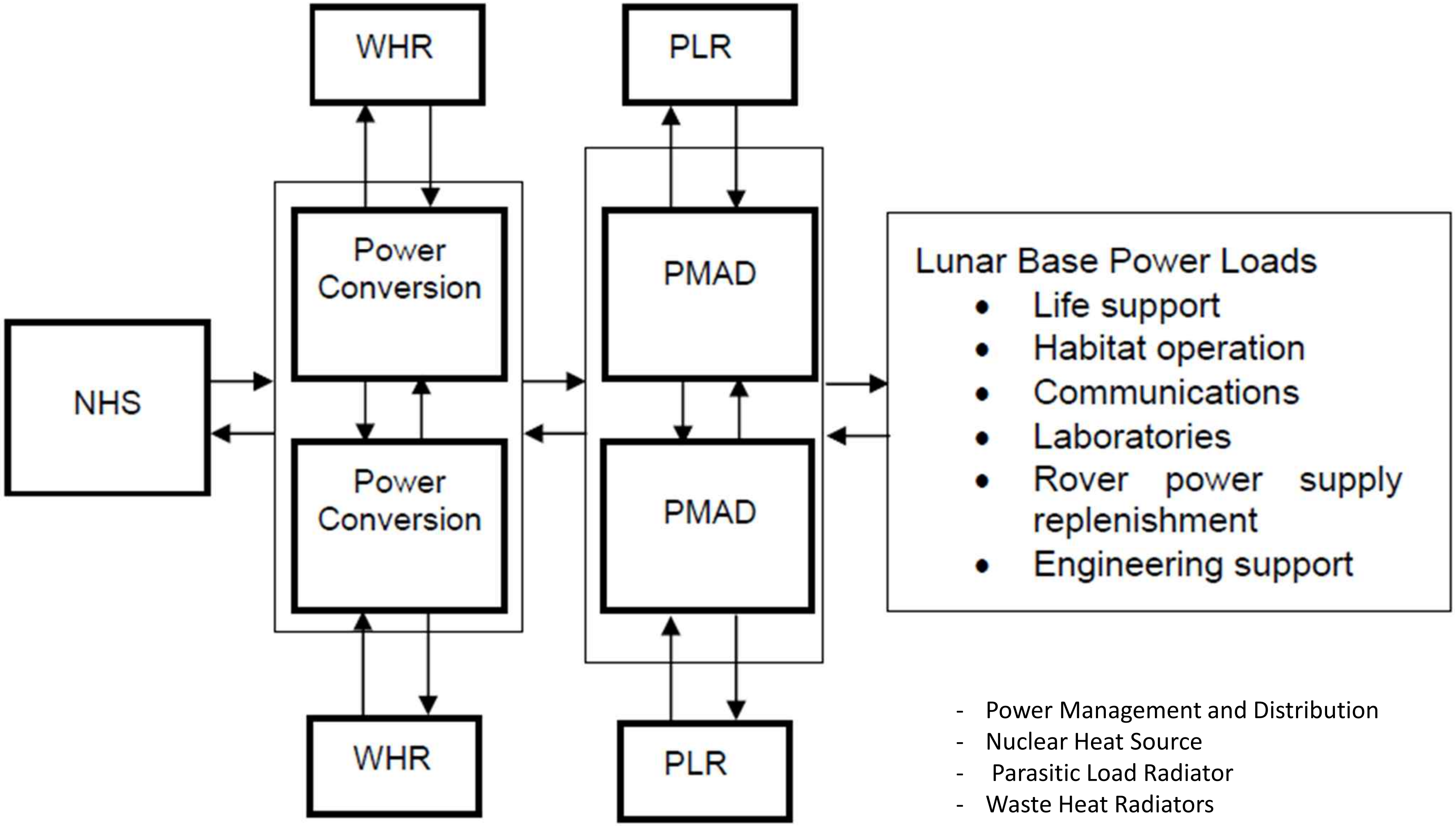
전력 운영·분배(PMAD) 및 전력 시스템 구성품

KIGAM



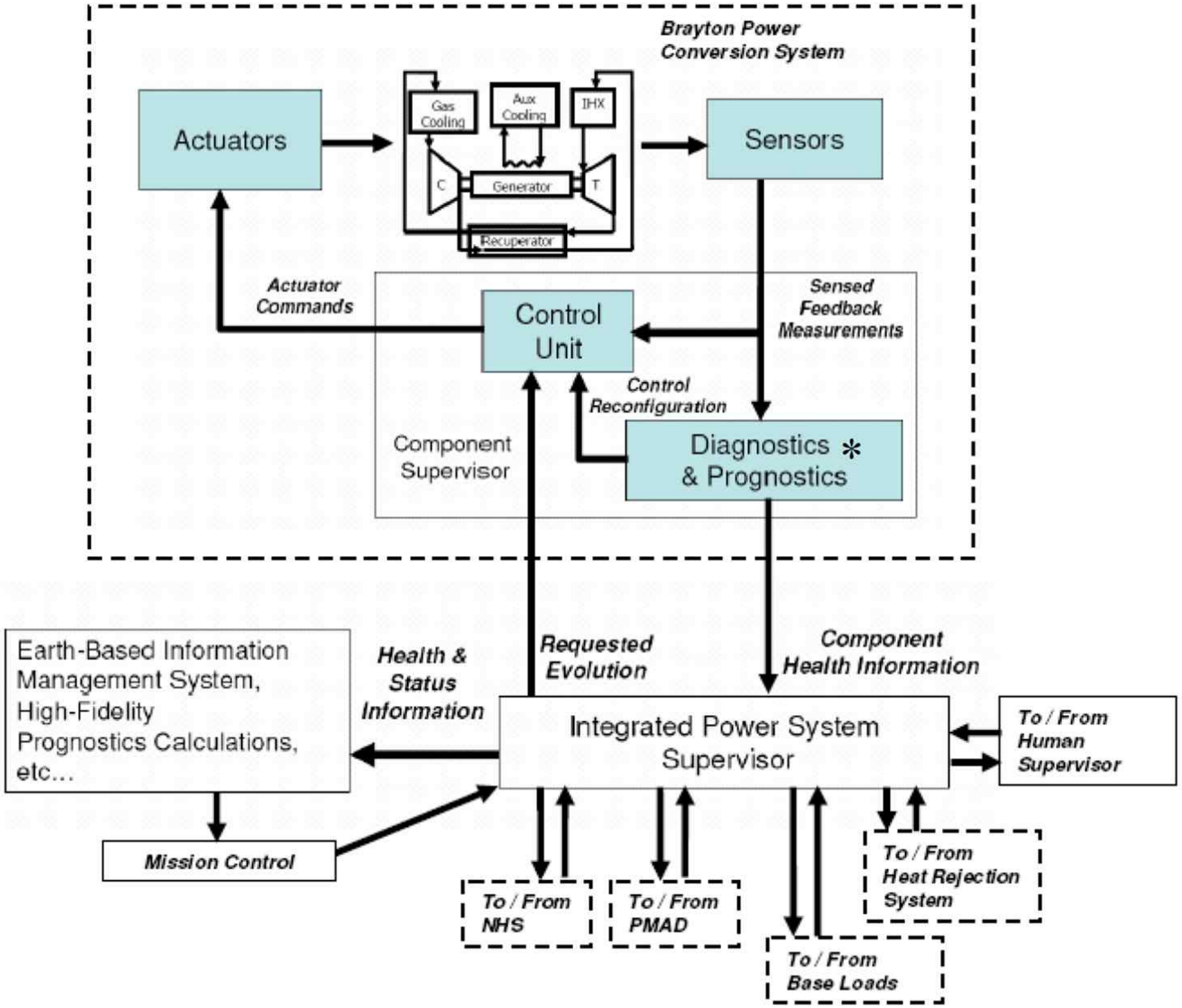
Bueno et al. 2020

Hypothetical Lunar Base Nuclear Power System



