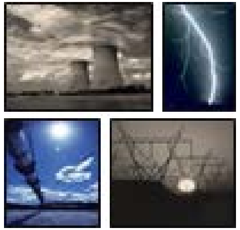


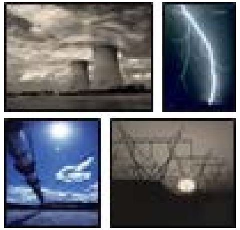
Priority Considerations for the Transportation of Commercial Spent Nuclear Fuel in the U.S.

WIEB-Stanford Internship Project Report

Chengliang Fan, Tristan Krueger

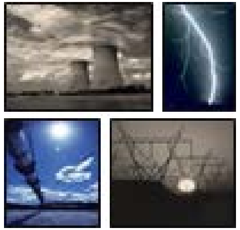
Wednesday, August 28, 2019

Outline

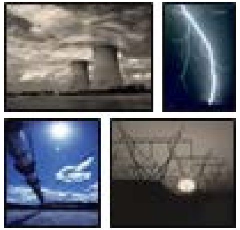


- Introduction
- Dry Storage Shipping Orders
    - Cask Risk
    - Site Risk
- Predict Casks from Pool Assemblies
- Combined Shipping Orders
- Key Findings
- Future Study

Project Goals



- Develop an effective age-based safety metric for spent nuclear fuel casks
- Develop cask shipment orders using this metric
- Compare strategies for clearing storage sites
- Develop pool fuel predictions based on estimated cask numbers
- Create shipment orders based on other priorities (e.g., site status, seismic risks, etc.)



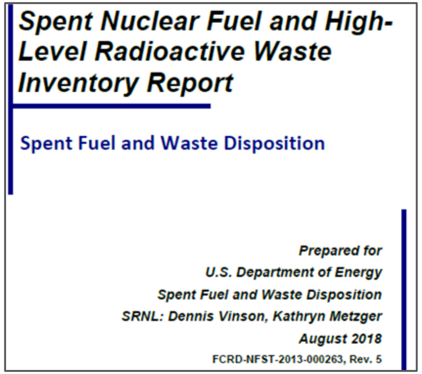
Database Introduction: Data Source

- Data are from the “Nuclear Fuel Data Survey” collected by Energy Information Administration (EIA) through the mandatory Form GC-859
- The latest survey was conducted in 2013, covering all spent nuclear fuel discharged from and stored at commercial sites before June 30, 2013.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-7227
ORNL/TM-2015/619

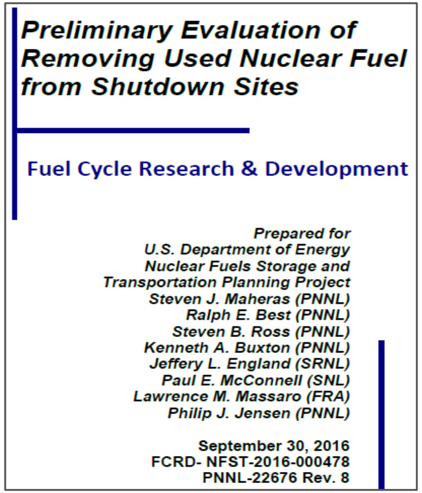
US Commercial Spent Nuclear Fuel Assembly Characteristics: 1968-2013



Spent Nuclear Fuel and High-Level Radioactive Waste Inventory Report

Spent Fuel and Waste Disposition

Prepared for
U.S. Department of Energy
Spent Fuel and Waste Disposition
SRNL: Dennis Vinson, Kathryn Metzger
August 2018
FCRD-NFST-2013-000263, Rev. 5

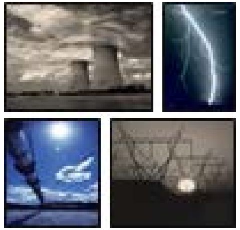


Preliminary Evaluation of Removing Used Nuclear Fuel from Shutdown Sites

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Nuclear Fuels Storage and Transportation Planning Project
Steven J. Maheras (PNNL)
Ralph E. Best (PNNL)
Steven B. Ross (PNNL)
Kenneth A. Buxton (PNNL)
Jeffery L. England (SRNL)
Paul E. McConnell (SNL)
Lawrence M. Massaro (FRA)
Philip J. Jensen (PNNL)

September 30, 2016
FCRD- NFST-2016-000478
PNNL-22676 Rev. 8



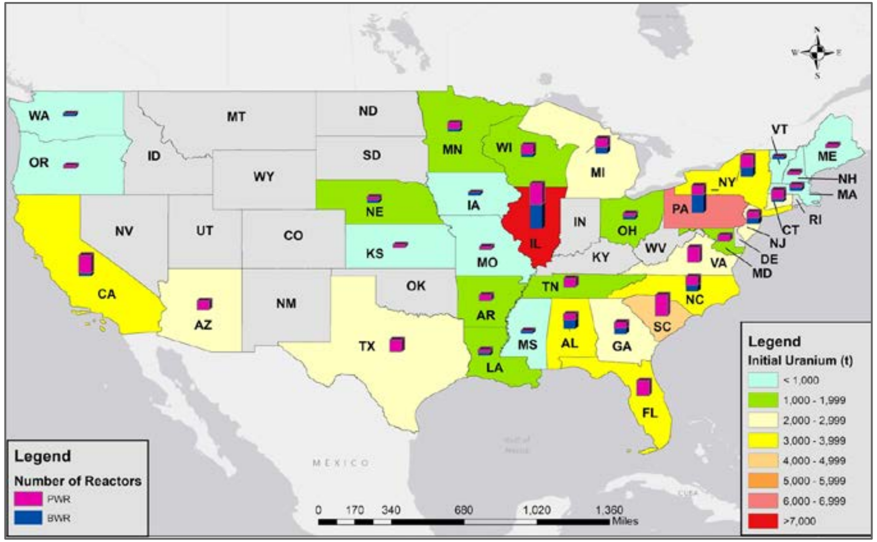
Variables in the Database

- 33 states have commercial nuclear reactors and storage facilities
- 74 sites: 64 active, 10 shutdown
- 40 utilities with generation or storage sites
- 59 dry storage sites
- 66 wet storage sites with 99 storage pools
- 1,760 dry storage casks

