Energy Hubs and Advanced Microreactors: Towards Land-Based Nuclear Power Capabilities in Contested and Austere Environments

Defense Energy Seminar
Naval Postgraduate School

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Nuclear Power Branch
Office of the Chief of Engineers
HQ Department of the Army

9 May 2023

Acknowledgements

- **Mr. Aaron Horwood**

  OCE NPB/INL Doctoral Fellow

  – https://madsciblog.tradoc.army.mil/439-history-doesnt-repeat-itself-but-it-does-rhyme/

- **Dr. Jeff Waksman**

  Project Pele Project Manager

  OSD Strategic Capabilities Office

BLUF

- ***Energy is at the heart of our warfighting capability…and the needs are ever increasing.***
- ***We don't have an energy problem per se. We know how to produce energy. We have a logistics problem.***
- ***Nuclear energy is the only viable power source to ensure that our warfighter's energy needs are met when and where they need to be met.***
- ***…and we also have a climate problem. It is, therefore, a very happy coincidence that nuclear energy also addresses our climate change problems.***

It’s all about logistics

The Washington Post
Democracy Dies in Darkness

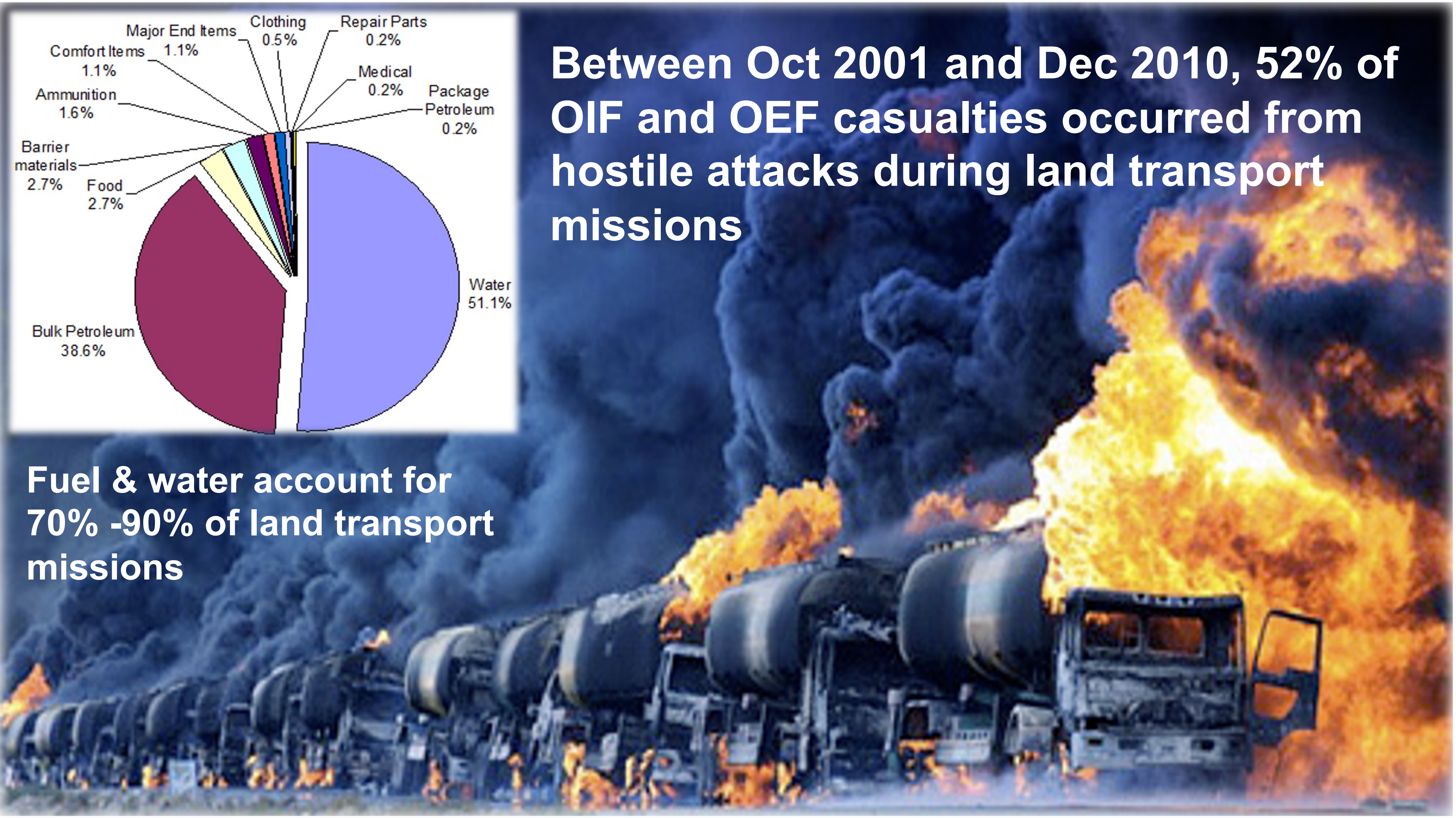
Why the Russian military is bogged down by logistics in Ukraine

Analysis by Bonnie Berkowitz and Artur Galocha
March 30, 2022 at 10:17 a.m. EDT

Comment 1451 Gift Article Share

Ambushed convoys and broken tanks. Generals killed close to the front. Expired rations. Frostbite. The Russian military was built for quick and overwhelming firepower, experts say, but its weakness is logistics. And on the roads of Ukraine a month after the first invasion, that weakness is showing.

Catalyst for Reevaluating Energy Options



Between Oct 2001 and Dec 2010, 52% of OIF and OEF casualties occurred from hostile attacks during land transport missions

Fuel & water account for 70% -90% of land transport missions

"Relieve the dependence of deployed forces on vulnerable fuel supply chains" ***Commanding General, 1st Marine Division in OIF***

Fool me once shame on you, Fool me twice…

“Had the Japanese destroyed the oil (Pearl Harbor), it would have prolonged the war another two years.” –ADM Nimitz

Past as Prologue: WW2 and the Pacific

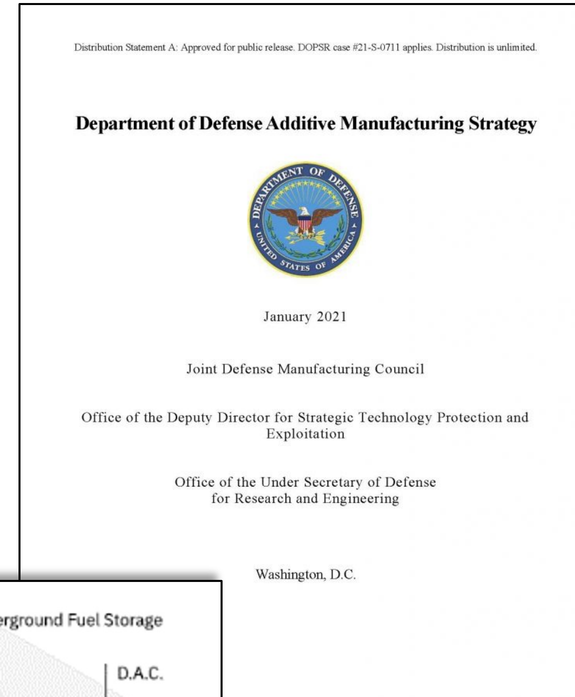
- Japan decided to attack due to an Oil Embargo
- Japan did not prioritize targeting any of the US fuel tankers or storage facilities in the Pacific
- In 1942 the Allies lost 1/4th their tanker fleet (191) to Germany.
- Battle of Guadalcanal saw mass starvation of US and Japanese forces due to bad logistics. The loss of all naval air support two days into the battle due to insufficient fuel.
- The turning point of the war was the battle of Leyte Gulf, which resulted in Japan's loss of its main supply of oil.
- Allied merchant raiding crippled Japanese industry and society, and was likely the single greatest contributor to their defeat.
- The Navy’s adoption of Nuclear Power can be traced to WW2 and how fuel was the single greatest constraint in the theater.