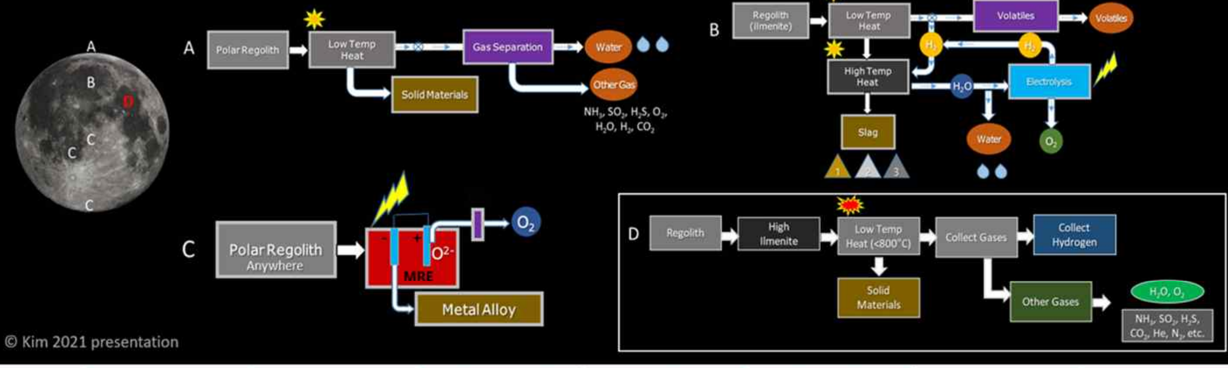
- Power Management and Distribution
- Nuclear Heat Source
- Parasitic Load Radiator
- Waste Heat Radiators

감독제어 아키텍처 : 자율적인 달 기지 원자력 발전 시스템