Variables in the Database

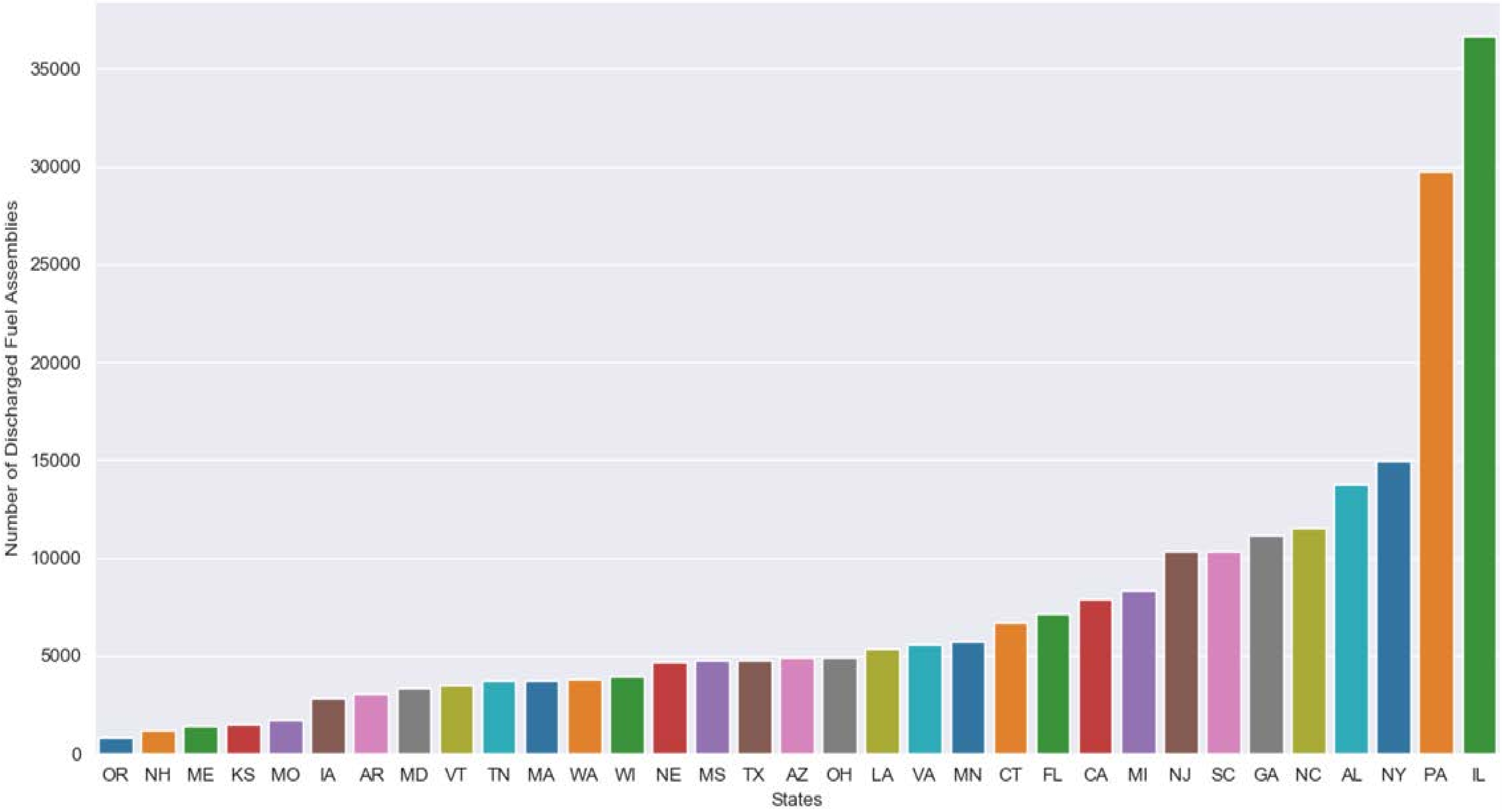
- 119 commercial reactors:
  - 104 active, 15 shutdown
  - 79 Pressurized Water Reactor; 40 Boiling Water Reactor

- 244,082 discharged assemblies: 70,214 in dry storage, 173,868 in wet.