Use Cases for Nuclear Power

- Austere and contested environments currently create a significant burden on those who need to move the source of energy. Nuclear power can remove the liquid logistics tail.
- Energy assurance & resilience of critical facilities and emergency response are other important use cases for nuclear power
- Energy requirements include traditional military energy usage, but energy needs are increasing exponentially with new and emerging capabilities

Emerging Energy Demands

- Power Beaming
- Additive Manufacturing (3D printing)
- Synthetic Fuel Production
- Electrification of vehicles



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Department of Defense Additive Manufacturing Strategy

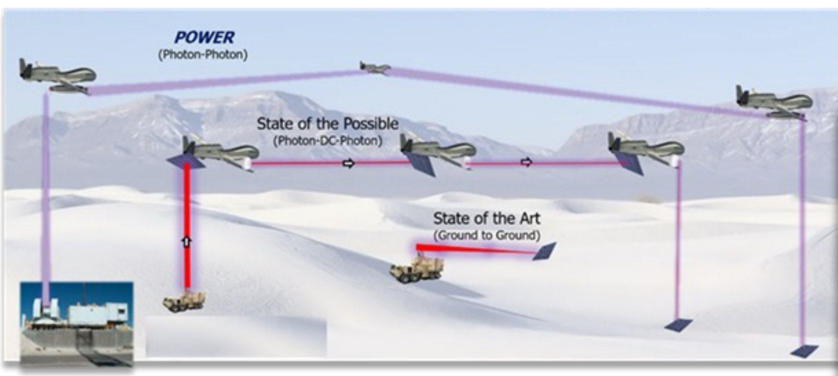
January 2021

Joint Defense Manufacturing Council

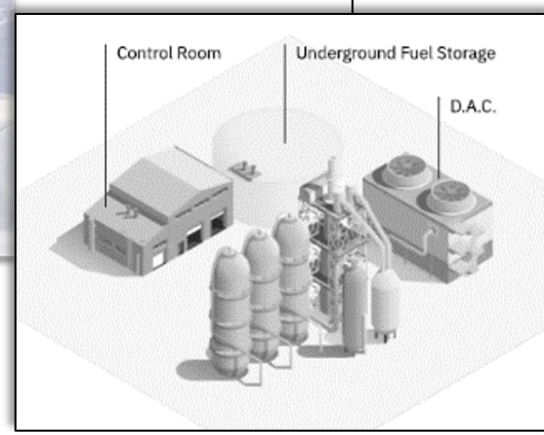
Office of the Deputy Director for Strategic Technology Protection and Exploitation

Office of the Under Secretary of Defense for Research and Engineering

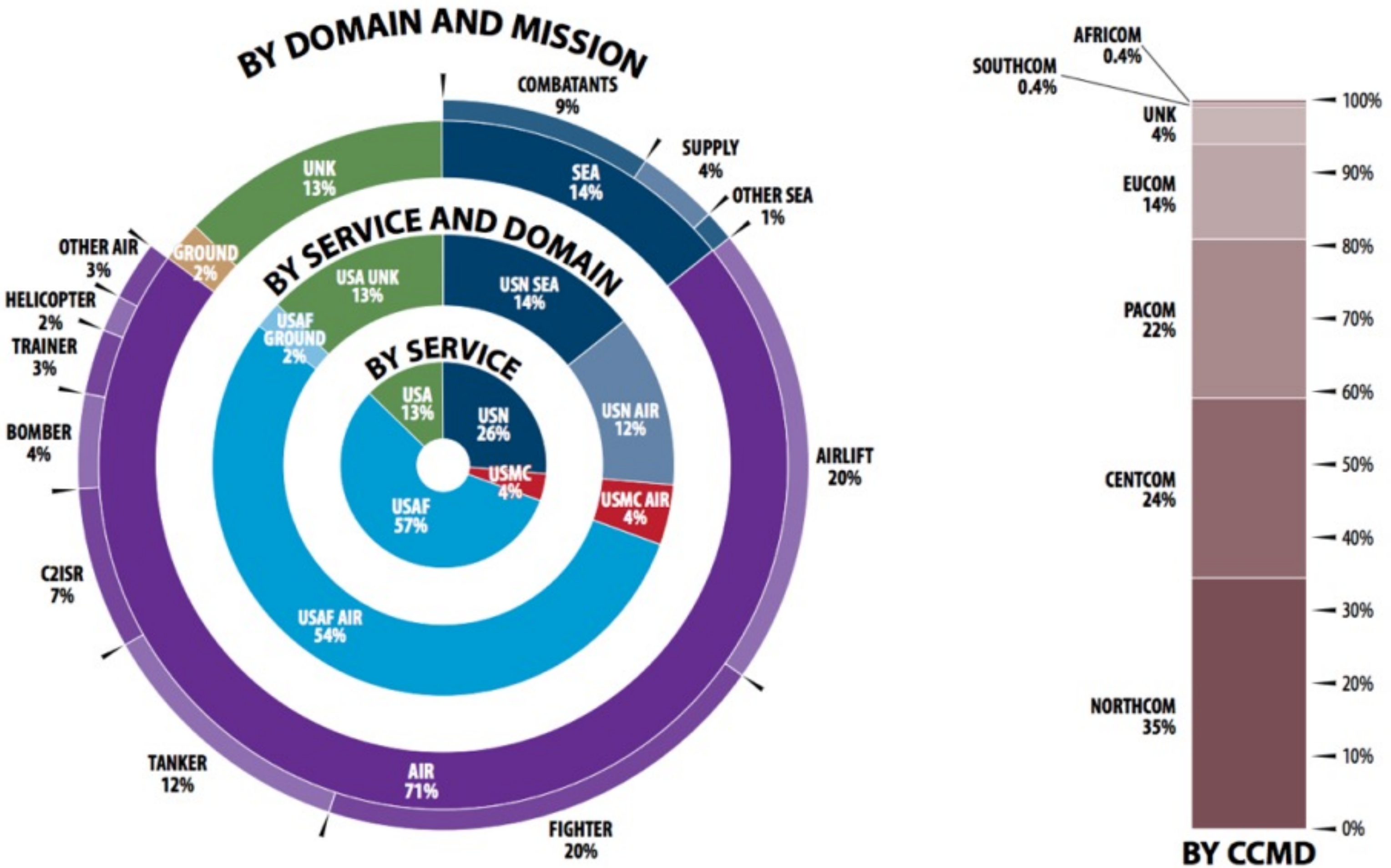
Washington, D.C.



https://www.darpa.mil/news-events/2022-10-05b



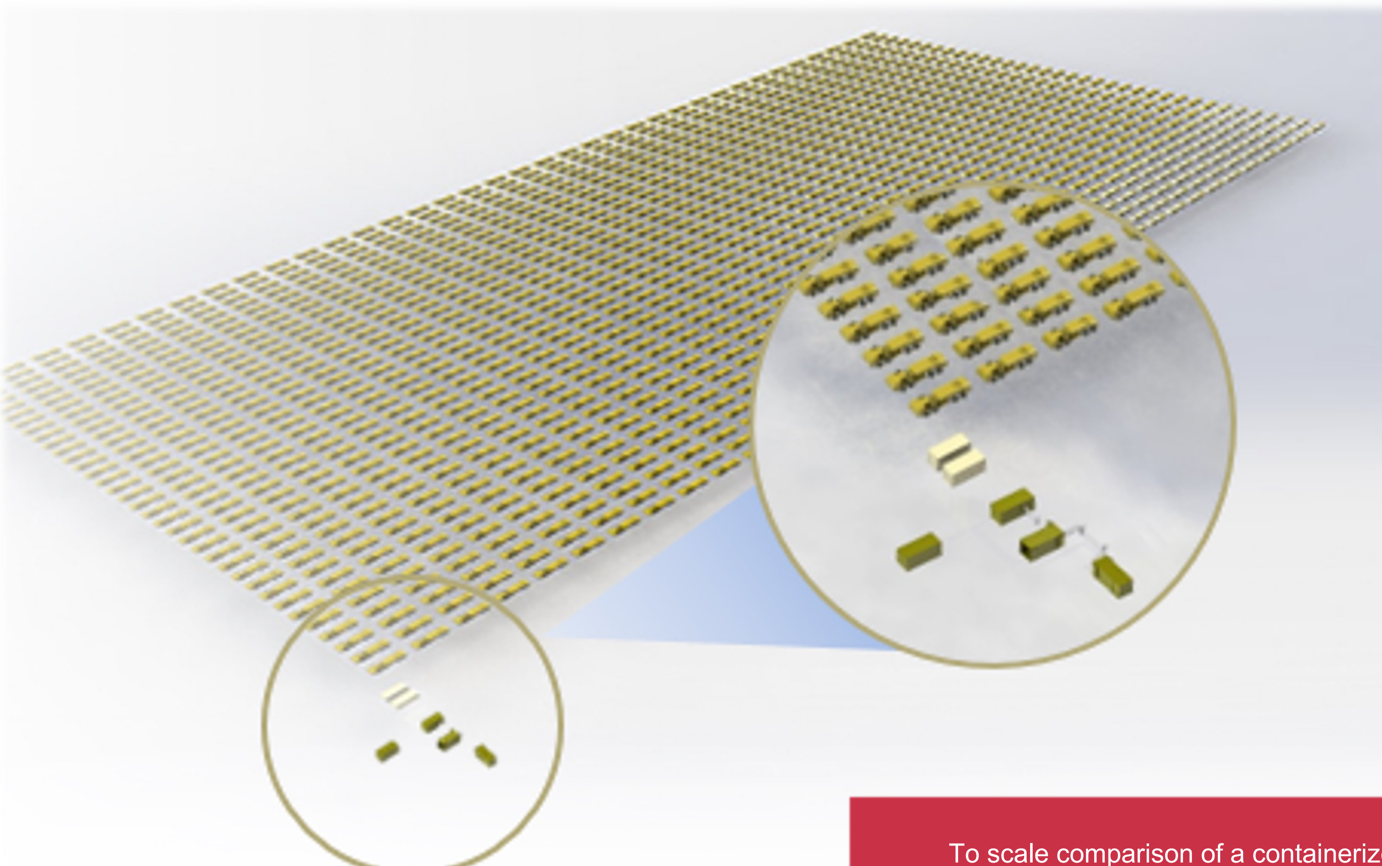
Operational Energy Use



Operational Energy Use, FY 2014

Nuclear Power Removes the Logistics Burden

Uranium-235 is *two million* times as energy dense as diesel



To scale comparison of a containerized microreactor and diesel energy delivery systems for 3 years of 1.5-megawatt full power operations

