# Introduction to Fusion Energy Safety and Regulation

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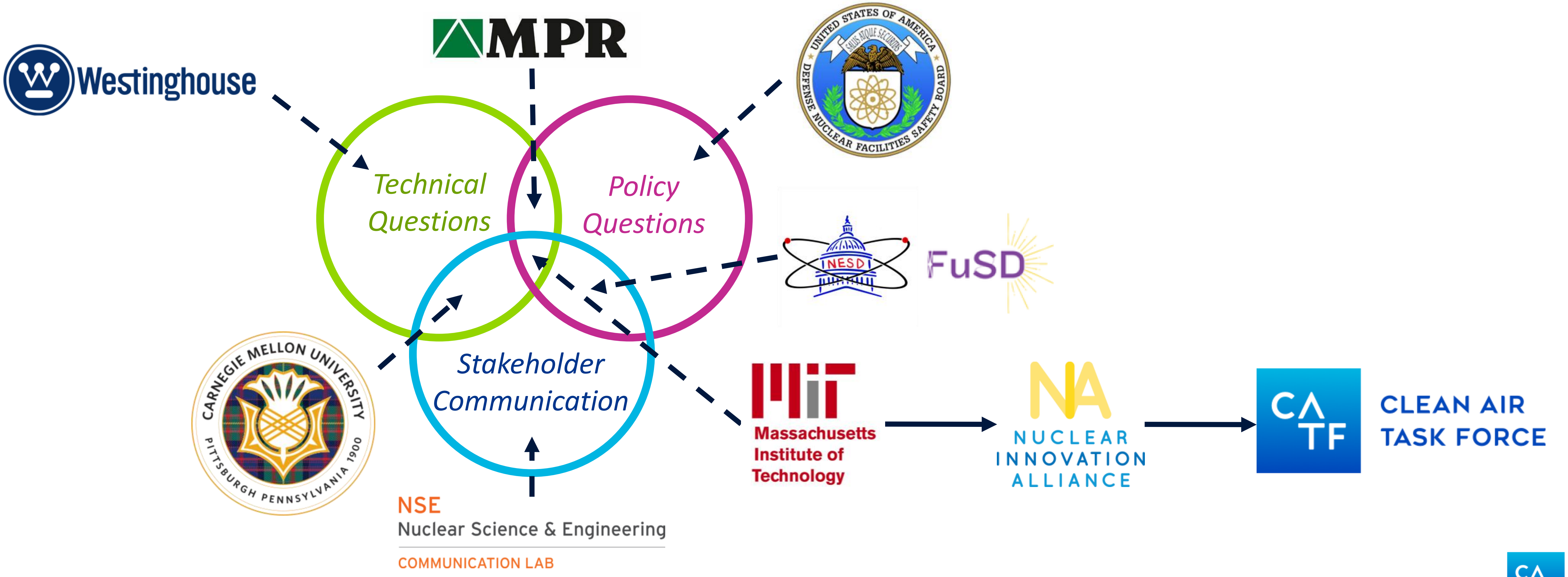
PPPL 2025 Introduction to Plasma and Fusion Course
June 4th, 2025

CLEAN AIR TASK FORCE

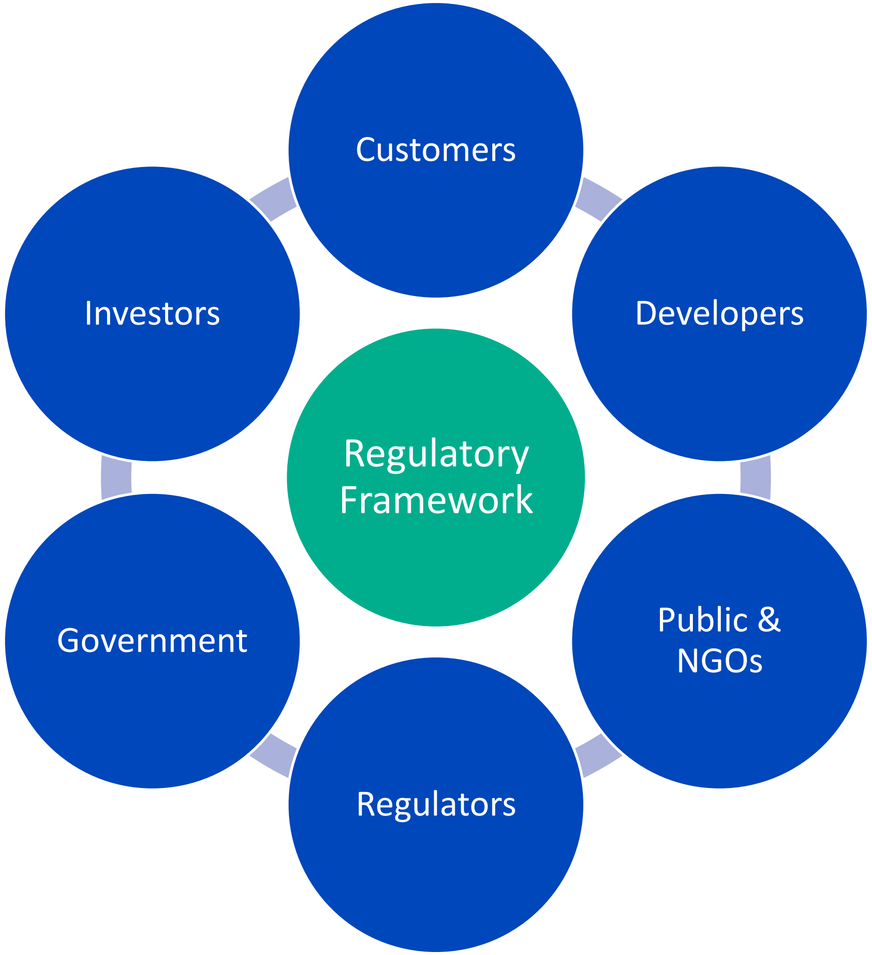
# — My personal background: thinking about hard questions at the intersection of technology and policy



# CATF Fusion Safety and Regulation Working Group

- Goal: Creating a harmonized framework for safety and regulation for commercial fusion energy that can be adopted internationally and enable the global deployment of fusion energy. This framework must include both public acceptance of fusion energy and commercial viability of the technology.