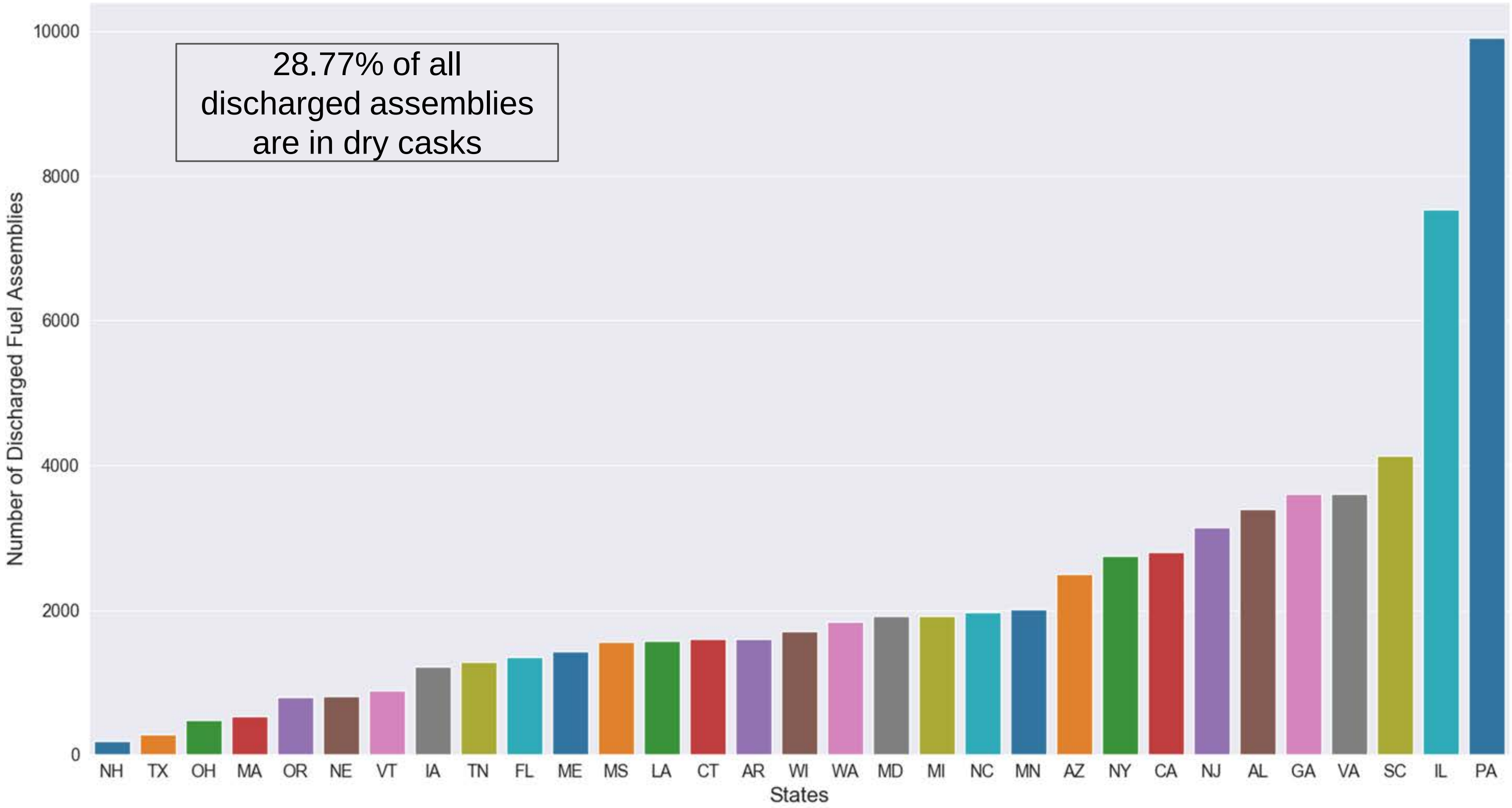


	Number of Assemblies	Initial Uranium (t)	Average U Enrichment (%)	Total Discharge Burnup (GWd/t)
PWR	105,146	45,527.78	3.722	4,169,945
BWR	138,936	24,711.47	3.148	4,682,439
Total	**244,082**	**70,239.25**	**3.395**	**8,852,384**

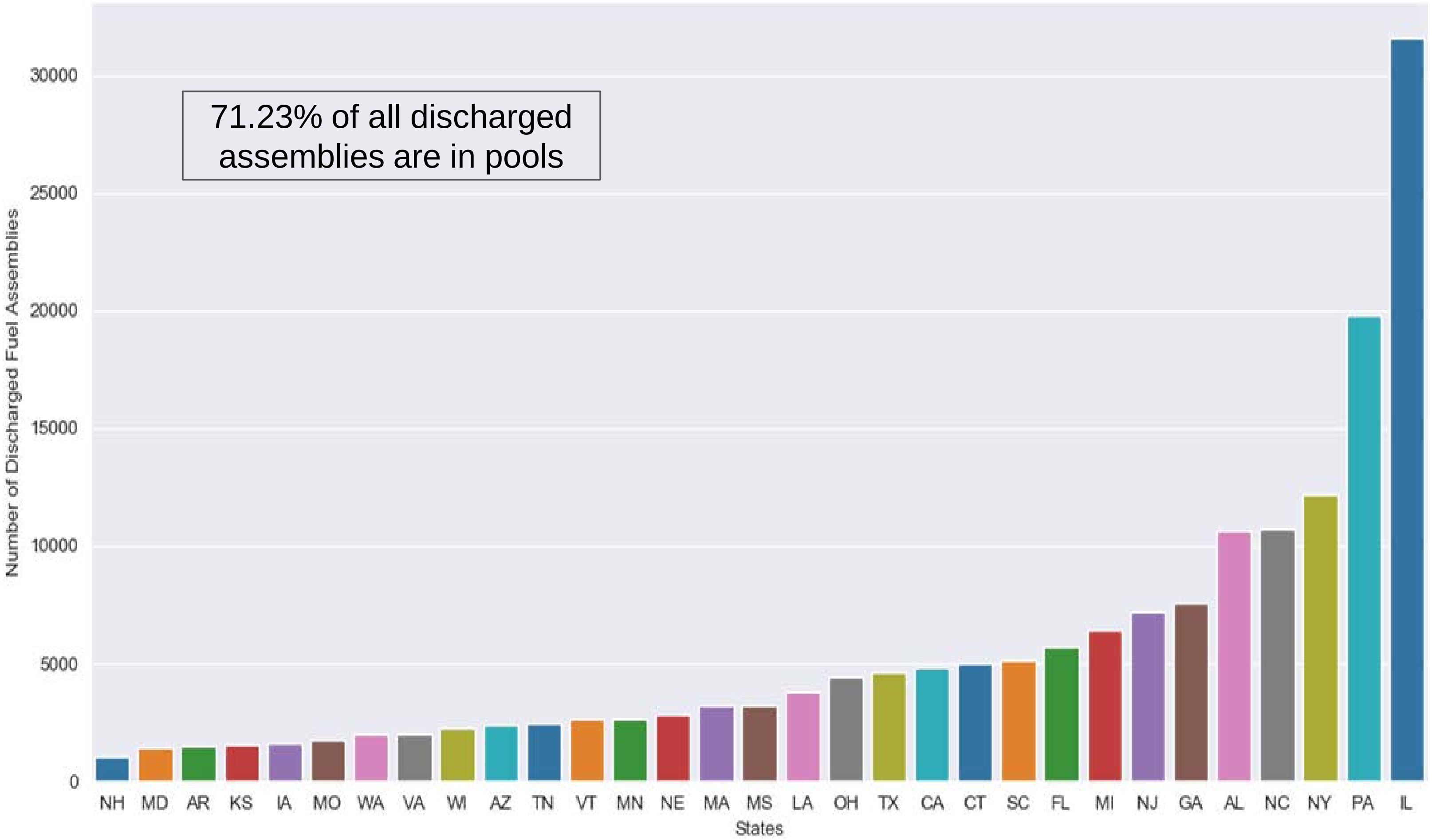
Number of Discharged Fuel Assemblies by State