https://www.ans.org/news/article-3858/dod-to-move-ahead-with-project-pele/

Energy Performance Requirements

- **Sufficiency**
- **Reliability**
- **Survivability**
- **Transportability**

Let’s look at some other theoretical options for expeditionary energy…

Why not Wind for Expeditionary Energy?

600 Turbines
80 Meters Ave Height
$2.875 Billion
13 KM^2

Ave Generating
Capacity: 364 MWe

Sufficiency?
~~Reliability~~
~~Survivability~~
~~Transportability~~

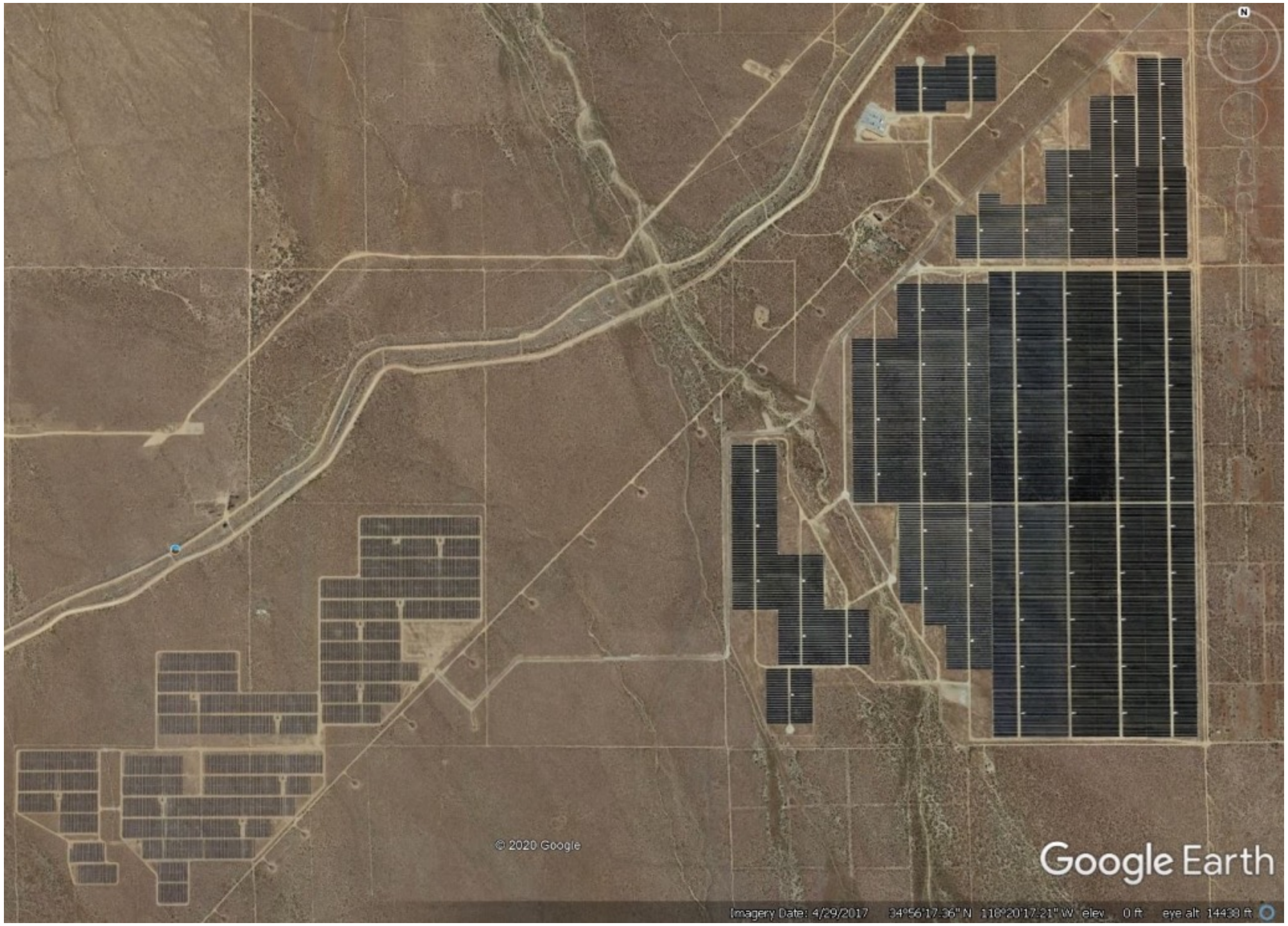
Alta Wind Farm (California)

Renewables cannot be relied upon

Monday's Energy Absurdity: Wind Power Went Negative in Saskatchewan Last Week

blackmon.substack.com • 3 min read

Why Not Solar for Expeditionary Energy?



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Sufficiency?
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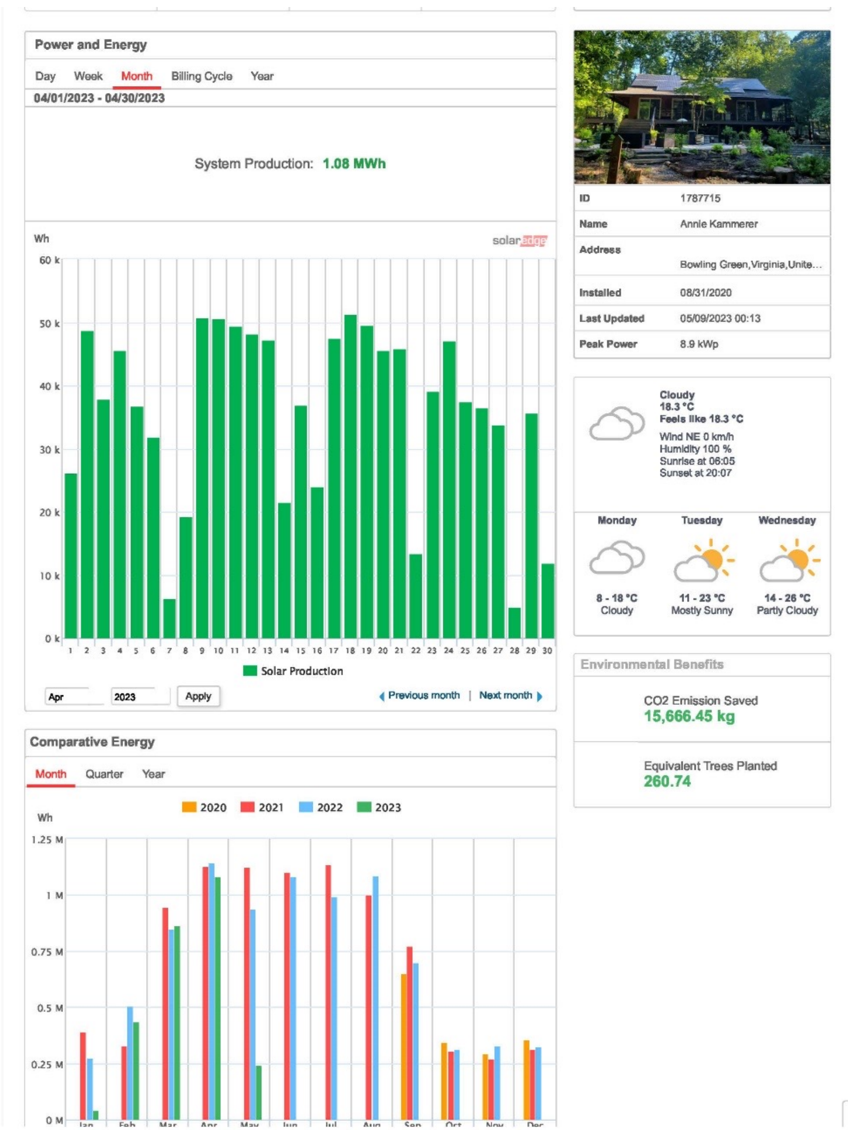
Solar Star Solar Farm (California)