- Challenge: Varying regulatory needs throughout based on the specific fusion machine, technology lifecycle, and during different stages of commercialization.



# Fusion energy has immense potential, but safety and regulation must be aligned to enable development

Commercial Fusion Landscape

Fusion Energy Regulation

Other Fusion Considerations

# — The commercial fusion energy landscape has a wide range of different proposed concepts and technologies

- **Commercial Fusion Landscape**
- Fusion Energy Regulation
- Other Fusion Considerations

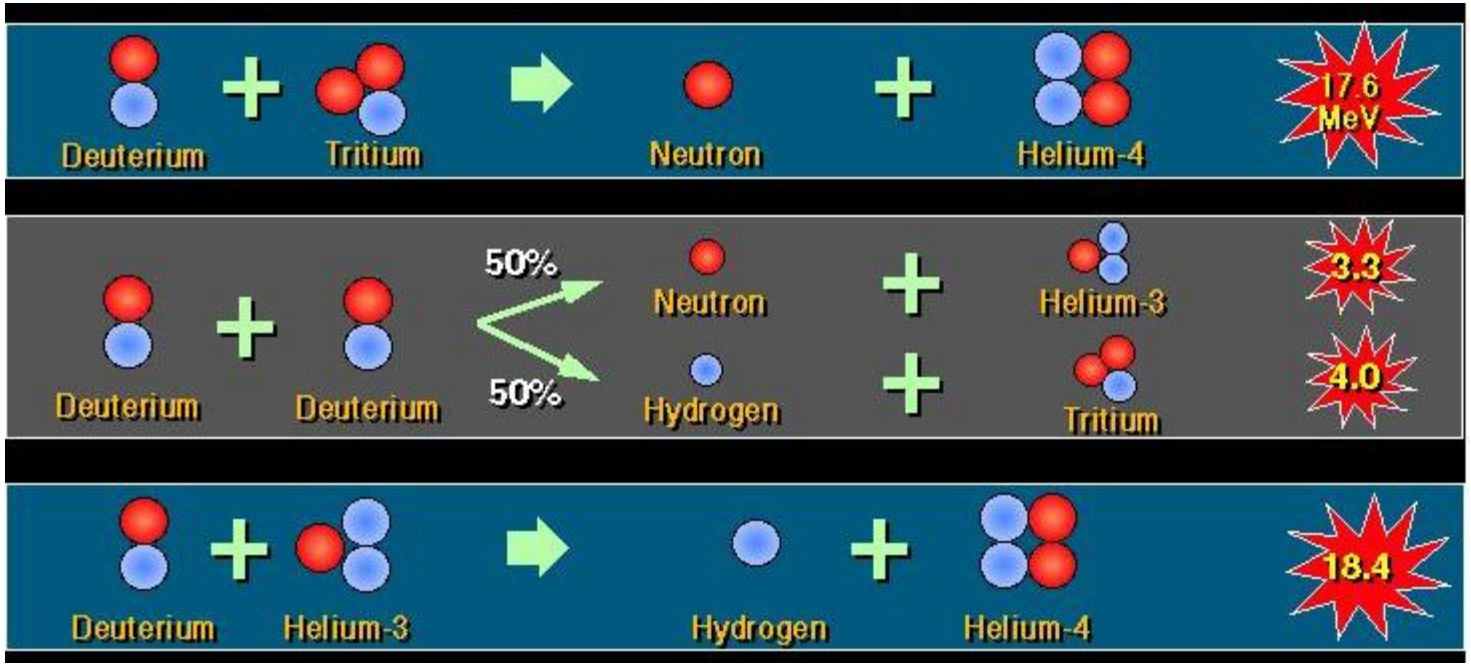
# Fusion machines under development use different approaches for commercial energy generations

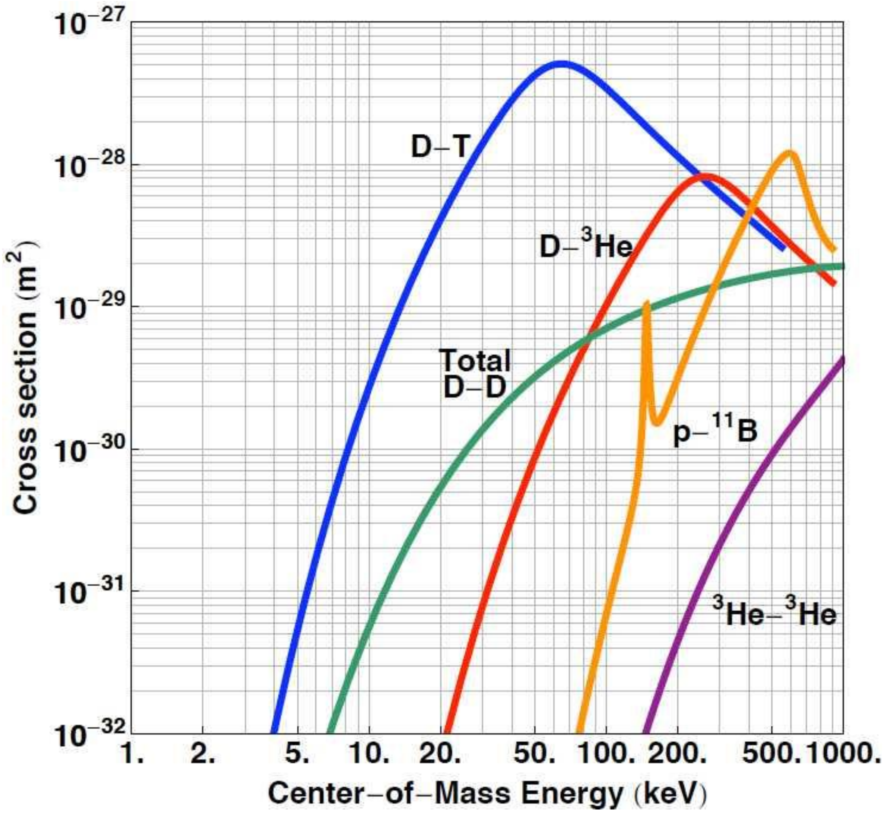
- Confinement Methods
- Fusion Reactions
- Fusion Fuel Cycles
- Power Conversion Cycle
- Facility Size