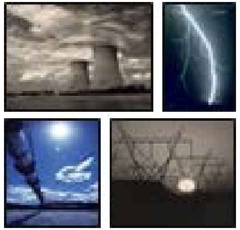


Number of Assemblies in Dry Storage Casks by State



Number of Discharged Assemblies in Storage Pools by State

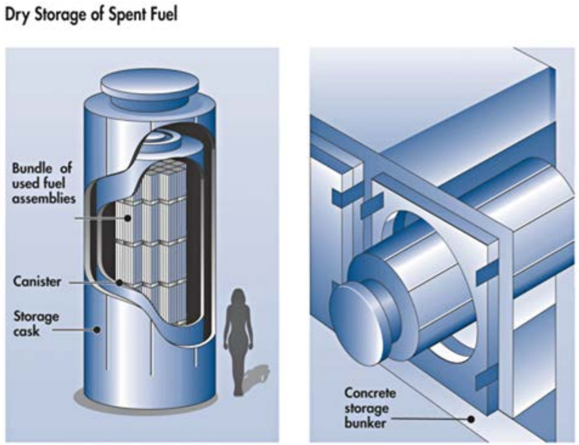




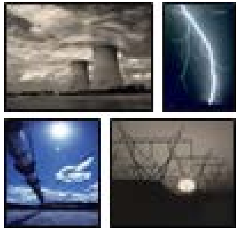
Background Concepts

- The most fundamental unit of our analysis is assemblies, which are bundles of fuel rods
- For dry storage, the assemblies are grouped into casks; each storage site has numerous casks.

Levels of our analysis:



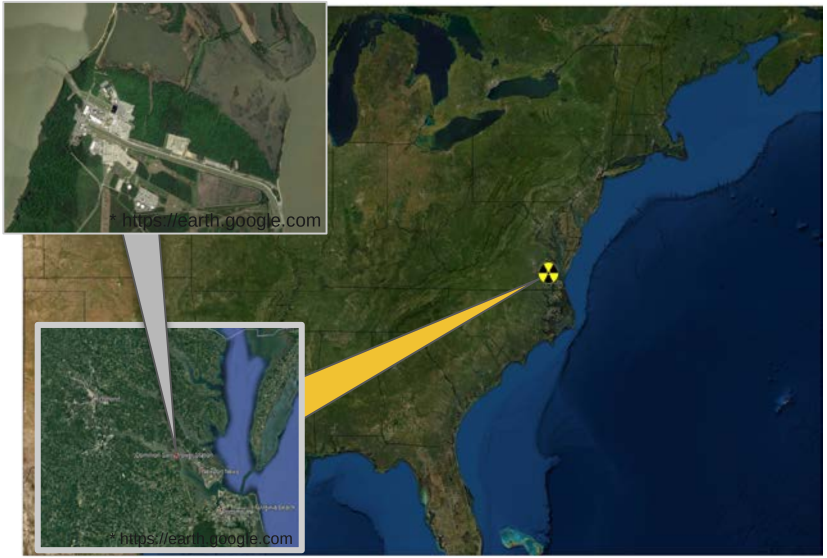
* http://large.stanford.edu/courses/2014/ph241/ng2/