달 자원채굴 시연과 파일럿 플랜트(전력/시스템) KIGAM

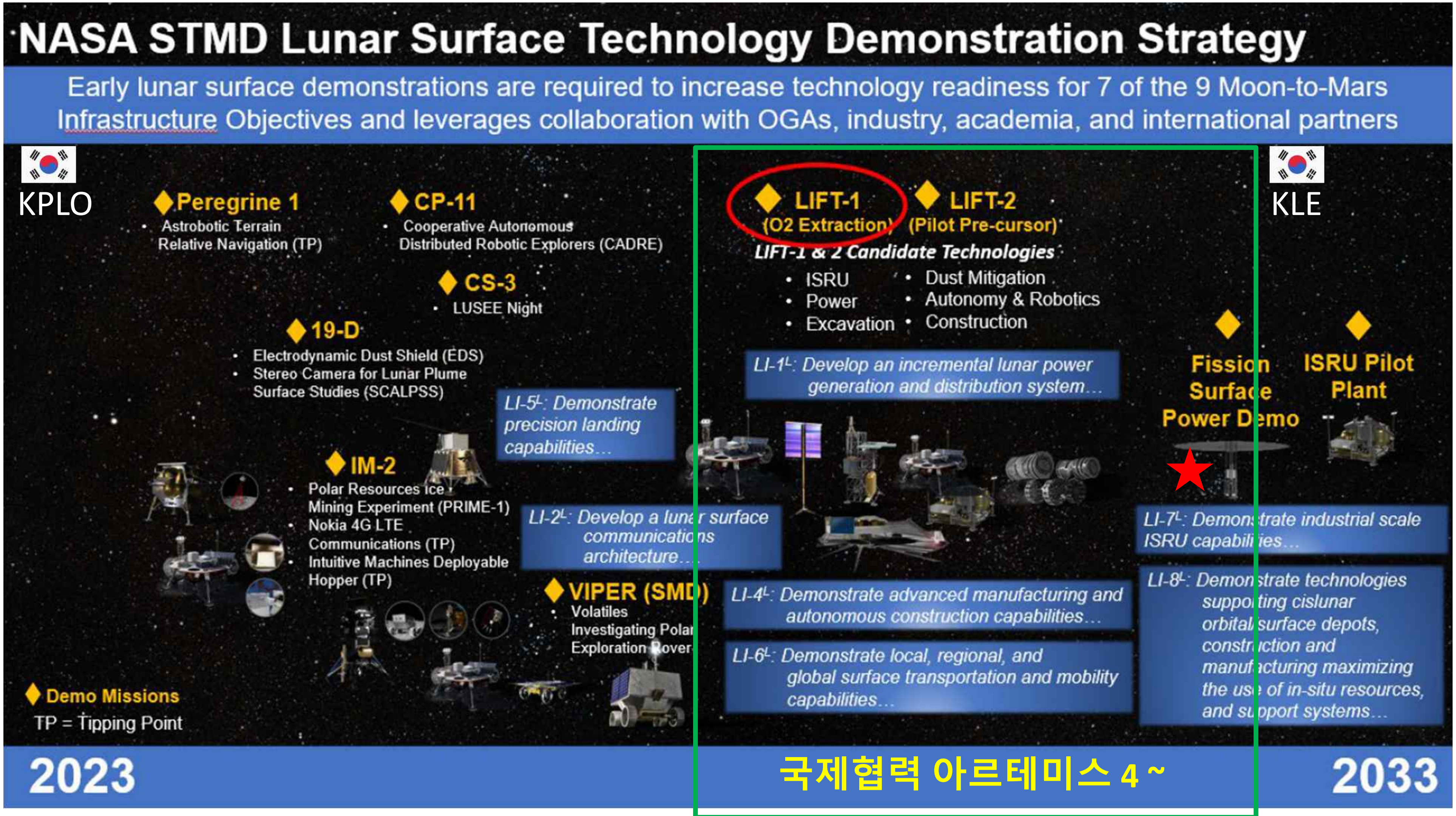
- 본 사업 산소 추출 방법 A, D
- 산소 추출기 시스템 : ~100 kg
- NASA 기준 시연 스케일에 적합
- 태양 전력 자체 생산 기능 가능