# Fusion energy technologies are typically defined based on how they confine the plasma

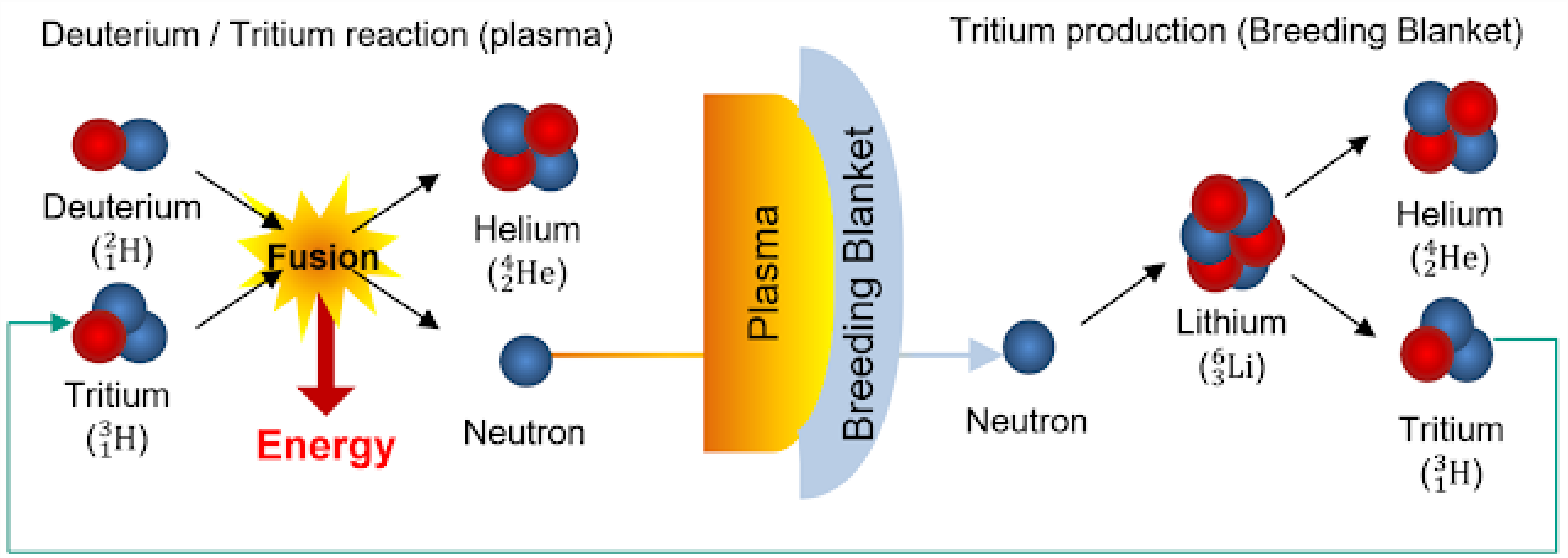
| Magnetic Confinement | Magneto – Inertial Confinement | Inertial Confinement | Alternative Confinement |
|---|---|---|---|
| *Includes:*<br>Tokamak<br>Stellerator | *Includes:*<br>Z-Pinch<br>Field Reverse Configuration (FRC) | *Includes:*<br>Direct ICF<br>Indirect ICF | *Includes:*<br>Electrostatic<br>Muon Catalyzed |