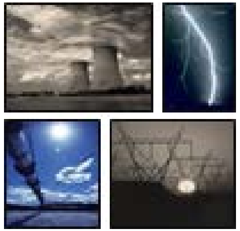


Age-Based Proxy for Cask Radioactivity

Dominion Surry

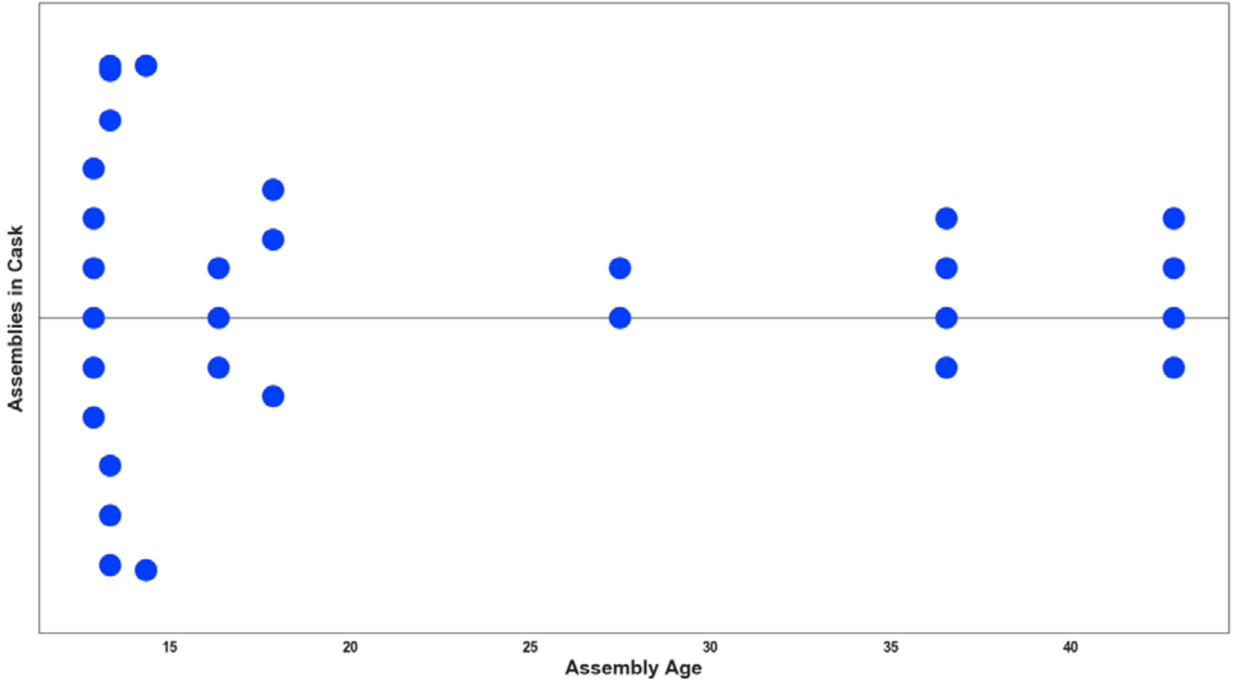
- 2 operating units. Unit 1 commissioned since 1972; Unit 2 commissioned since 1973
- Spent fuel assemblies in dry storage: 2,171
  - Stored in 77 multi-assembly casks
  - Uses 6 cask models, but 95% of casks are in three models
- Oldest assemblies from 1974 (dry storage)
- Youngest assemblies from 2006 (dry storage)



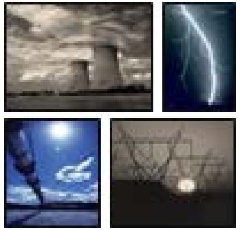


Surry: A Single Cask (DOM-32PTH-025-D)

- 32 assemblies in this cask
- Oldest assembly: 43 years old (from 1976); Youngest assembly: 13 years old (from 2006)
- Fuel age range of 30 years

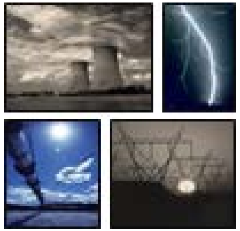


Difficulty of Assigning Age Values to Casks



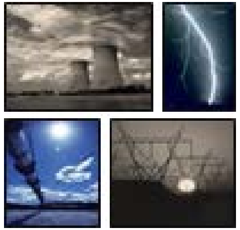
- Age Range for a Cask = Oldest Assembly Age - Youngest Assembly Age
    - Old assemblies often used to shield most dangerous fuel
- At Surry, cask age range varies from 0 to 30 years
    - Many sites show this variance
- How do we assign age values to casks?

Back to the Basics: Why Age?



- Intention was to use Oak Ridge National Laboratory's ORIGEN tool to estimate cask radioactivity. Time limitations precluded the use of this tool.
- Age is a proxy for fuel radioactivity (risk)
  - Doesn’t incorporate other factors
    - Burnup, number of cycles, initial kilograms of fuel, reactor type, fuel type, etc.
  - Primarily for fuel risk comparisons
- But age is, perhaps, the most important factor
  - A simple way to think about assembly risk/safety

Criteria for an Age-Based Cask Risk Metric



1. Age of each assembly in cask matters (older ⬆ assemblies less risky)

2. Number of assemblies in cask matters (fewer ⬇ assemblies less risky)

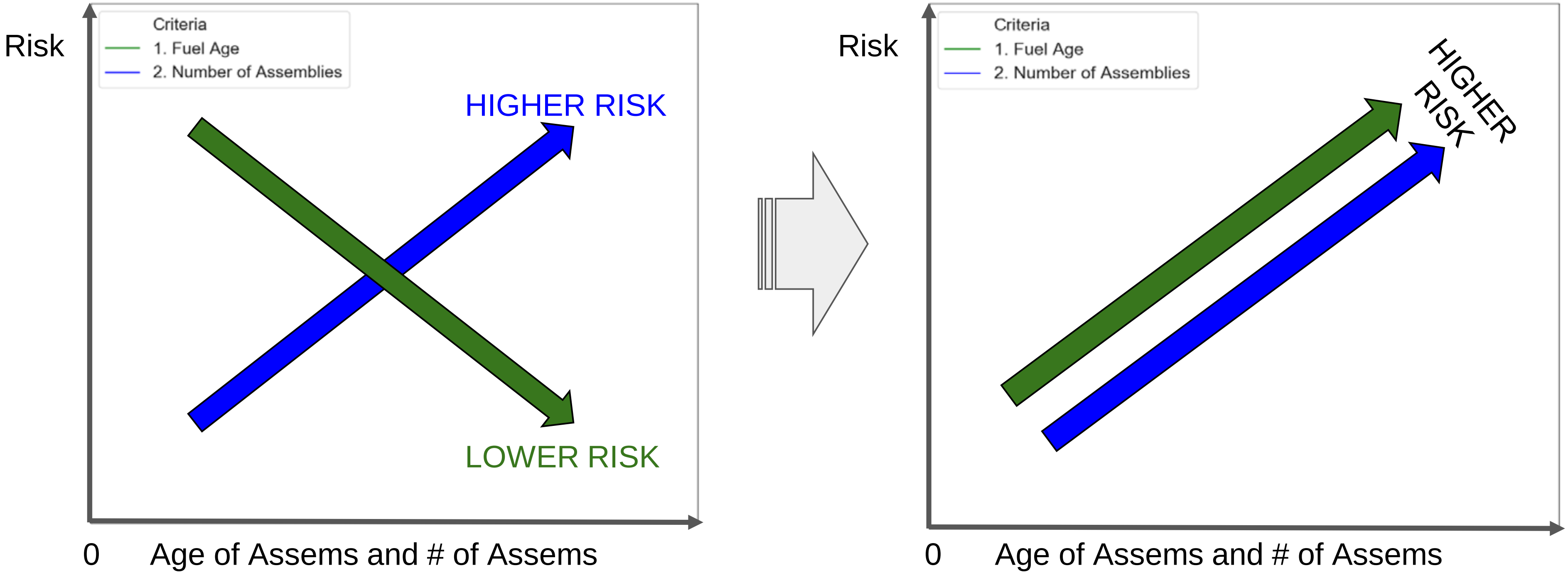
    - Average age of assemblies in cask does not meet this criterion