`27-`28 LIFT-1   `29-`30 LIFT-2   `31-`32 LIFT-3

구분	시연 스케일	파일럿 플랜트	승무원 상승 차량	풀 하강 단계	록히드 마틴	나이네틱스 단일 단계/드롭 탱크들	단일 단계 → NRHO	유인착륙시스템 우주선 스타쉽	유인 화성 교통편	상업용-시스-루나 교통편
기간	수일 ~ 수개월	6개월-1년	1 미션/년	1 미션/년	미션 당	미션 당	미션 당	미션 당	연간	연간
데모/시스템 질량	★ 10kgs~ 100kgs	1 mt O_2 파일럿 1.3~2.5톤 얼음 채굴	1400 ~ 2200 kg	2400 ~ 3700 kg	-	-	정의되지 않음	-	정의되지 않음	29,000 ~ 41,000 kg
O_2 양 LSIC meeting : 2 kg	10's kg	1000 kg	4,000 ~ 6,000 kg	8,000 ~ 10,000 kg	33,000 kg	32,000 kg	30,000 ~ 50,000kg	120,000 (NRHO) 440,000 (지구)	185,000 ~ 267,000kg	400,000 ~ 2,175,000 kg
H_2양	10'S g ~ kgs	125 kg	-	1,400 ~ 1,900 kg	7,000 kg	메탄 연료	5,500 ~ 9,100kg	메탄 연료	23,000 ~ 33,000 kg	50,000 ~ 275,000 kg
NPS : O_2 용 전력	100's W	5 ~ 6 KW	20~32 KW	40 ~ 55 KW	-	-	N/A	-	N/A	N/A
PSR : H_2O 전력	100's W	~ 2 KW	-	~ 25KW	-	-	14 ~ 23 KW	-	-	150~800 KW
NPS : 전력 $O_2 \rightarrow O_2 / H_2$	-	~ 6 KW	-	~ 48 KWe	9	-	55 ~ 100 K_{we}	-	-	370~ 2,000 KWe