Renewables cannot be relied upon



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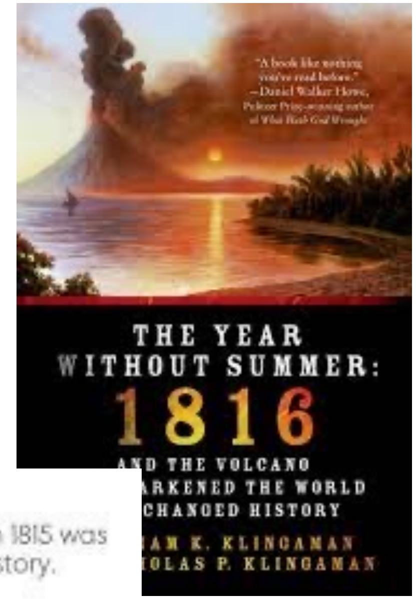
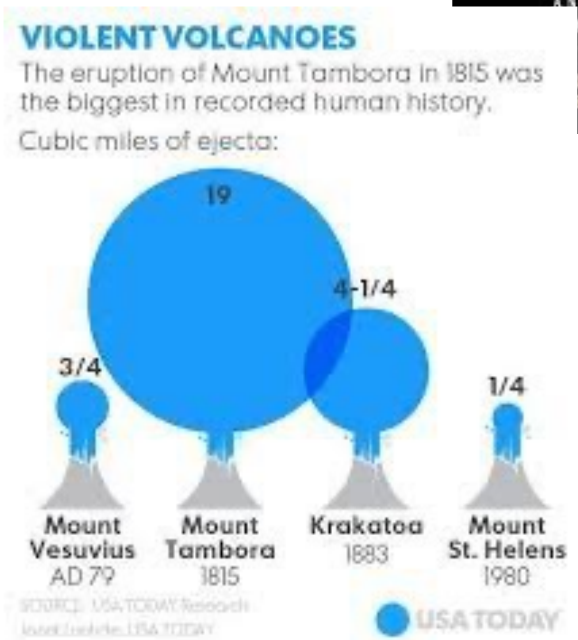
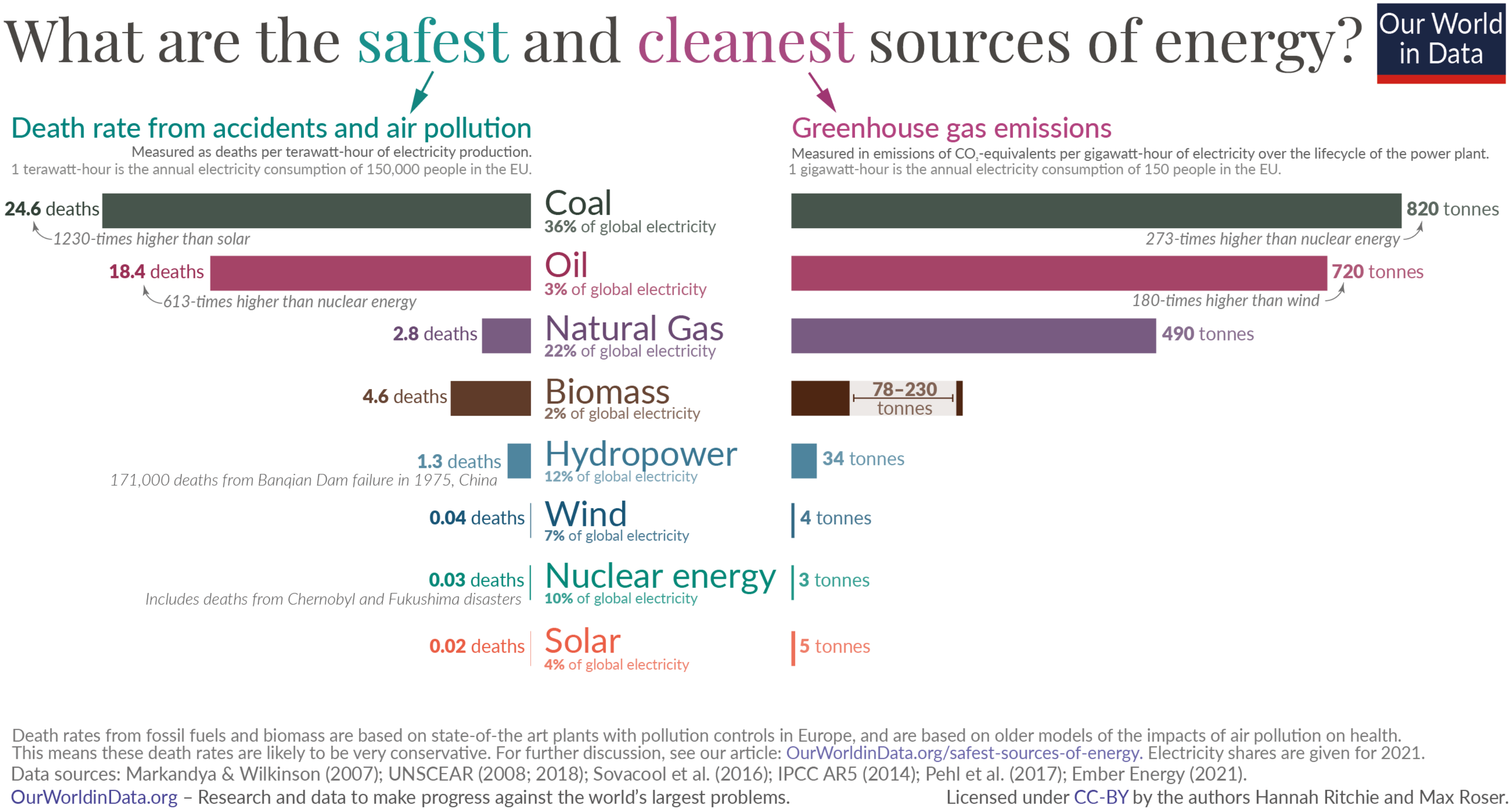


