SYSTEMS PERSPECTIVE ON ADVANCED FUEL CYCLES AND WASTE MANAGEMENT

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Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and Waste Aspects of Advanced Nuclear Reactors
National Academy of Sciences Review Panel
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OBJECTIVES

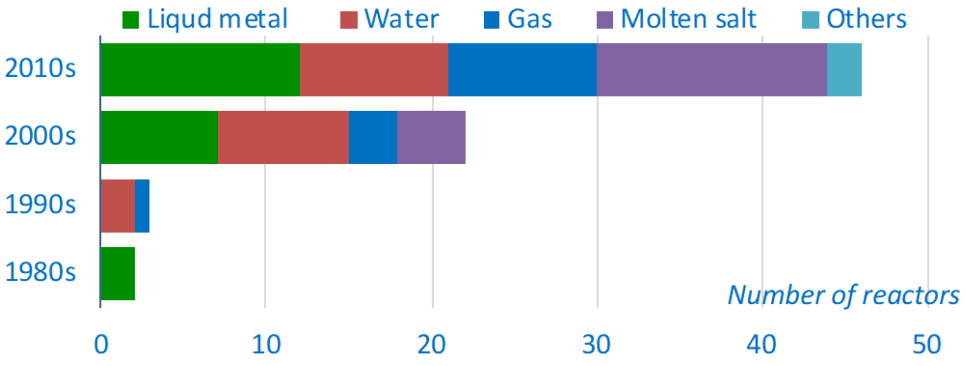
- **Purpose of presentation is to provide fuel cycle systems level information on types and characteristics of advanced nuclear systems being considered by various stakeholder groups**
  - Industry, national laboratories and universities are developers
  - Reactor data based on evaluations conducted in FY 2017 – 2019 within the Systems Analysis and Integration Campaign of U.S. DOE
  - Utilizes information from Nuclear Fuel Cycle Evaluation and Screening Study: https://fuelcycleevaluation.inl.gov/SitePages/Home.aspx

- **Information will set the stage for the follow-on presentations today by technical experts on nuclear fuel recycle systems**

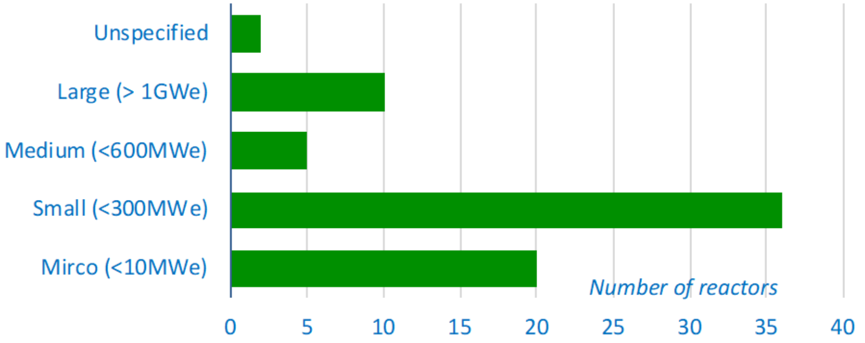
ADVANCED REACTORS

BACKGROUND INFORMATION

- **Advanced Reactor Concepts**
  - Number of advanced reactor concepts has been increasing since 2000 with investment of private capital through entrepreneurs and various initiatives by U.S. government organizations (e.g., DOE, DOD, NASA)
  - Small or micro reactors are a recent trend targeting affordable construction through modular and factory construction and small grids, harsh locations, and special purposes



- **Available Data**
  - Collected information on more than 70 reactor concepts being developed by industry, university, national Labs (mainly in the U.S.)
  - Pure fusion reactors and some evolutionary reactors (Gen-III+) are excluded