# — Different fusion fuels will have design and operational advantages and challenges



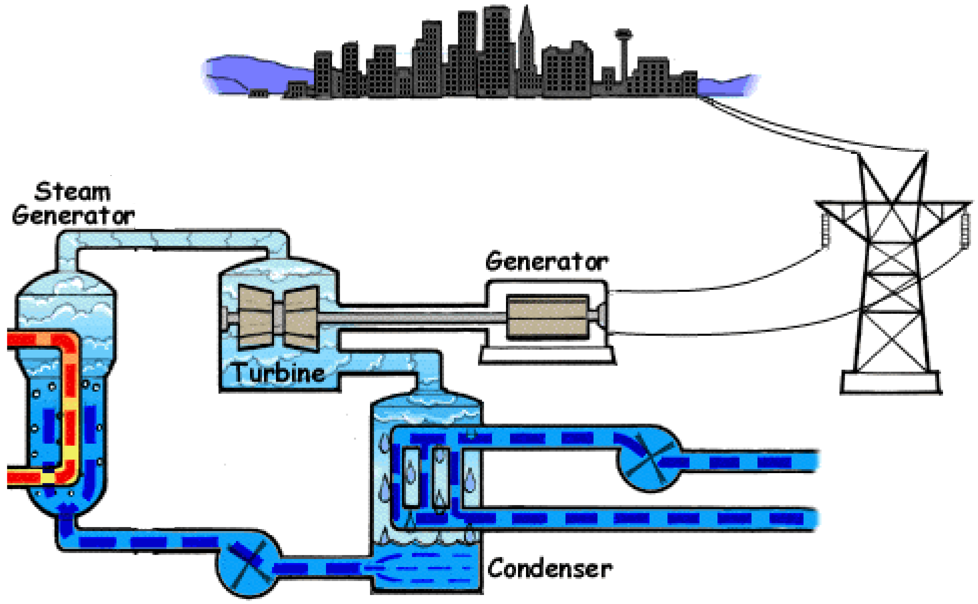



## — Fusion fuel cycles are needed to produce the specific isotopes required for fusion reactions

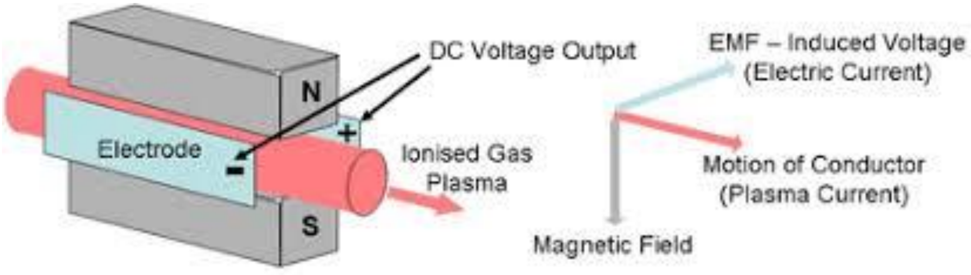



Example: Deuterium-Tritium Fuel Production with Lithium-6

# — Fusion power conversion cycles may use traditional thermodynamic cycles or novel technologies




Example: Steam Rankine Cycle




Example: Direct Energy Conversion

# Private companies are developing machines based on an array of different fusion energy technologies

- Confinement Methods
- Fusion Reactions
- Fusion Fuel Cycles
- Power Conversion Cycle
- Facility Size

Commonwealth Fusion Systems
Tokamak Energy
HELION
TYPE ONE ENERGY
XCIMER
generalfusion
Proxima Fusion
ZAP ENERGY