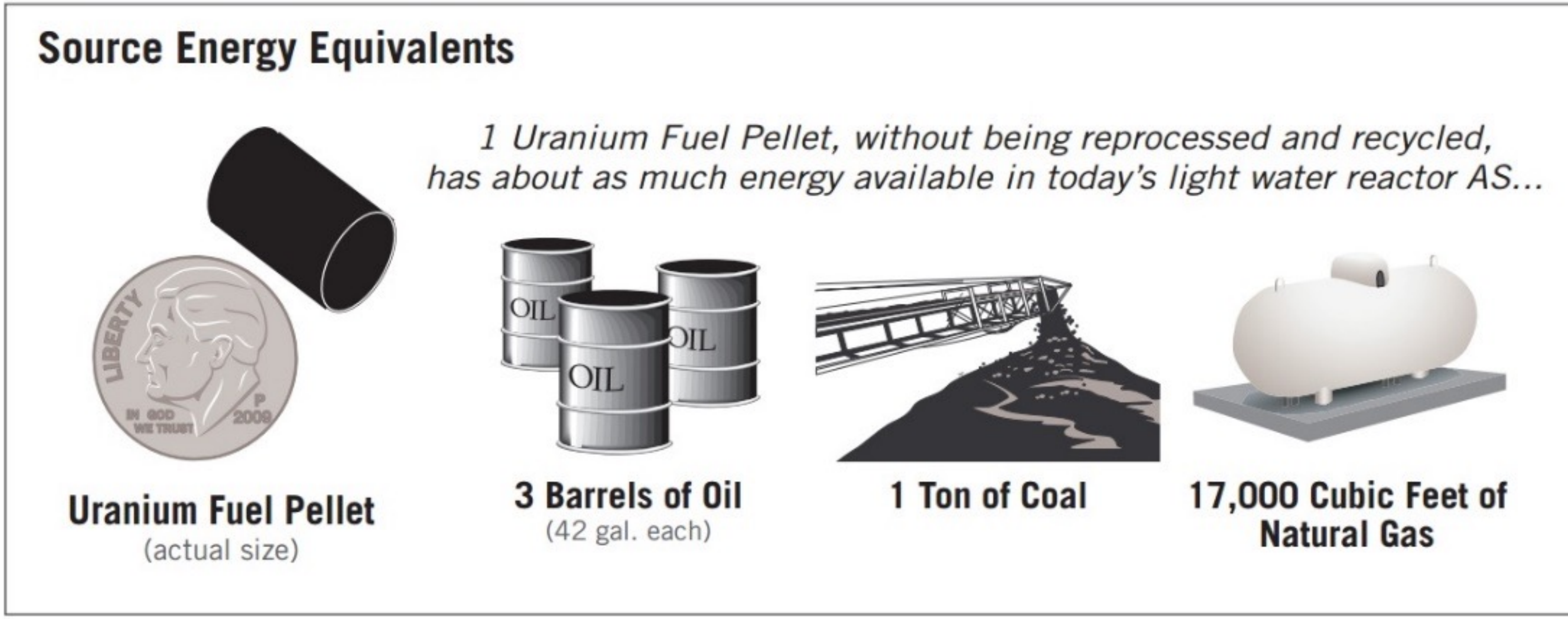


Climate Change



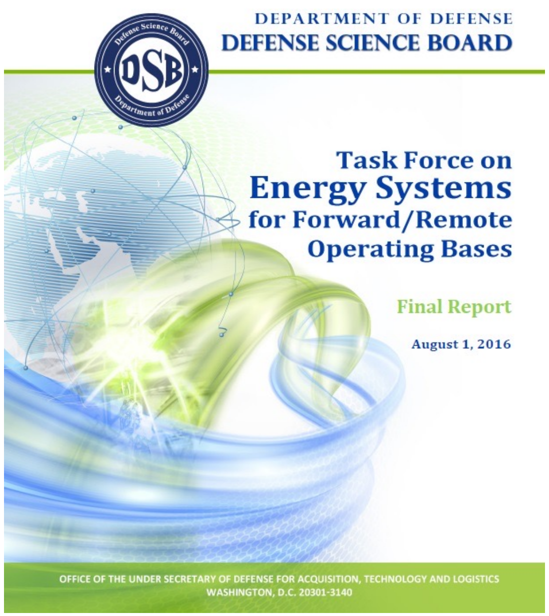
Nuclear provides a secondary benefit of clean, safe, emission free power without compromising the DoD's operational readiness.

Energy Density Comparison



Transportable Nuclear Power: Why Now?

- **Defense Science Board in 2016 identified critical growing energy challenges**
  - Energy usage on the battlefield is likely to increase significantly over the next few decades making energy delivery and management a continuing challenge.
  - Exponential growth in energy demand is forcing a serious re-evaluation of DoD energy logistics
  - Longer-term energy solutions should support sustainment of technical superiority.
  - New modern warfighting systems (e.g. directed-energy lasers, railguns, and UAVs) have ever-increasing demands for reliable, high-density energy.
- **Significant technological advances in nuclear power since the 1960s**
  - Generation III reactors have been operating safely since 1996, and significant development and risk-reduction on Generation IV reactors is already complete.
  - Fully inherently safe reactors have been built and tested, allowing autonomous operation and eliminating meltdown risks.


DEPARTMENT OF DEFENSE
DEFENSE SCIENCE BOARD
Task Force on
Energy Systems
for Forward/Remote
Operating Bases
Final Report
August 1, 2016
OFFICE OF THE UNDER SECRETARY OF DEFENSE FOR ACQUISITION, TECHNOLOGY AND LOGISTICS
WASHINGTON, D.C. 20301-3140

DSB Conclusion: "There is opportunity to invert the paradigm of military energy. The U.S. military could become the beneficiaries of reliable, abundant, and continuous energy through the deployment of nuclear energy power systems."

Transportable Nuclear Power: Why Now?

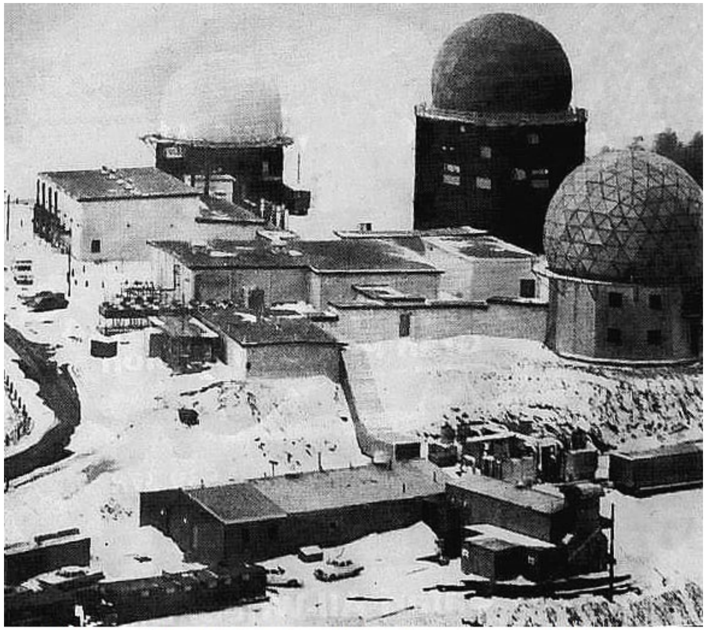
The US Navy Nuclear Program

- Built ~526 Reactor Cores
- Operates ~92 Reactor Cores
- 5,700 Accident-Free Reactor Years
- Average dose of <5 mrem/year

US Reactors Built Since 1993	US Commercial	US Navy
Built	4	50
Under Construction	1	15
On Order	2	11

Portable Nuclear Power: An Old Idea

- **The U.S. Army Nuclear Power Program ran from 1954 through 1977.**
  - Eight reactors were constructed (five were portable), each between 1-10 MWe, of various designs and for various purposes.
- **The first U.S. nuclear reactor to be connected to an electrical grid, in 1957, was an Army reactor (SM-1).**
- **As some of the earliest nuclear reactors ever built, they were technologically difficult to operate, unreliable, and too expensive relative to abundant fossil fuel alternatives.**



PM-1 Nuclear Plant (PWR), Sundance Air Force Station, Wyoming, 1962-1968

ML-1 US Army reactor, 1958, Arco, Idaho

So, what happened?

- As some of the earliest nuclear reactors ever built, the Army reactors were technologically difficult to operate, unreliable, and too expensive relative to abundant fossil fuel alternatives.
- Additionally, the Army Nuclear Power Program (ANPP) had several accomplishments, but ultimately it was considered to be "a solution in search of a problem.“
- While the Navy has always been dependent on significant levels of energy, the same was not always true of the Army.
- Increasing energy needs, coupled with recognized logistics complications, mean that now the solution has a problem to address.

Project Pele

In Hawaiian religion, Pele is the goddess of volcanoes and fire and the creator of the Hawaiian Islands. Often referred to as "Madame Pele" or "Tūtū Pele" as a sign of respect, she is a well-known deity within Hawaiian mythology and is notable for her contemporary presence and cultural influence as an enduring figure from ancient Hawaii.

Wikipedia

Project Pele Overview

Mobile Nuclear Power For Future DoD Needs

Slides with SCO header courtesy of

Dr. Jeff Waksman

Project Pele Project Manager

Project Pele

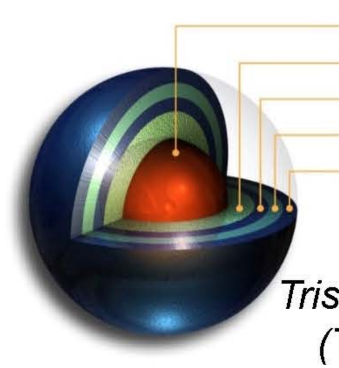
- **A 2016 Defense Science Board (DSB) study[1] found the Department of Defense (DoD) has a need for a mobile, reliable, sustainable, and resilient power source which does not require a long logistics tail**
  - Nuclear power is uniquely suited to meet DoD needs (2M x energy density of diesel)
  - Advances in technology have made feasible highly autonomous, inherently safe, reactors
  - Funded as a Climate program (can offset >1 million gallons of diesel/year)
- **Incorporates Advanced Tristructural Isotropic (TRISO) encapsulated nuclear fuel for safe operations**
  - Robust particle coatings are extremely resistant to meltdown or kinetic destruction
  - SCO/DOE/NASA have re-established a national TRISO production capability
- **Two-year reactor design competition kicked off in March 2020**
  - BWXT selected as winning design in Spring 2022
- **Pele hardware purchases have begun**
  - Fuel fabrication began in December 2022
  - Long lead item hardware purchases began in early-2023
- **Pele fabrication will begin once final design received initial DOE approval**
  - Submission of engineering design to DOE targeted for end of Q42023
  - Targeting delivery of reactor module to Idaho National Laboratory by end of 2024

[1] Defense Science Board, Final Report, Task Force on Energy Systems for Forward/Remote Operating Bases (August 1, 2016)