LIST OF ADVANCED REACTOR CONCEPTS

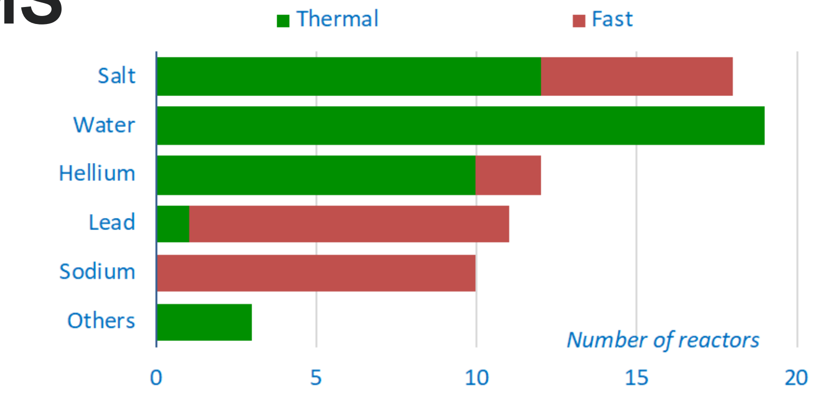
Type	Reactor	Proponent
ADS	ADAMS	Texas A&M
	MUSTAR	Virginia Tech.
	MYRRHA	SCK.CEN
BWR	ABWR-II	GE-Hitachi
	ESBWR	GE-Hitachi
	VSBWR	GE-Hitachi
FFH	SABR	GA-Tech
FHR	FHR	MIT
	Kairos	Kairos
	PB-FHR	MIT & UCB
	SmAHTR	ORNL
GCR	GT-MHR	GA
	Holos	HolosGen
	MMR	USNC
	PHTR	GA
	U-Battery	URENCO
GFR	EM^2	GA
	GFR2400	EU
HTGR	Hybrid	Hybrid Power
	NGNP	INL
	STARCORE	StarCore Nuc.
	SC-HTGR or	Areva
	XE-100	X-Energy

Type	Reactor	Proponent
LFR	BREST-300	Rosatom
	ENHS	UC-Berkeley
	EFIT	SCK.CEN
	G4M	Gen4 Energy
	LBFR	CBCG
	LC-E-SSTAR	Lakechime
	LFR-AS-200	Hydromine
	SEALER	Essel (Sweden)
	STAR	ANL / LLNL
LTR	LEADIR-PS	Northern Nuclear
MSR	CMFR	TerraPower
	Elysium	Elysium (Canada)
	IMSR	Terrestrial Energy
	LFTR	Flibe Energy
	LSFR	MIT
	MNSR	Yellowstone
	MOSART	Kurchatov, Russia
	MSTW	Denmark
	SSR	Moltex Energy (UK)
	ThorCon	Martingale Inc.
	Thorenco	Thorenco
	TAP	Transatomic Power

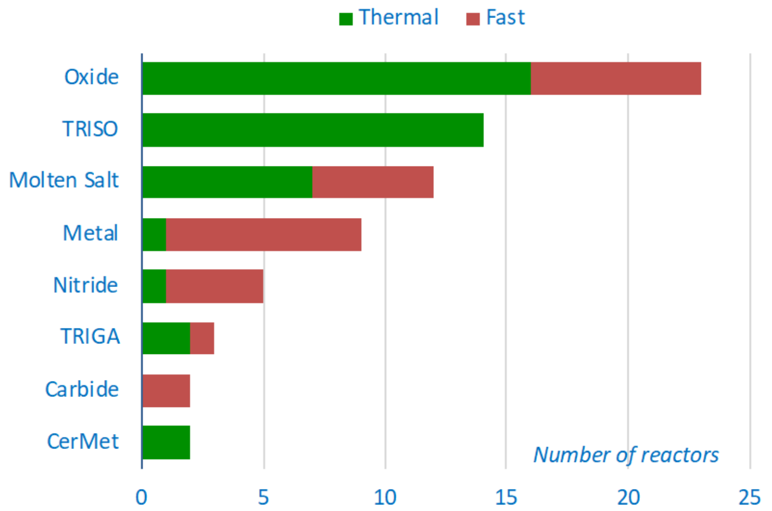
Type	Reactor	Proponent
PWR	ACRP50S	China
	ATMEA1	AREVA/MHI
	Flexblue	DCNS
	IRIS	Westinghouse
	KLT-40S	OKBM, Russia
	Akademik Lomonosov *)	OKBM, Russia
	Lightbridge	Lightbridge
	mPower	Gen. mPower
	NuScale	NuScale Power
	RADIX	Radix Power
	SMART (D)	Dunedin
	SMART (K)	KAERI, Korea
	SMR	Westinghouse
	SMR-160	Holtec
	TPS	General Atomics
	VBER-300	OKBM (Russia)
SFR	AFR-100	ANL
	ARC-100	ARC
	ASTRID	CEA
	BN-800	OKBM
	PRISM	GE
	S&B SFR	UC-Berkley
	TWR	TerraPower
Special	eVinci	Westinghouse
	MegaPower	LANL
	MsNB	MicroNuclear
	Oklo	Oklo
	ORSN	MIT