# Example: Commonwealth Fusion Systems ($2B+ Private Funding)

Confinement Methods

Magnetic Tokamak

Fusion Reactions

D-T

Fusion Fuel Cycles

FLiBe Blanket Breeding

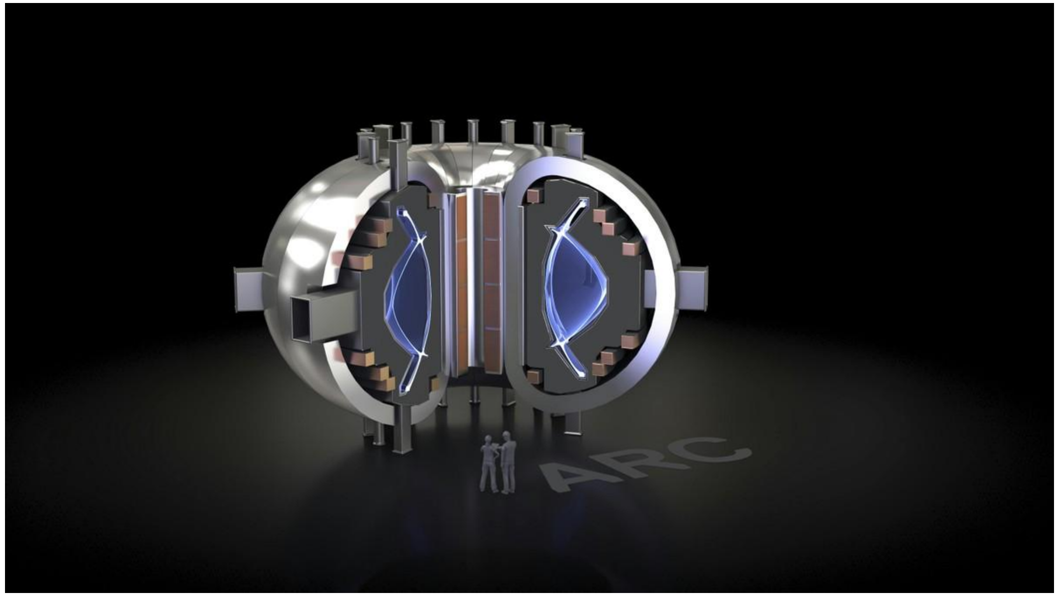
Power Conversion

FLiBe Blanket to Rankine Cycle

Facility Size

400 $MW_e$

Commonwealth Fusion Systems




CATF

# Example: Helion ($1B+ Private Funding)

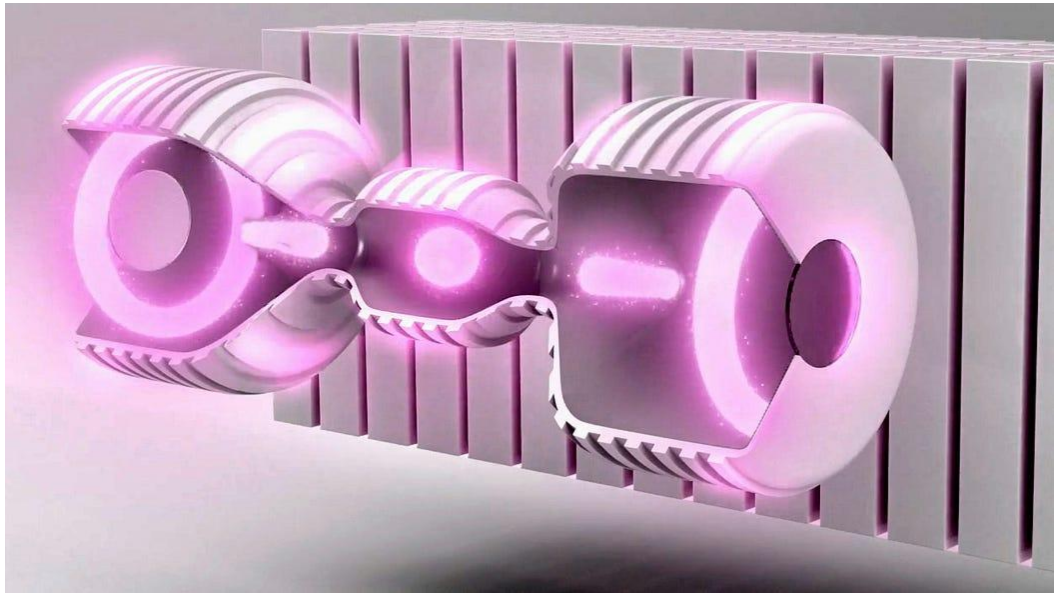
**Confinement Methods**
Magneto Inertial

**Fusion Reactions**
D-$^3$He

**Fusion Fuel Cycles**
D-D $^3$He Production, T Decay

**Power Conversion**
Direct Energy Conversion

**Facility Size**
50 $MW_e$



# — Example: Xcimer ($100M+ Private Funding)

Confinement Methods

Laser Inertial Confinement

Fusion Reactions

D-T

Fusion Fuel Cycles

FLiBe

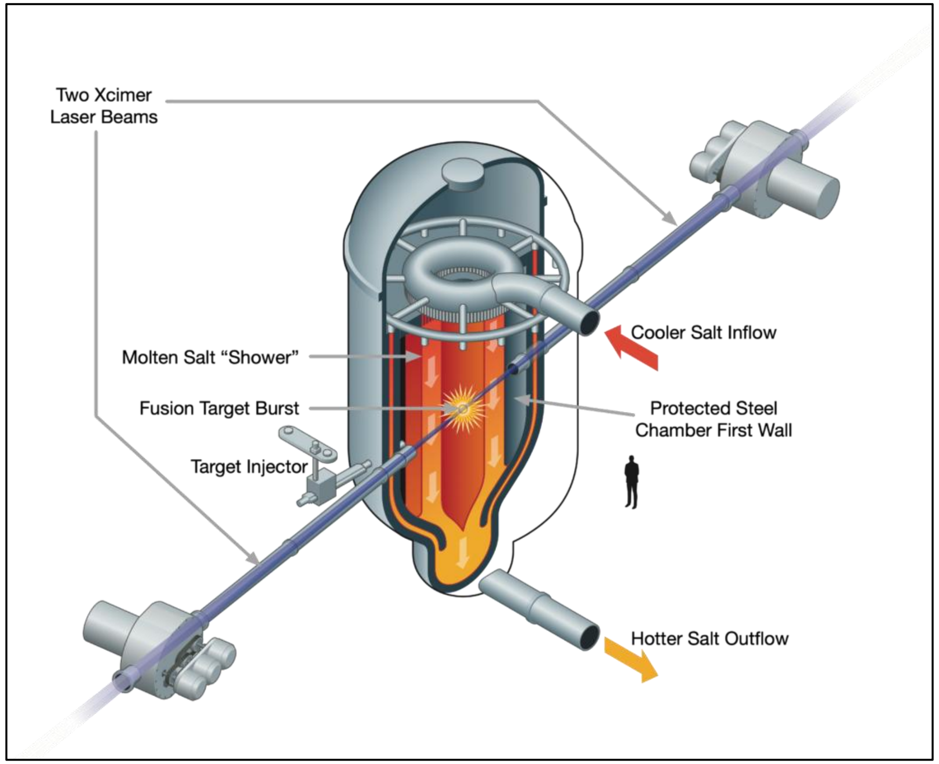
Power Conversion

FLiBe Blanket to Rankine Cycle

Facility Size

100 $MW_e$

XCIMER



# Development of commercial fusion energy will require multiple advances in fusion science and technology

| Scientific Demonstration Machines | Engineering Demonstration Machines | Commercial Demonstration Machines | Commercial Machines At Scale |
|---|---|---|---|
| $Q_{scientific} > 1$ | $Q_{scientific} >> 1$<br>$Q_{engineering} > 1$ | $Q_{engineering} >> 1$ | Cost competitive fusion energy |

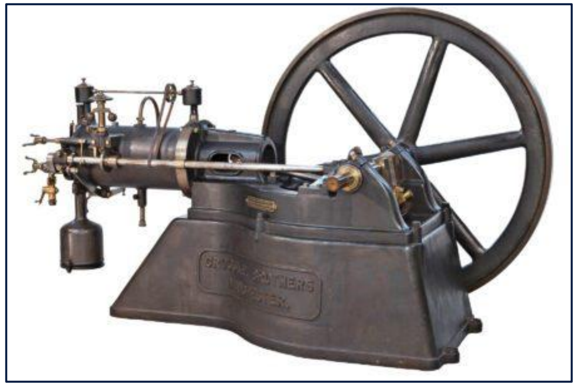
# — Regulation of commercial fusion energy will require efficient and effective licensing of many technologies