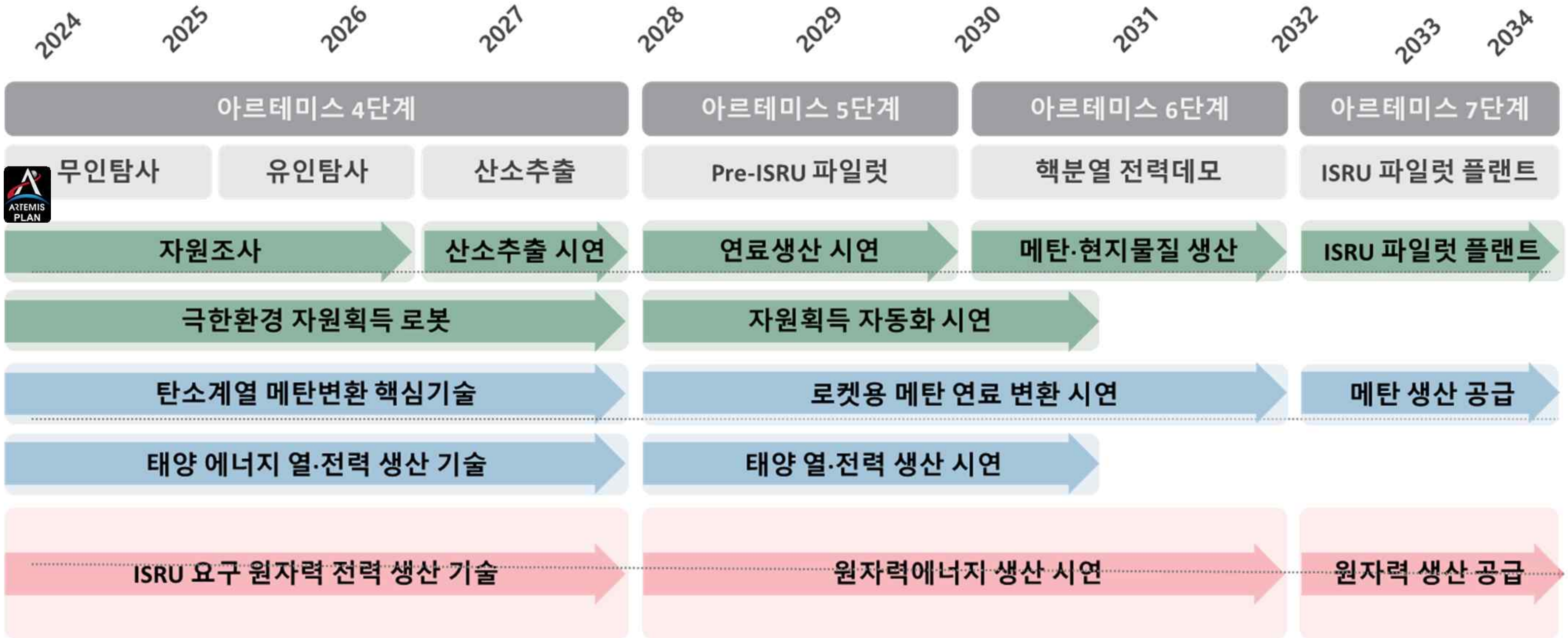
NASA의 달 표면 기술 시연 전략



NASA 아르테미스 4+ (국제협력 참여 기회)