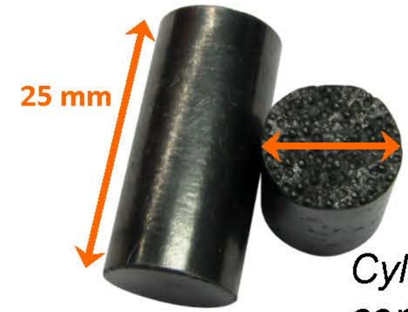
TRISO Fuel: A Paradigm Shift For Nuclear Power

- **The Advanced Gas Reactor (AGR) Fuel Development Program was initiated in 2002**
  - TRISO fuel has already been subjected to rigorous testing by DoE, eliminating the need for DOD/SCO to develop or qualify a new fuel
- **Silicon carbide keeps fission products sealed inside, meaning that a containment vessel failure is no longer catastrophic**
  - Design reduces diversion and proliferation risks due to low (< 20% U235) enrichment and individually coated particles
  - Rugged, robust fuel structure deters use as an improvised weapon such as a dirty bomb
- **Innovative design as first line of containment is a paradigm shift in safety for nuclear power**
  - TRISO fuel and compacts could significantly lower safety/O&M/regulatory costs
  - Pellets minimize consequences to the environment and population from events affecting integrity of reactor or threatening release of contamination

Kinetic impact testing of TRISO simulants is an element of Project Pele



Tristructural isotropic (TRISO) particle



Cylindrical fuel compacts

Whole of Government Approach

- **Interagency collaboration is crucial to the success achieved by SCO's Project Pele. This includes:**
  - Department of Energy (DOE) and Nuclear Regulatory Commission (NRC) are providing technical support, design/safety advice, and guidance on reducing current and future licensing risk
  - DOE is providing reactor safety oversight and authorization, and through an interagency agreement is providing an extension of Price-Anderson nuclear indemnification
  - NRC is participating in a licensing modernization approach for review and approval of over-the-road transport
  - Army Corps of Engineers and DOE supported NEPA Environmental Impact Statement
  - NNSA is providing Pele with enriched uranium from its stockpile
  - NASA and DOE have developed, jointly with SCO, a commercial-scale TRISO facility

US Army Corps of Engineers®

National Nuclear Security Administration

Pathfinder To Commercial Advanced Reactors

- **Regulatory Test Case**
  - NRC has been instructed by Congress to develop a new regulatory approach for advanced reactors[1]
  - In 2020, the NRC approved the risk-informed regulatory approach of the Licensing Modernization Project, but there has yet to be a commercial reactor design licensed through this process
  - The NRC is participating in Project Pele as an observer, giving them hands-on experience and data for the initial safety basis demonstration testing of an advanced non-light water reactor
  - NRC is also working closely with SCO to advise on qualification of materials/components, which will significantly advance the regulatory readiness of a commercial spin-off of Pele

- **TRISO was designed to be a commercial reactor game-changer**
  - AGR particles have already been extensively tested and qualified by DOE
  - High melting temperatures allow for a passively safe reactor which can significantly reduce capital investment and O&M costs

- **DoD requirements and application can drive commercial future**
  - Shippingport reactor (1957) was built by the Navy out of a surplus aircraft carrier reactor
    - To this day, most commercial nuclear reactors around the world are light water PWRs[2] because that's what Admiral Rickover chose for the USS Nautilus
  - Pele is designed to be maximally resilient to external hazards and nuclear proliferation
    - Potential to drive high standards for nuclear safety and non-proliferation if a U.S. DoD reactor becomes the pathfinder for Generation IV reactors, rather than Chinese or Russian designs

[1] Nuclear Energy Innovation and Modernization Act (NEIMA) and Nuclear Energy Innovation Capabilities Act (NEICA)
[2] Pressurized Water Reactors

Nuclear Power Is Hard

"An academic reactor or reactor plant almost always has the following 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. It will use mostly "off-the-shelf" components. (8) The reactor is in the study phase. It is not being built now.

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 heavy. (8) It is complicated."

--Hyman Rickover, 1953
"The Father of the Nuclear Navy"

Number of non-Naval power reactors currently under construction, by nation*:

19: China
8: India
4: Russia
3: South Korea, Turkey
2: Bangladesh, Egypt, Japan, Ukraine, United Kingdom, **USA**
1: Argentina, Belarus, Brazil, France, Iran, Slovakia UAE

The last successfully completed non-Naval nuclear power reactor in the United States broke ground on construction in 1978.**

*As of March 2023, per https://pris.iaea.org/PRIS/WorldStatistics/UnderConstructionReactorsByCountry.aspx
**Shearon Harris Nuclear Power Plant

Design → Power

Engineering Design + Safety Approach

- Make final design decisions
- Purchase long lead hardware[1]
- Fabricate Pele fuel
- Review all significant design decisions with INL and DOE safety officials
- Submit PSAR (Preliminary Safety Analysis Report)
- Finalize engineering design

As of April 2023, we are here

DOE approves preliminary safety analysis

Fabricate Pele prototype

- Change Control Board reviews any design changes
- Non-nuclear integration testing/quality assurance
- Transport TRISO fuel compacts to INL
- Submit FSAR (Final Safety Analysis Report)

DOE approves final safety analysis

Deliver Completed Reactor

- Transport prototype to INL
- Readiness review for fueling
- **Fuel reactor** in TREAT (Transient Reactor Test Facility)
- Deliver prototype to CITRC (Critical Infrastructure Test Range Complex)

DOE approves Operational Readiness Review

Initial Operational Testing

- **Turn reactor on**
- Validate reactor modeling
- Demonstrate safety
- Initiate TEMP (Test and Evaluation Master Plan)

[1] All long lead item purchases are approved by SCO, DOE-ID, and INL

Path Toward Successful Transition

- **Enforce quality of entire supply chain**
  - Rigorous process to approve all technical specifications before ordering components
  - Audits to ensure quality from both sub-contractors and other suppliers
- **Develop training program**
  - U.S. Army Office of the Chief of Engineers is collaborating with INL and USMA West Point on development of a training program, simulator work, and an operational manual
  - National Guard Bureau personnel will participate in reactor transport/assembly
- **DOTMLPF-P analysis**
  - Doctrine, Organization, Training, materiel, Leadership, Personnel, Facilities, Policy
    - U.S. Army Reactor Office has lead revising and modernizing Army Regulation AR50-7 (Army Reactor Program)
- **Transition must be cost-efficient**
  - Microreactors must be ordered in sufficient quantities and at sufficient speed for assembly efficiencies of scale to drive costs down to current prices in remote/austere locations
  - The DoD must tie nuclear decision to larger policy question of carbon-free energy and energy resiliency, and how much it is willing to spend to achieve those goals

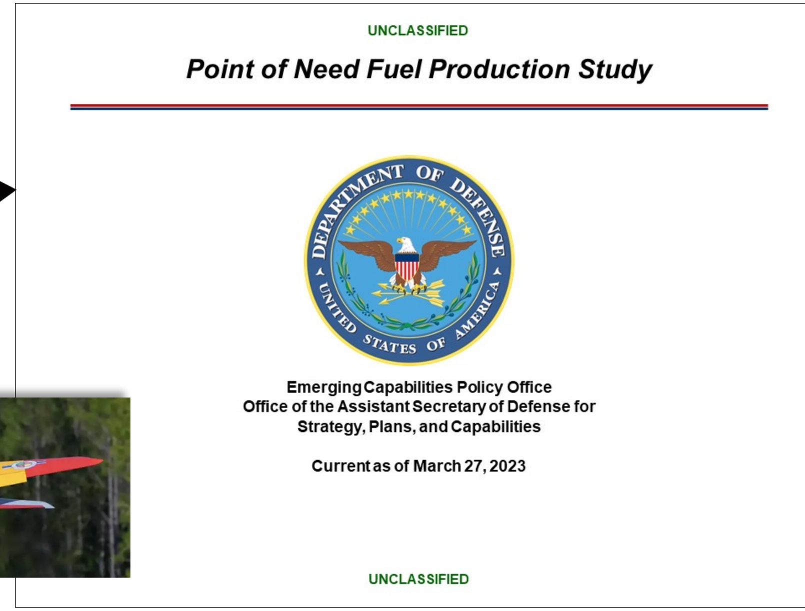
Whole-of-government decision on future of nuclear power must consider both military and commercial uses of microreactors and SMRs