Commercial Fusion Landscape

**Fusion Energy Regulation**

Other Fusion Considerations

# — Example: How to regulate every car and engine?



Otto Engine
*1876*

Ford Model T
*1908*

Chevy Styleline
*1950*

DMC Delorean
*1981*

Honda Civic
*2016*

Shelby Supercars (SSC) Tuatara
*2020*

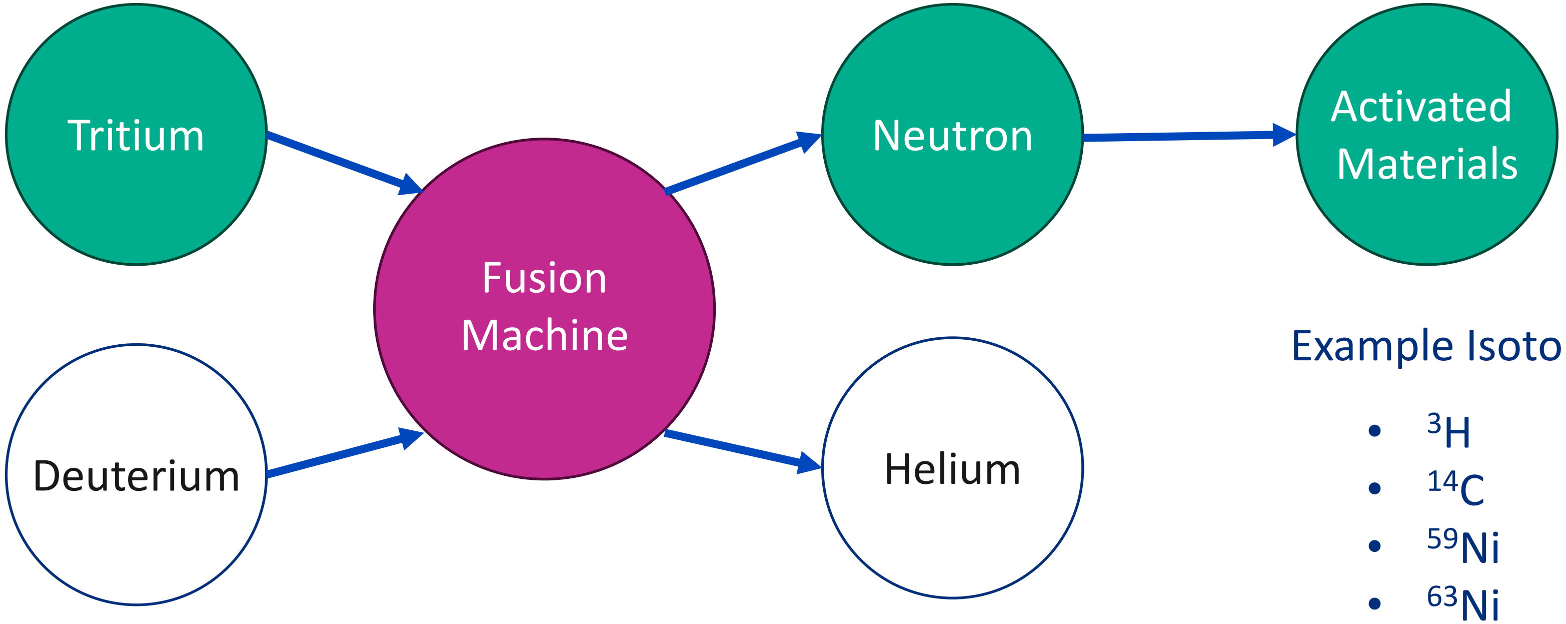
Wiztem Go Kart
*2025*

# Challenges facing fusion machine deployment will evolve during fusion energy development and commercialization

- Scientific Demonstration Machines
- Engineering Demonstration Machines
- Commercial Demonstration Machines
- Commercial Machines At Scale

Example: Regulatory needs for fusion will evolve over time based on machines purpose, hazards, experience, and industry maturity

# Fusion reactions will have radiological hazards that need to be safely managed




Example Isotopes of Concern:

- $^{3}H$
- $^{14}C$
- $^{59}Ni$
- $^{63}Ni$
- $^{60}Co$
- $^{94}Nb$
- $^{93}Mo$
- $^{179}Ta$
- $^{182}Ta$
- $^{183}Ta$
- $^{184}Re$
- $^{186}Re$
- $^{187}W$
- $^{185}W$