KIGAM

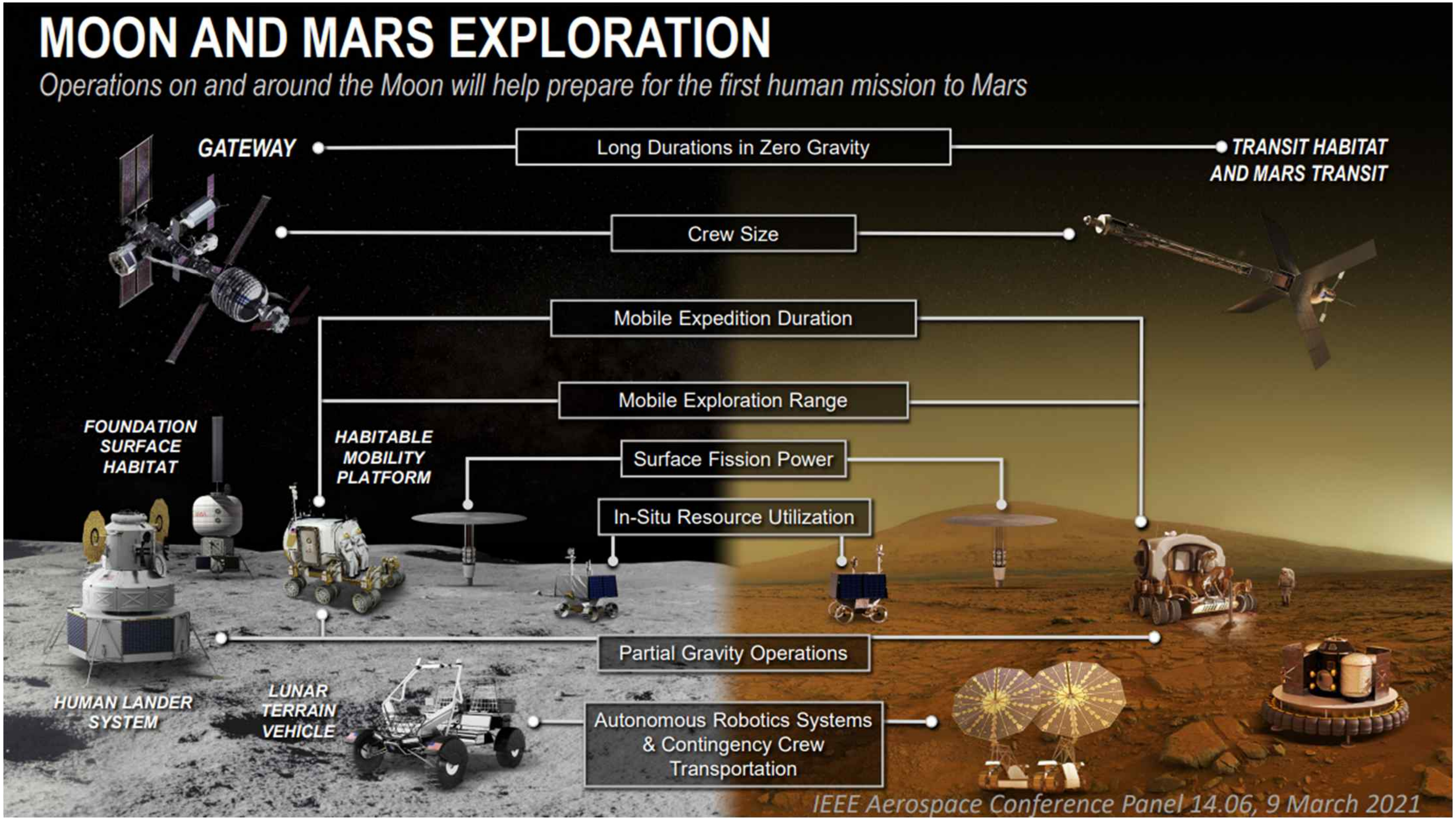
출연(연) 글로벌 TOP 전략연구단 연구개발 개발 로드맵(안)