Key US Army Activities To Develop Capability

- Army Mobile Reactor Advisory Council formed and provided input to Pele requirements
- Supported NEPA activities to develop EIS (completed 2022)
- Army Test and Evaluation Master Plan (95% draft)
- Significant revision to Regulation AR 50-7 (*Army Reactor Program*) and development of new DA-PAM by Army Reactor Office (i.e. the Army's nuclear regulator)
- Ongoing development of documentation (policy, procedures, manuals, etc.) for Army Nuclear Power Management Program
- Operational Team Training Plans (submitted for certification 2023)
- Army-Specific Operational Readiness Review (Plan developed 2023, completed prior to any transition to Army)
- Development of use cases/CONOPS/Cost-Benefit analyses, etc.
- Endorsements: USAEUR-AF, ARNORTH, ARCENT, ARSOUTH, USARPAC

Project FIERCE – Joint Capability

- **SynCE (Synthetic Fuel for Contested Environments) is a US AF project**
- **Objective is to produce jet/ground fuel at or near the point of need**
  - 100% synthetic drop-in replacement
  - In situ carbon and hydrogen feedstocks
  - Modular, mobile, and highly autonomous
- **Successful demonstration**
- **Next to containerize, automate, and optimize**

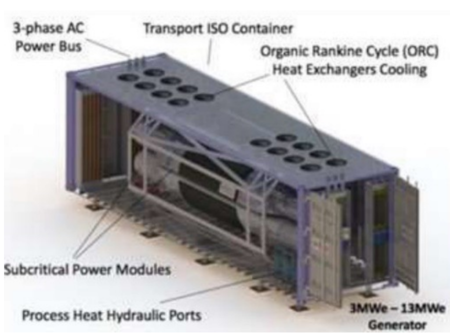

UNCLASSIFIED

Point of Need Fuel Production Study

Emerging Capabilities Policy Office
Office of the Assistant Secretary of Defense for Strategy, Plans, and Capabilities

Current as of March 27, 2023

UNCLASSIFIED



Pele-like reactor

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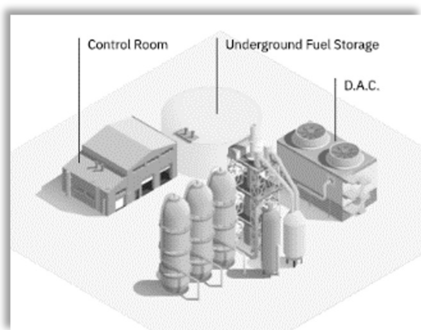


SynCE system

=

FIERCE Energy Hub

(forward integrated energy for remote and contested environments)

BLUF

- ***Energy is at the heart of our warfighting capability…and the needs are ever increasing.***

- ***We don't have an energy problem per se. We know how to produce energy. We have a logistics problem.***

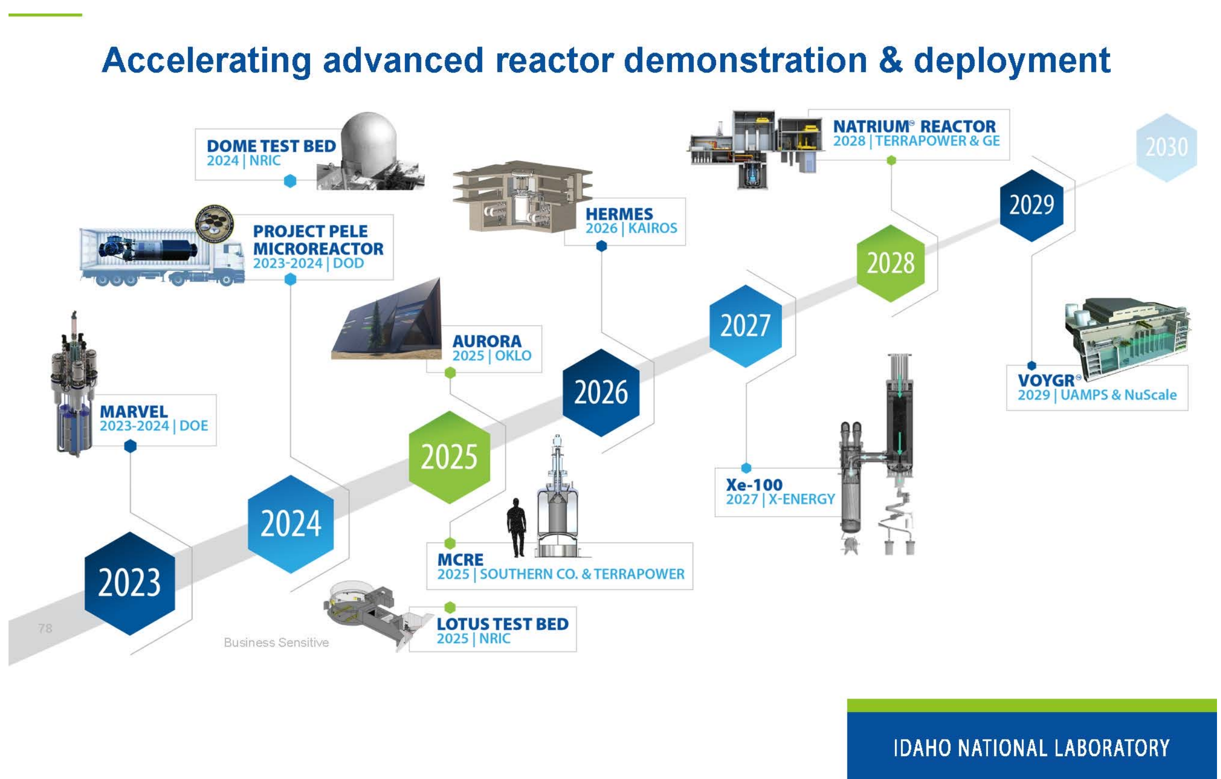
- ***Nuclear energy is the only viable power source to ensure that our warfighter's energy needs are met when and where they need to be met.***

- ***…and we also have a climate problem. It is, therefore, a very happy coincidence that nuclear energy also addresses our climate change problems.***

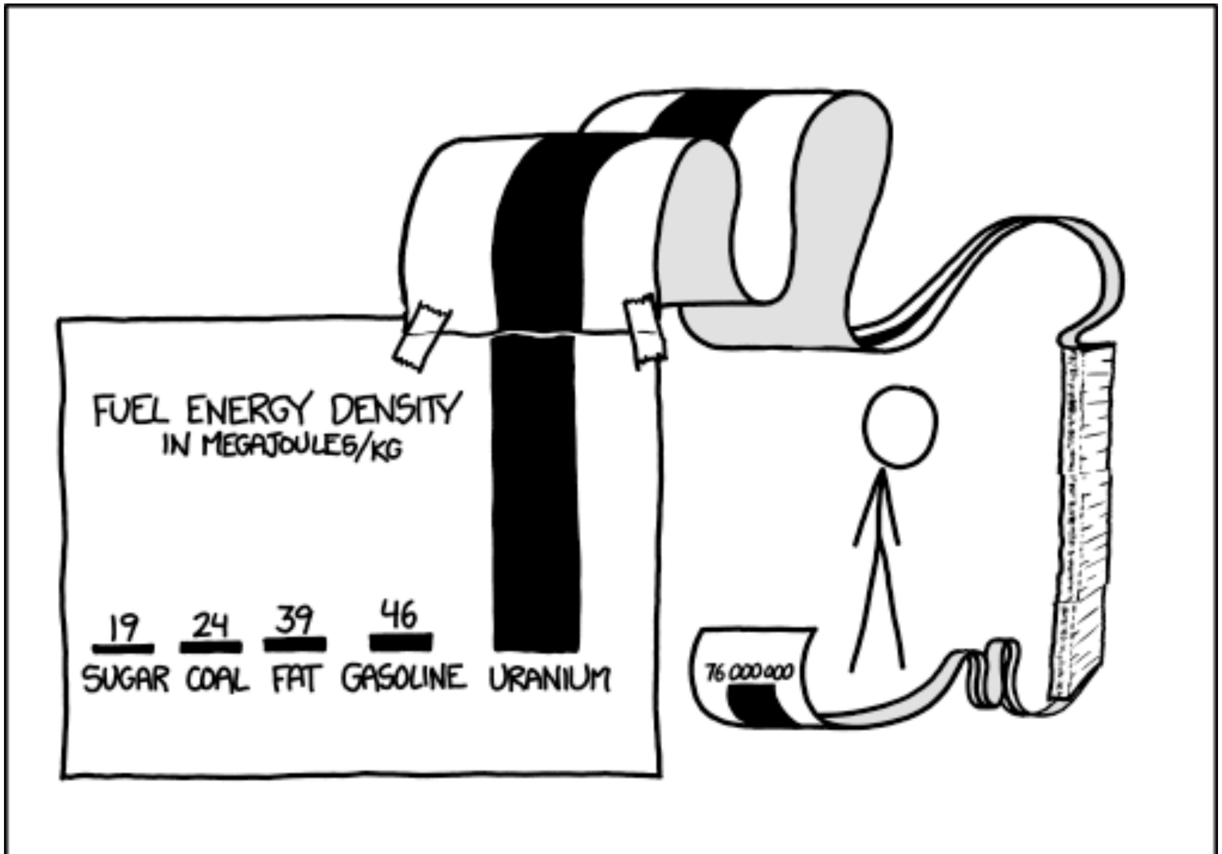
Questions?