# Commercial deployment of fusion energy will requirement management of fusion hazards

**Example Radiological Hazards**

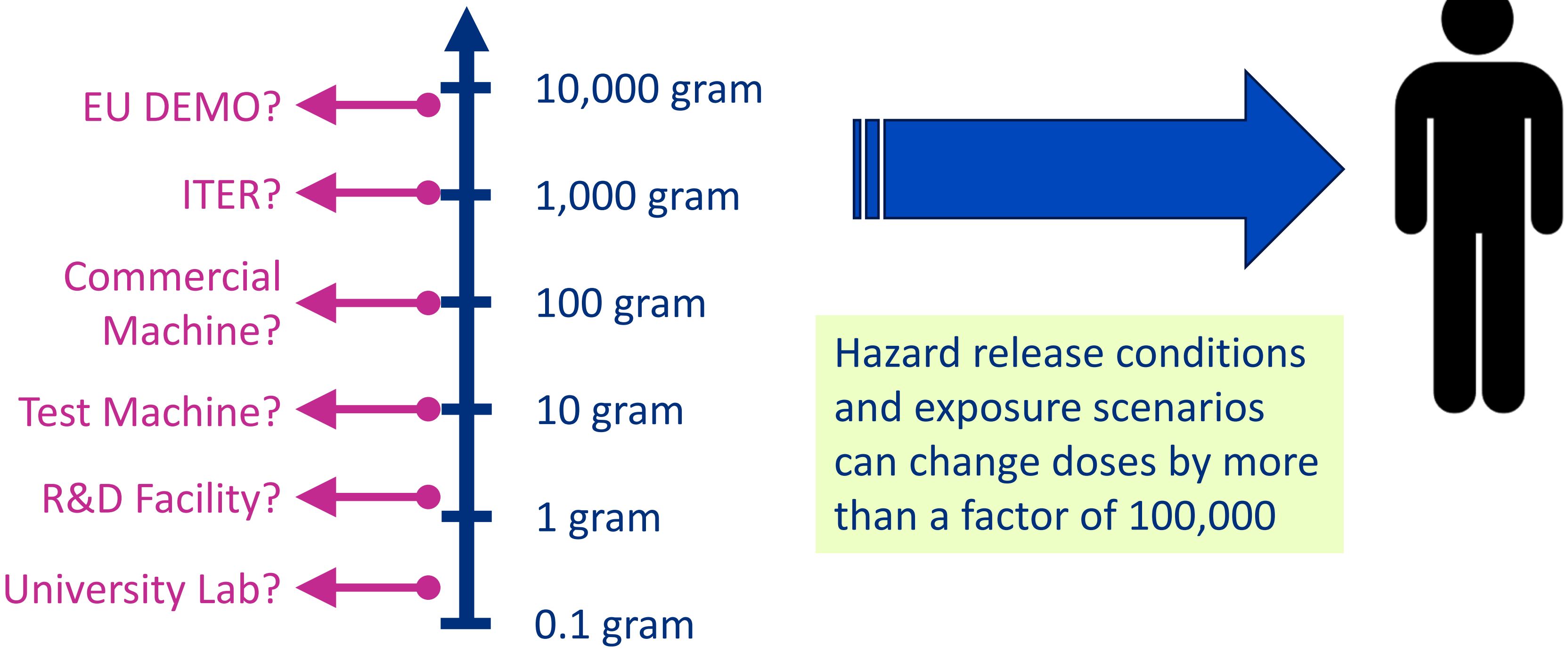
- Neutron Activation
- Material Contamination
- Direct Radiation Exposure
- Tritium

**Example Industrial Hazards**

- Cryogenic Systems
- Magnetic Fields
- Toxic Materials
- Stored Energy and Materials

# — Diversity of technical approaches and design maturity makes regulation of commercial fusion challenging

*Example: Regulating tritium hazards*




Total Tritium Inventory

Potential fusion machine safety analyses could vary by factor of more than 10,000,000 based on machine-specific technology, design, and analysis choices!

# — Fusion regulation in the United States is currently under development by NRC and agreement states

**1980s – 1990s**
DOE regulation
PPPL *TFTR*

**1990s**
DOE development of ITER relevant safety guidance

**2009**
NRC Commission asserts regulatory jurisdiction on fusion energy

**2019**
NEIMA defines fusion as advanced nuclear and directs rulemaking

**2020**
Commission directs NRC staff to develop new options for licensing fusion energy

**2020 – January 2023**
NRC staff develop options paper for Commission on fusion licensing

# — NRC staff developed three different options for the near-term regulation of commercial fusion energy

Recommended by Staff

Regulate fusion energy systems under a utilization facility framework

Regulate fusion energy systems under a byproduct material framework

Regulate fusion energy systems under a hybrid framework based on potential hazards

<u>Option 1</u>
10 CFR Part 50

<u>Option 2</u>
10 CFR Part 30

<u>Option 3</u>
10 CFR Part 30 for low hazards
10 CFR Part 50 for high hazards

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**April 2023**
Commission votes to license near-term fusion energy using 10 CFR Part 30

# Commission voted to regulate fusion using the byproduct materials framework for near-term licensing

Regulate fusion energy systems under a byproduct material framework

Option 2
10 CFR Part 30

Staff Implementation Actions

- Limited Scope Rulemaking on Fusion Energy Definitions
- Development of Guidance for Fusion Energy in NUREG-1556 Volume 22
- Engagement with NRC Agreement States on Fusion Energy Regulation

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**December 2024**
NRC staff submit proposed fusion energy regulation rule to Commission

# — Proportional, technology-inclusive, and performance-based regulation enable effective, scalable fusion licensing

| | | |
|---|---|---|
| Technology-Inclusive Requirements → | Applies to any proposed fusion machine → | Lowers barriers to fusion technology innovation |
| Performance-Based Requirements → | Utilizes quantifiable health and safety licensing criteria → | Enables demonstration of multiple approaches to fusion safety |
| Proportional Licensing Requirements → | Scales reviews based on the specific level of hazards in application → | Ensures safety while reducing opportunities for over-regulation |