COOLANTS AND FUEL FORMS

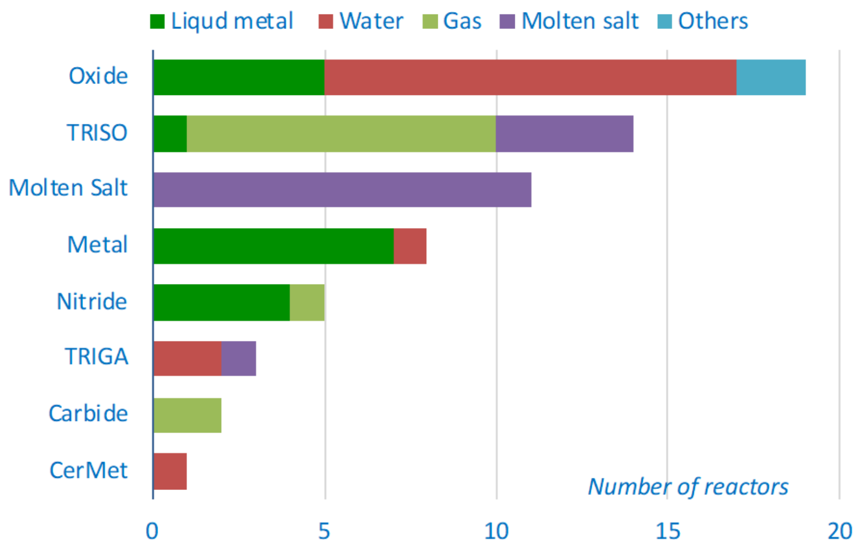
- **Coolants**
  – Traditional dependency of coolants on neutron spectra broken in some designs, e.g.,
    - Fast-spectrum molten-salt and gas-cooled reactor concepts
    - Thermal lead cooled reactor concept with graphite moderator (LEADIR)

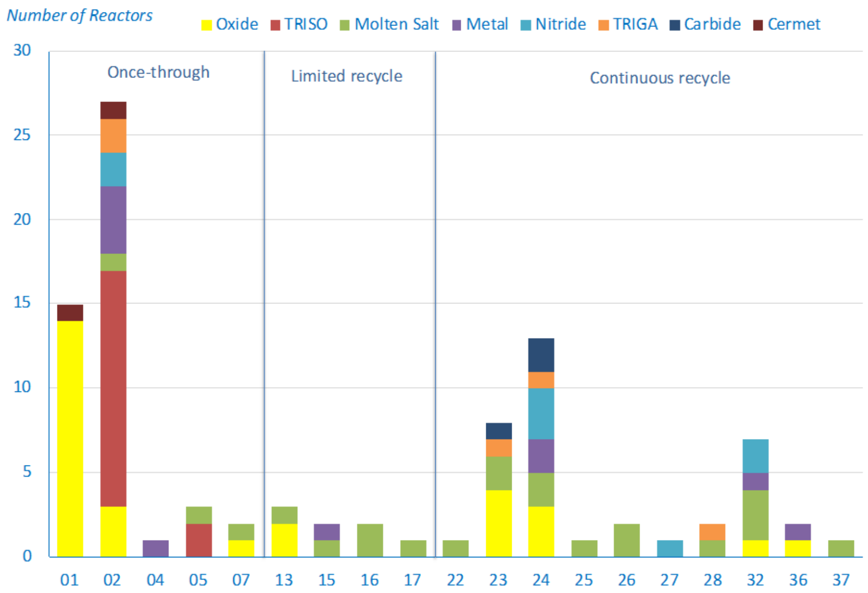


- **Fuel Forms**
  - Oxide and TRISO fuels are dominant
  - TRISO fuels primarily for thermal reactors, while metallic, nitride, and carbide fuels are mainly used for fast reactors
  - Some LWR concepts use non-conventional fuel forms, e.g.,
    - Lightbridge with a binary metallic fuel (U-Zr)
    - RADIX and TPS with TRIGA ($UZrH_{1.x}$) fuel
    - SMART(Dunedin) with CerMet fuel
  - Molten salt reactor fuels
    - Fluoride-based salts for thermal MSRs
    - Chloride-salts for fast MSRs (CMFR, LSFR)