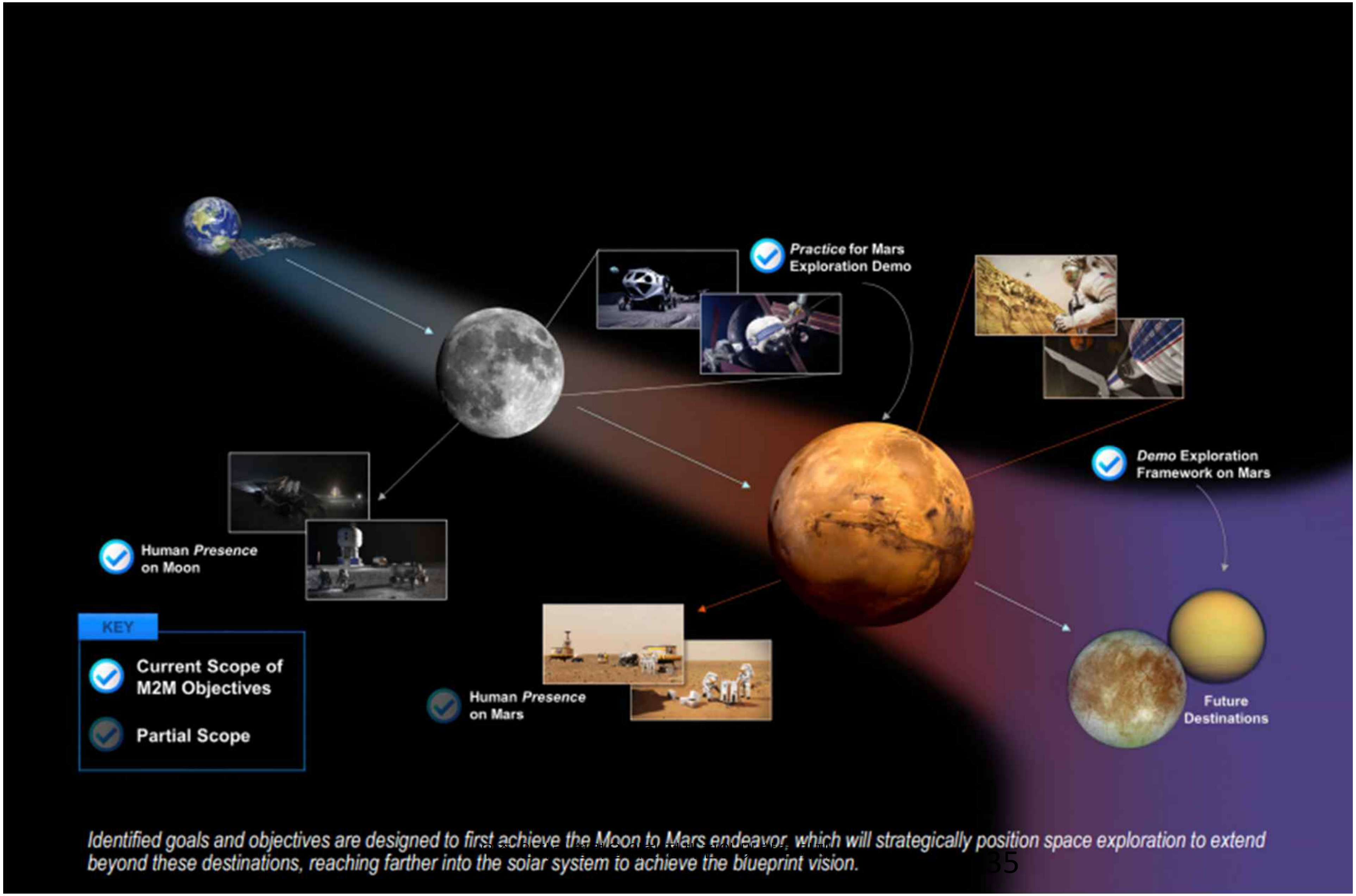
* CBS 뉴스: 러시아-중국: 원자력발전소 설치 ('33-'35)