3. Metric must be directionally consistent (“safer” must be in the same direction for criteria 1 and 2)

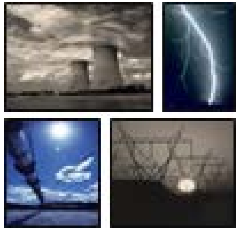
    - Cumulative age of assemblies in cask does not meet this criterion

Ideally, metric should mimic the trends of radioactive decay

Criteria 1 and 2 Must Be Directionally Consistent



Solution: Cumulative Inverse Cask Age (CICA)



- For each assembly:

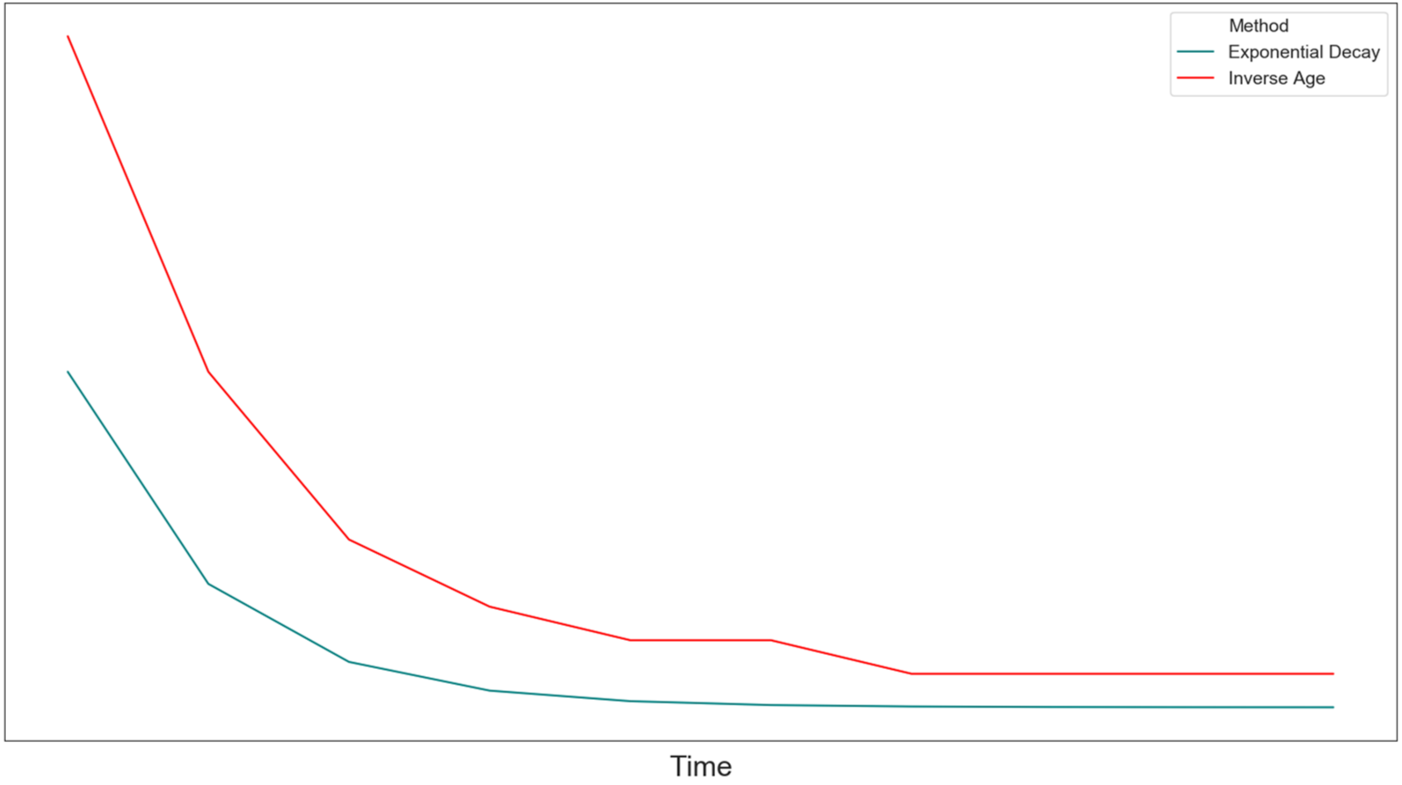
$$Inverse\ Age = \frac{1}{Assembly\ Age}$$

- For a cask containing n assemblies:

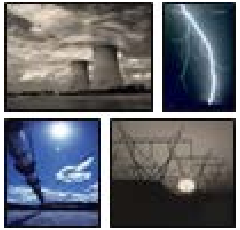
$$CICA = \frac{1}{Assembly\ 1\ Age} + \frac{1}{Assembly\ 2\ Age} + \cdots + \frac{1}{Assembly\ n\ Age}$$

- Proxy for Radioactivity?
  1. Risk decreases as inverse age decreases (smaller ⬇ values are less risky)
  2. Risk decreases as number of assemblies decreases (smaller ⬇ values are less risky)
  3. Criteria 1 and 2 directionally consistent