TARGET FUEL CYCLES DEPENDING ON FUEL FORMS

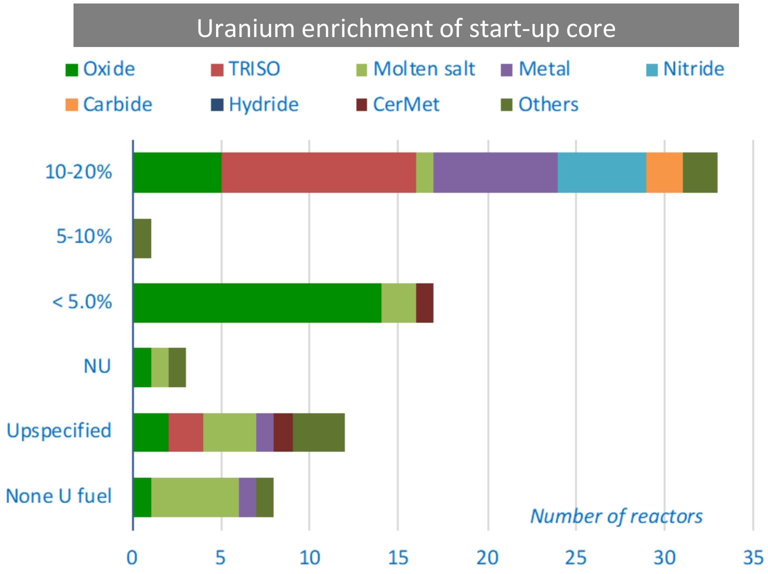


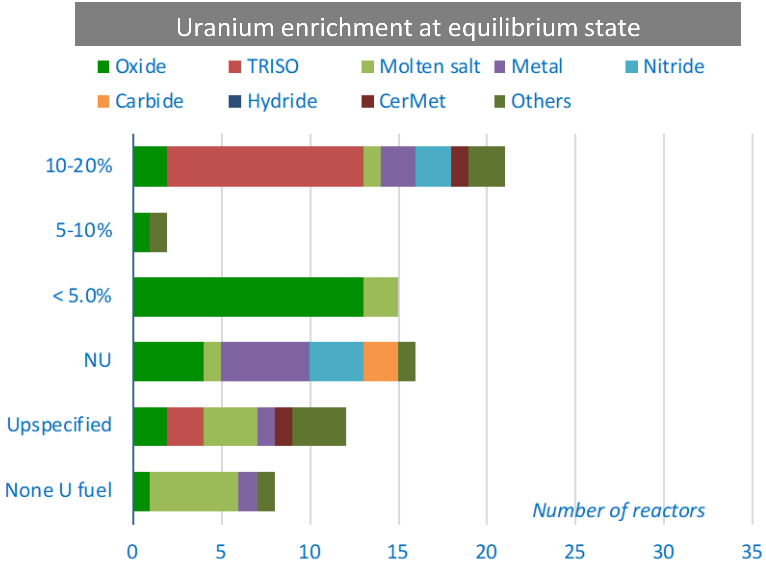


Note: Evaluation Groups from Evaluation and Screening Study

- Oxide, metal, and molten salt fuels are used in once-through, limited, and continuous recycling fuel cycle options
- TRISO fuels are used in once-through fuel cycle options