Microreactors in the US

- **The US Nuclear Regulatory Commission has a licensing modernization project to address advanced reactors**
- **SCO has been supporting work at the Pacific Northwest National Laboratory to develop risk-informed licensing approaches for transportation packaging**



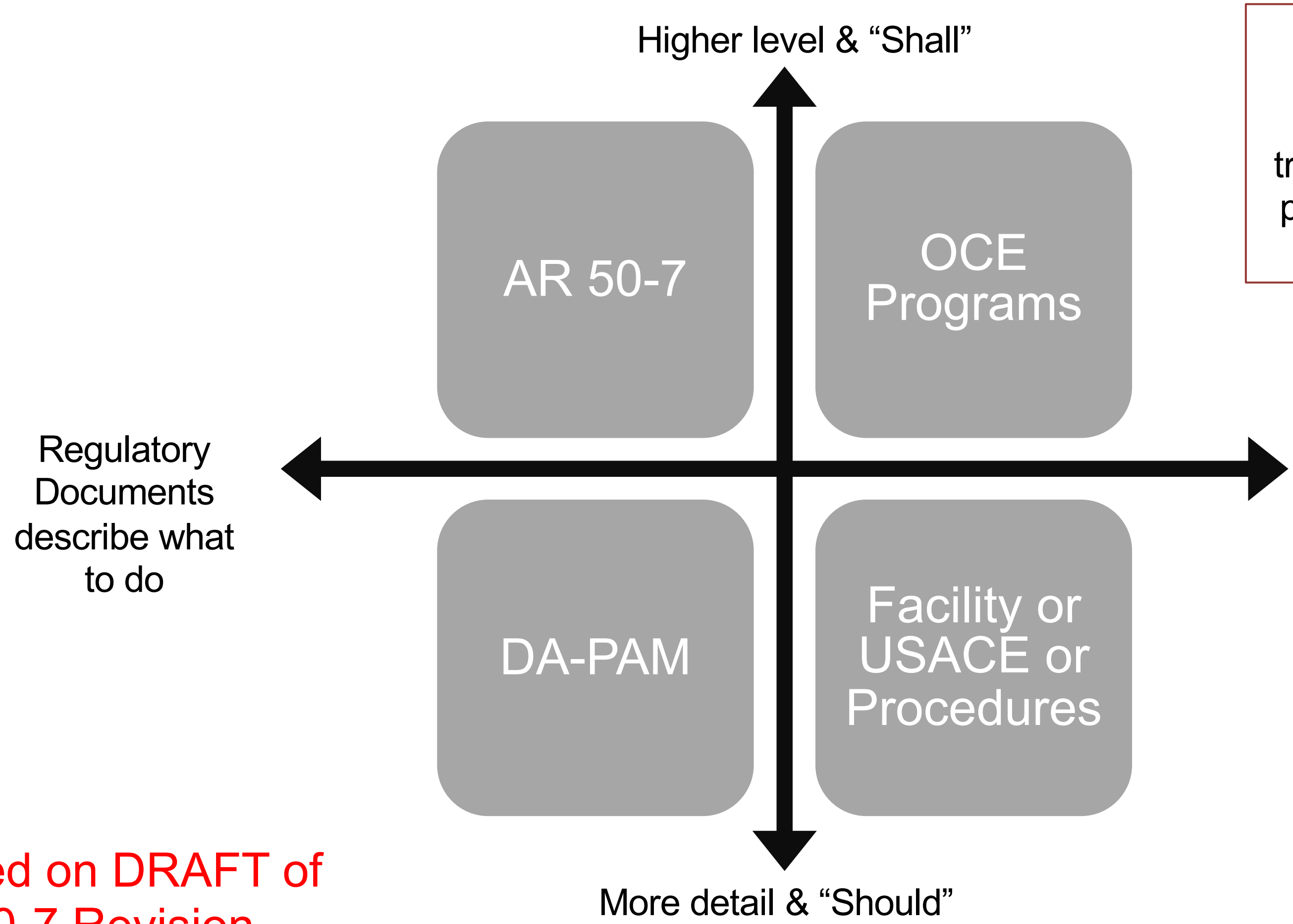
Energy Density Comparison



SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT *PROPERLY.*

US Army Nuclear Regulatory Framework

AR50-7 covers stationary facility nuclear power, transportable nuclear power, and research reactors



Based on DRAFT of AR50-7 Revision. Subject to change.

US Army Nuclear Regulatory Framework

ARO — Oversight

OCE — Leads Nuclear Power Management Program & Provides SME Expertise

USACE — Operation of Transportable Reactors

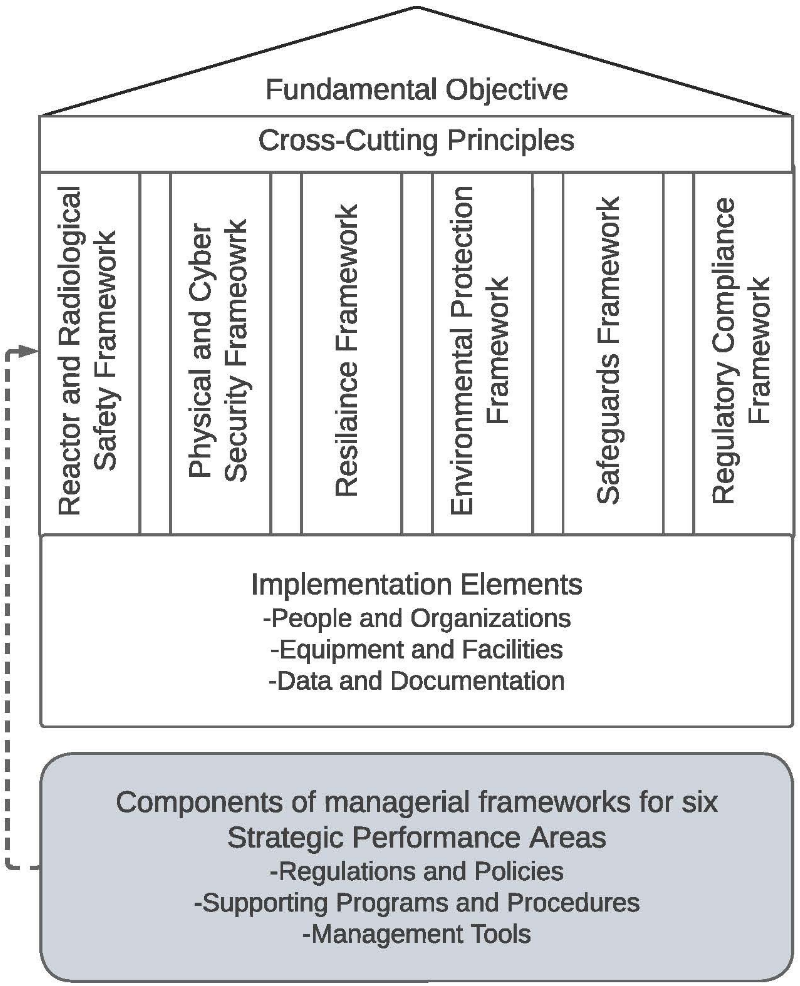
PEO — Equipment Life Cycle

Movement ← Uses existing processes for Unit Movement Officers

Based on DRAFT of AR50-7 Revision. Subject to change.

Numerous organizations are involved to various degrees

OCE Supporting Programs Required in AR50-7



Army Nuclear Reactor Management Program Overview

FUNDAMENTAL OBJECTIVE

The fundamental objective is the overarching goal that drives all aspects of the program. The Fundamental Objective is to:

To provide for the safe, reliable, and environmentally responsible use of nuclear power in support of the Army's principal objective to fight and win the nation's wars

DRAFT CROSS-CUTTING PRINCIPALS

1. **Performance-Based Objectives.**
2. **Risk-Informed Decision-Making Framework.**
3. **Army compliance.**
4. **Full regulatory compliance. Transparency & traceability.**
5. **Nuclear defense-in-depth.**
6. **Continuous improvement.**
7. **Safety culture, operational excellence**
8. **Army and nuclear ethics and professionalism**
9. **People – appropriate staffing, appropriate backgrounds, training, leadership**

DRAFT Concepts. Subject to change.

Electric Fleet - Don't Become This

A move towards electric vehicles is great, but an appropriate infrastructure is needed to support them