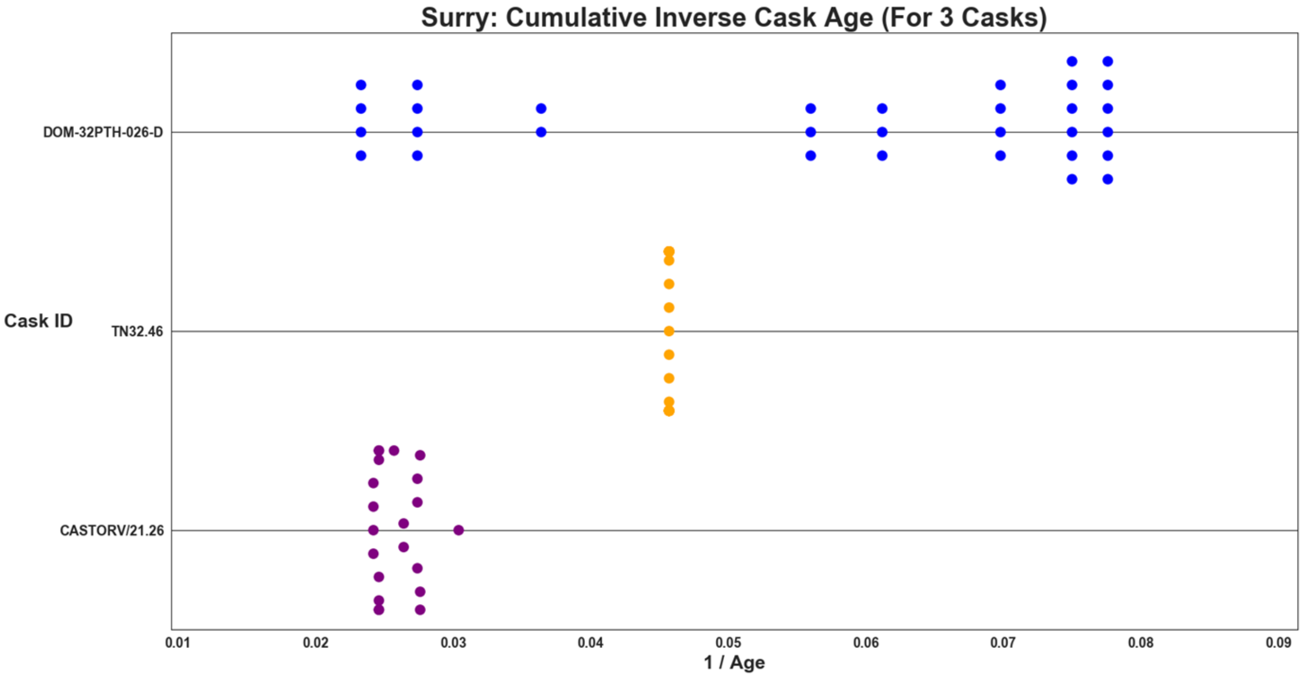
Exponential Decay vs Inverse Age



Surry: Three Casks



- DOM-32PTH-026-D
  - Same cask as before (32 assemblies)
  - **Large number of assemblies with large age range**
- TN32.46
  - 32 assemblies
  - All assemblies 22 years old
  - **Large number of mid-aged assemblies with no age range**
- CASTORV/21.26
  - 21 assemblies
  - Oldest assembly 41 years old
  - Youngest 33 years old
  - **Small number of old assemblies with small age range**

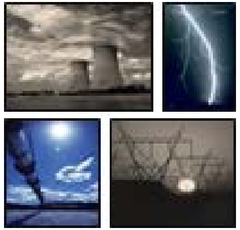


DOM-32PTH-026-D
⇒ CICA = 1.8248

TN32.46
⇒ CICA = 1.4624

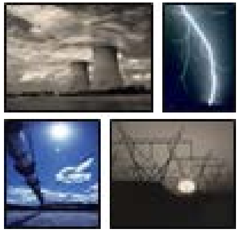
CASTORV/21.26
⇒ CICA = 0.5441

- Each dot represents an assembly
- This graph displays 3 casks (blue, orange, and purple)
- The lower CICA value, the safer the cask