달과 화성 탐사 연관성 (원자력의 활용)

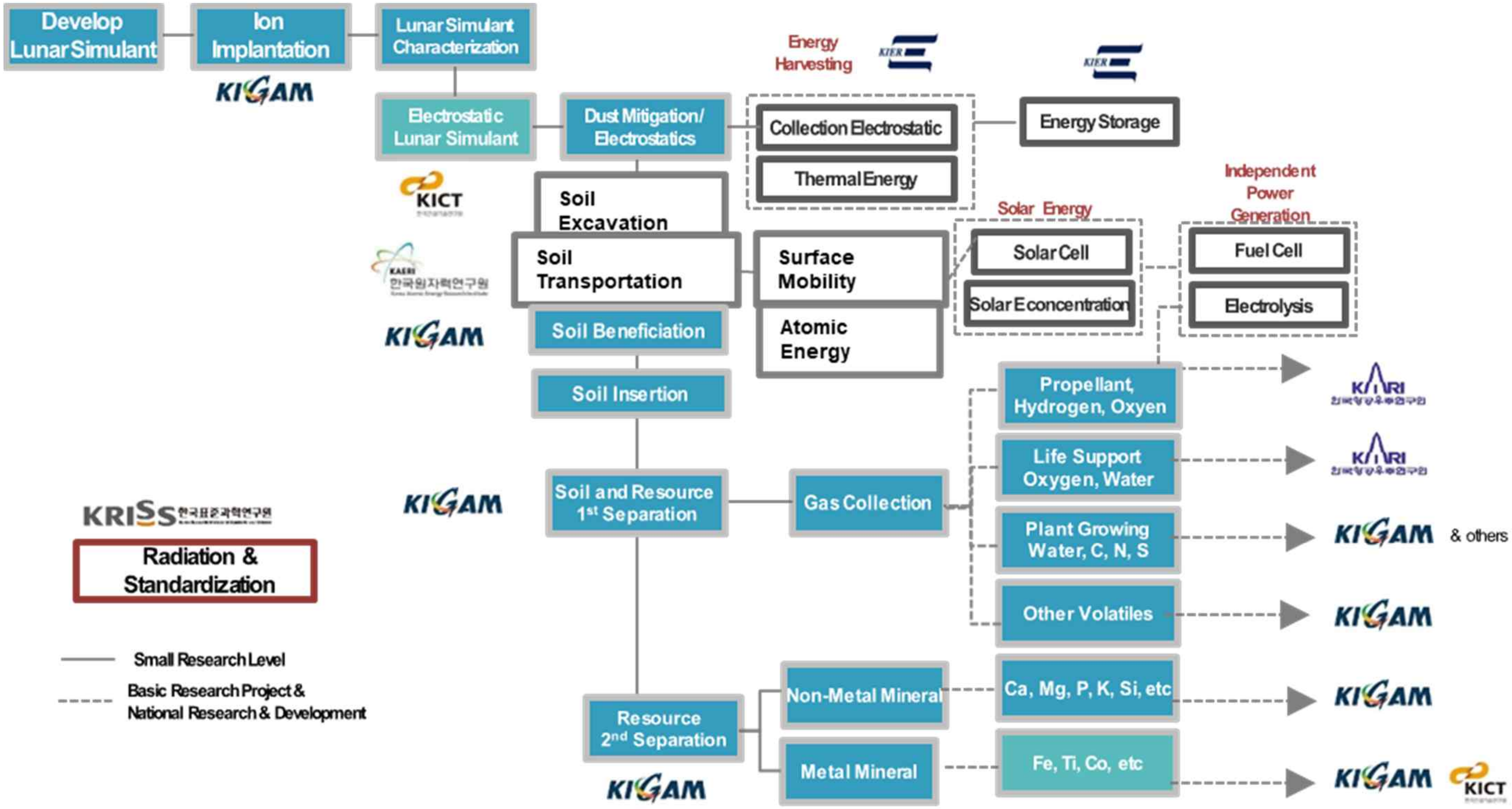
KIGAM



현재의 달에서 화성으로의 전망



정출연(연) 현지자원활용 기술개발 네트워크



전략 : 궁극적 목표(우주자원 · 영역 확보)

KIGAM

- ➢ 원자력 추진체('27 데모미션)
- ➢ '30~ 원자력활용/발전소/기지
- ➢ '35 화성 ISRU

NASA esa

- ➢ '32 달 착륙선
- ➢ '35 화성 궤도탐사
- ➢ 소행성 탐사
- ➢ '35 달 기지 건설(협력)
  - ✓ ISRU Pilot Plant, N Power
- ➢ '45 화성 착륙선
  - ✓ NTP

39

ARTEMIS

- ❖ 아르테미스 국제협력
- ❖ 독자적 ISRU 파일럿 플랜트 건설
- ❖ 달 기지 건설
- ❖ 달-화성 ISRU 기술개발
  - ✓ 자원조사, 자원획득, 처리/소모품 생산, 현지물질생산, 현지 건설, 에너지 생산

원자력

- ❖ 우주 주권 확보
- ❖ 우주 자원 확보
- ❖ 우주 영역 확보
- ❖ 국가 위상제고
- ❖ 국민 자긍심 고취
- ❖ 인류 영속성 번영 기여

달 – 화성 ISRU부터 화성 테라포밍 까지

https://medium.datadriveninvestor.com/how-to-build-a-martian-economy-74faf8db8951

달 ·화성 ISRU부터 화성 테라포밍 까지 원자력 활용

https://science.howstuffworks.com/imagining-colonized-mars-with-marshall-brain.htm

푸른 화성 (Green Mars) 원자력과 함께

Image credit : Dane Spangle

https://www.science20.com/robert_inventor/imagined_colours_of_future_mars_what_happens_if_we_treat_a_planet_as_a_giant_petri_dish-137590

참고문헌

- ✓ Campbell, Michael D., J . D. King, H. M. Wise, B. Handley, J. L. Conca, and M. David Campbell, 2013, Nuclear power and associated environmental issues in the transition of exploration and mining on Earth to the development of off-world natural resources in the 21st century, in Energy resources for human settlement in the solar system and Earth's future in space:; (eds) W. A. Ambrose, J. F. Reilly II, and D. C. Peters, AAPG Memoir 101, p. 163 –213.
- ✓ Bueno et al. 2020. Bliss voic User Interface(VUI) NASA X-HAB Moon to Mars Academic Innovation Challenge College of Engineering Fall 2020: Final Report Report Prepared by.