URANIUM ENRICHMENT



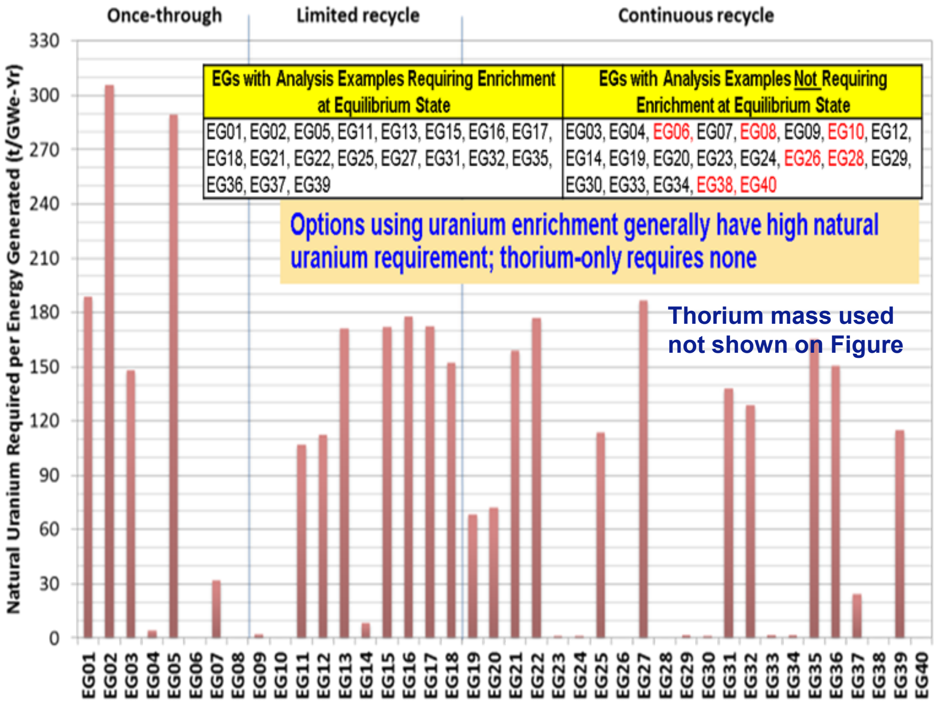


- **High Assay Low Enriched Uranium (HALEU >5%) needed for most advanced reactors**
  - Low enriched (< 5% or slightly higher) UOx fuels are dominant in the current and evolutionary LWR concepts
  - Advanced reactor concepts require HALEU fuels (>10%) with various fuel forms for either enhancement of fuel cycle performance or igniting start-up cores

FUEL CYCLE PERFORMANCE

ENRICHMENT AND RECYCLE IMPACTS ON RESOURCE USE

- **Options using uranium enrichment generally have high natural uranium requirement**
  - Externally-driven systems or deep breed and burn offer relief
- **Continuous recycle of fuel without uranium enrichment can significantly increase fuel utilization (less fuel resource needed)**
  - Resource utilization could be greater than 90%, depending on transuranic separation efficiency



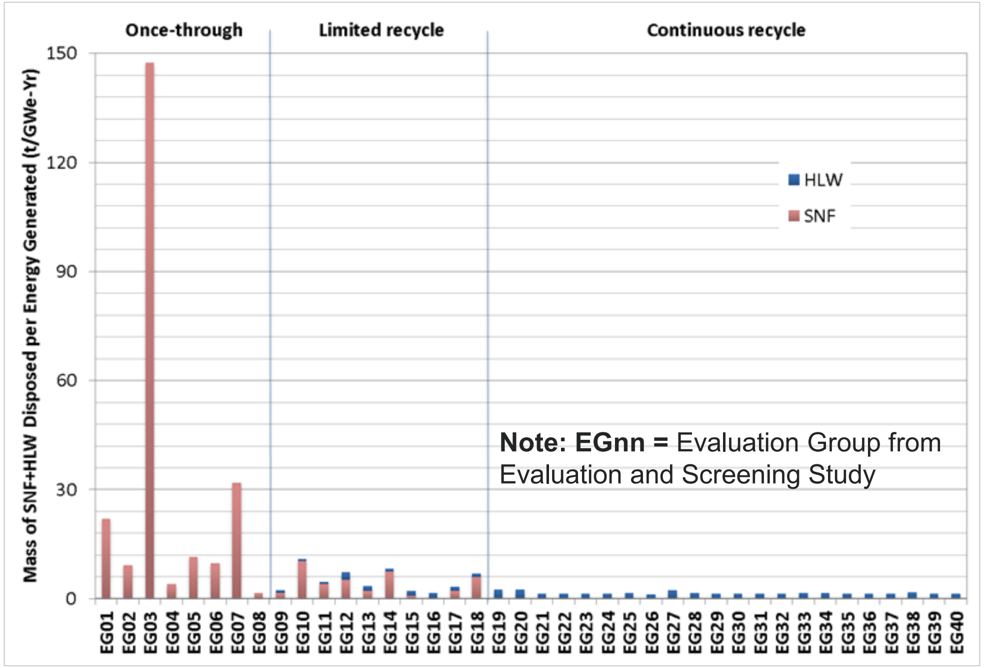
EGnn = Evaluation Group from Evaluation and Screening Study