# Proportional licensing requirements enable regulations to scale based on the specific application

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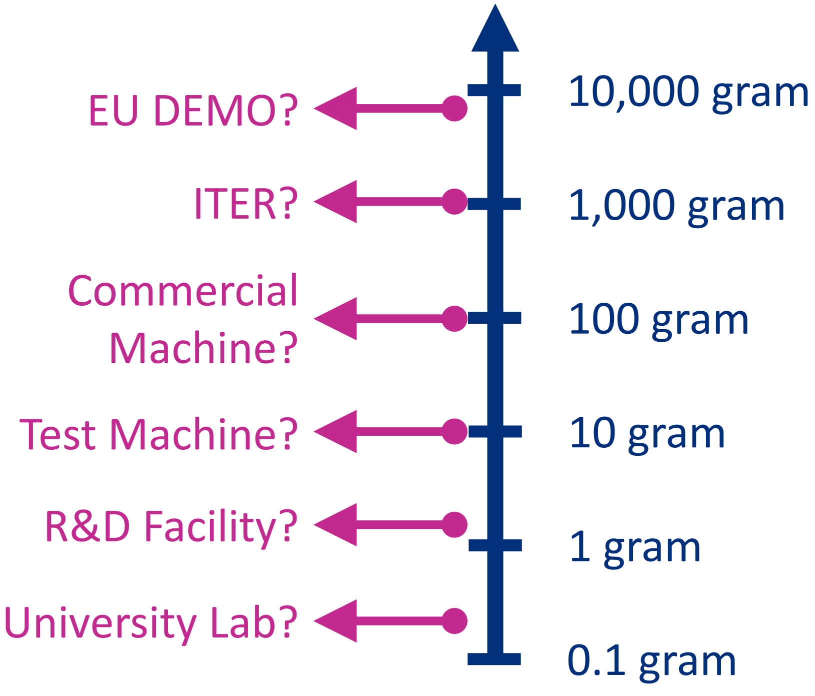
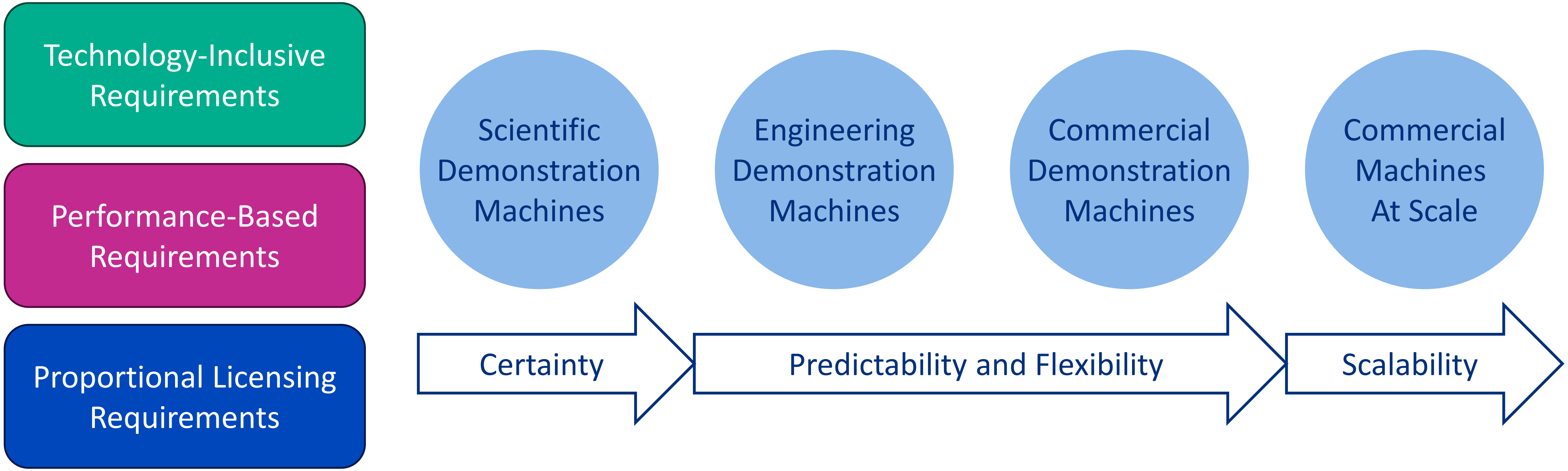



Total Tritium Inventory

- Documentation of Licensing Safety Case
- Licensing Analysis of Machine Safety
- Engineered Safety Systems and Operational Safety Programs
- Off-site Emergency Planning and Response Requirements
- Environmental Impact Review and Siting Requirements

## — Consensus on fusion regulatory principles and national implementation creates pathways for fusion deployment



# Widescale deployment of fusion energy must also consider byproduct and non-proliferation questions

Commercial Fusion Landscape

Fusion Energy Regulation

**Other Fusion Considerations**

# Fusion machines will produce varying activated and contaminated materials based on design and operation

- Activated Structural Materials
- Tritiated Contaminated Materials
- Other Radioactive Contaminated Materials

← Radioactive material production will depend on fusion neutron energy, flux, and fluence; material selection and material impurities; operational time… →

# Successful deployment of fusion energy should include management of byproducts from a commercial lifecycle

## Sustainable FPPs by Design

- FPP Design Process

## FPP Lifecycle Characterization

- FPP Construction
- FPP Operation
- FPP Maintenance
- FPP Decomm.

## FPP Waste Characterization

- On-going Wastes
- Periodic Wastes
- One-time Wastes

## Sustainability Strategies for FPP

**Reduce**
- Reduce by Design and Operation
- Reduce Waste Quantity/Volume
- Reduce by Post-Processing
- Reduce Waste Hazards

**Reuse**
- Direct Material Reuse
- Material Refurbishment

**Recycle**
- Recycle for FPP Use
- Recycle for Industrial Use

## FPP Lifecycle Management

**Storage**
- On-site or In-situ Storage
- Consolidated Storage

**Transportation**
- Existing Infrastructure
- New Infrastructure

**Disposal**
- Effluent Release
- Hazardous Waste Disposal
- Industrial Waste Disposal
- Radiological Waste Disposal

- Waste Quantity and Volume
- Waste Physical Characteristics
- Waste Hazards (Rad., Chem., Bio.)

# Evaluation of existing export controls and systems is needed to assess impact of fusion energy on proliferation

| High energy and high fluence neutron source | Sensitive dual-use materials | Sensitive dual-use technology | Sensitive dual-use knowledge |
| --- | --- | --- | --- |
| *Production of special nuclear material* | *Tritium, enriched lithium* | *Lithium isotope separation, high energy and high fluence neutron generators* | *Inertial confinement fusion data* |

## — Fusion energy has immense potential, but safety and regulation can be aligned to enable deployment

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