MASS OF SNF+HLW DISPOSED

- **In general, the mass of SNF+HLW disposed per energy generated decreases from the once-through fuel cycle options to those of continuous recycle options**

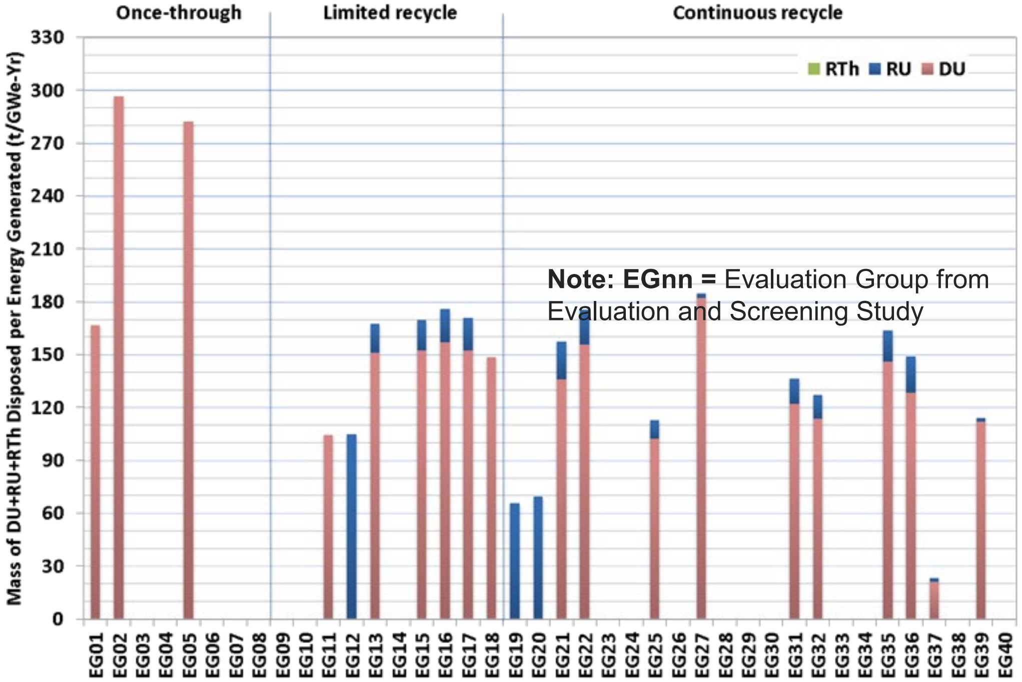
- **SNF is the dominant contributor for the once-through fuel cycle options, and is zero for the continuous recycle options**
  –

- **For the once-through fuel cycle options, the SNF mass is inversely proportional to the average discharge burnup**
  - EG03, has highest SNF+HLW mass because fuel discharge burnup for HWRs is low
  - Low SNF+HLW mass for the once-through strategy EG08 is due to the fact that the system assumes only natural uranium as fuel and that fuel has a very high burnup (~75%)



SNF = Spent nuclear fuel; HLW = High level waste

MASS OF DU+RU+RTH DISPOSED



DU = depleted uranium; RU = recovered uranium; RTh = recovered thorium

- **Regardless of the fuel cycle, a sizeable amount of DU is produced for fuel cycles that need enriched uranium fuel**
- **Generally, DU is the dominant contributor to the mass of DU+RU+RTh and RU is the second leading contributor**
- **Continuous recycle with no enrichment eliminates this waste stream**

CONCLUSIONS

CONCLUDING STATEMENTS

- **Advanced reactor concepts are under development by different stakeholders**
  - Some are small or micro size reactors
  - Fuel cycle options are once-through, or limited recycle, or continuous recycle
  - Most advanced once-through LWR designs are targeting evolutionary improvements to fuel cycle performance of current nuclear fleet
  - Lots of options are advanced reactor concepts for continuous recycle of U/Pu or U/TRU using natural U fuel in fast reactors
- **Except for externally driven systems and evolutionary LWRs, advanced reactor concepts require high assay low enriched uranium for igniting startup-cores, as driver fuels, or to compensate the low neutron economy of small and micro-reactor**
- **Fuel cycle performance for resource utilization, and front end and back end waste masses are greatly improved with nuclear fuel recycle**
  - Uranium enrichment can be detrimental to fuel cycle performance

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