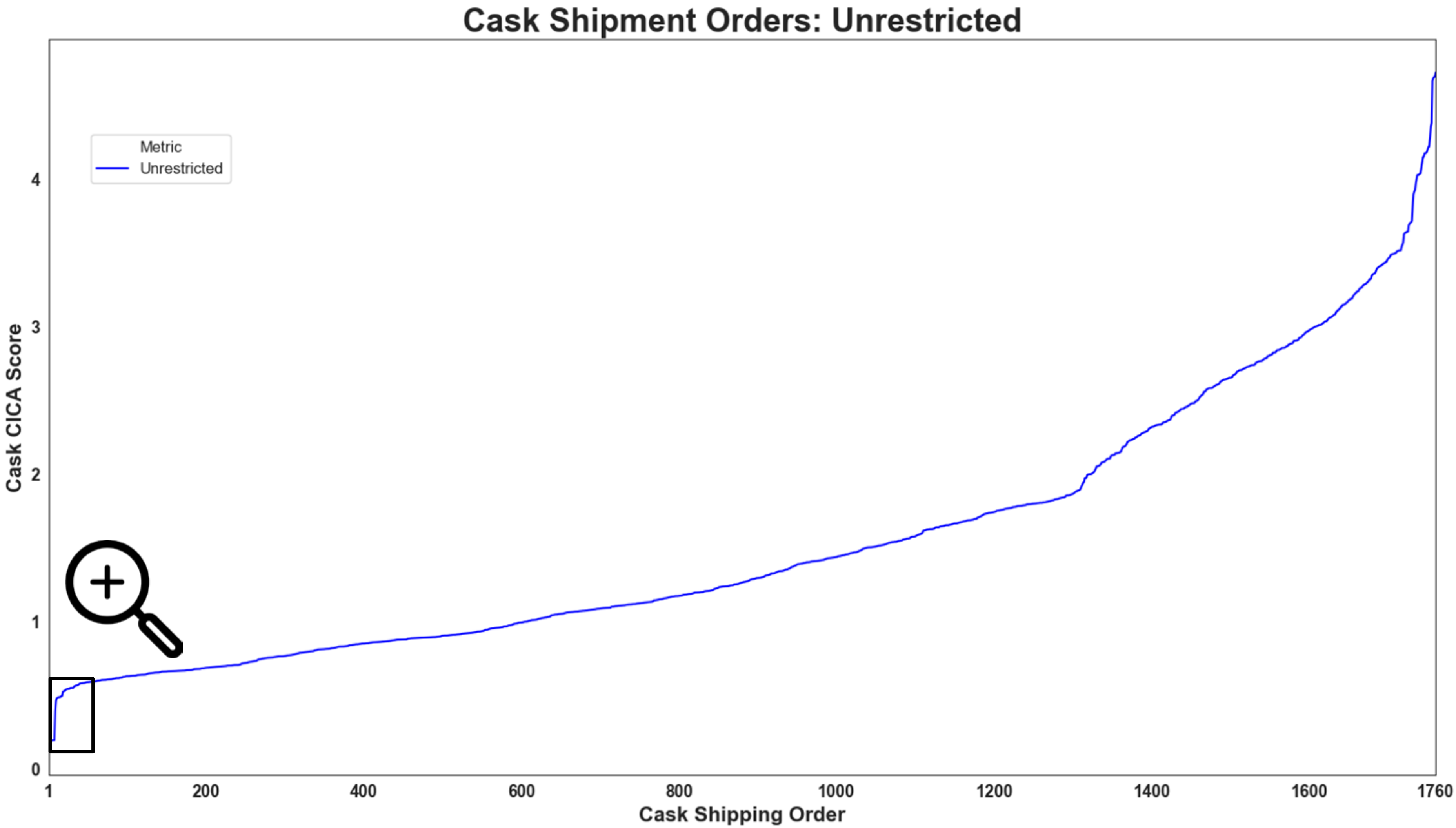


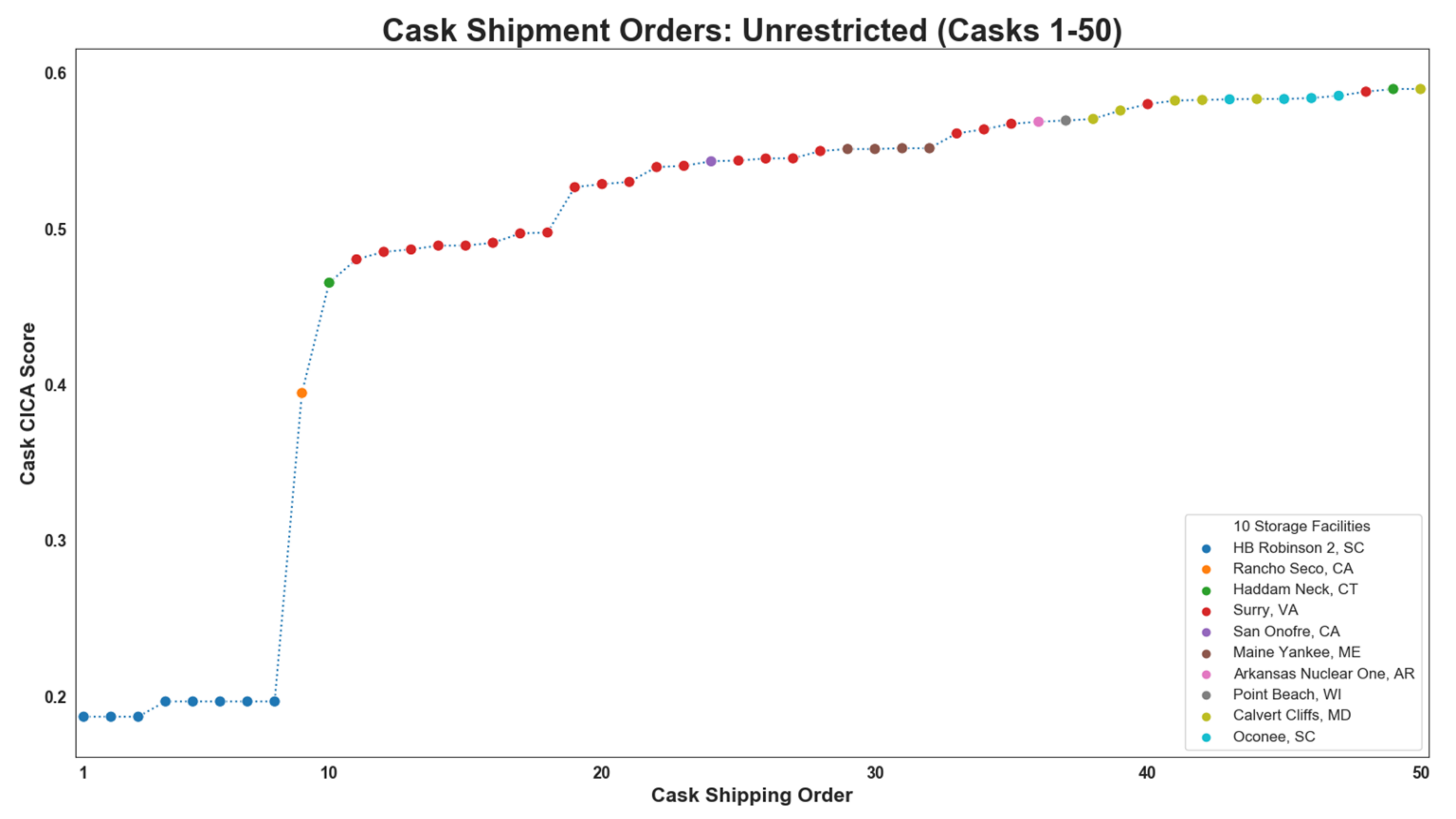
Determine Cask Priority Shipping Order

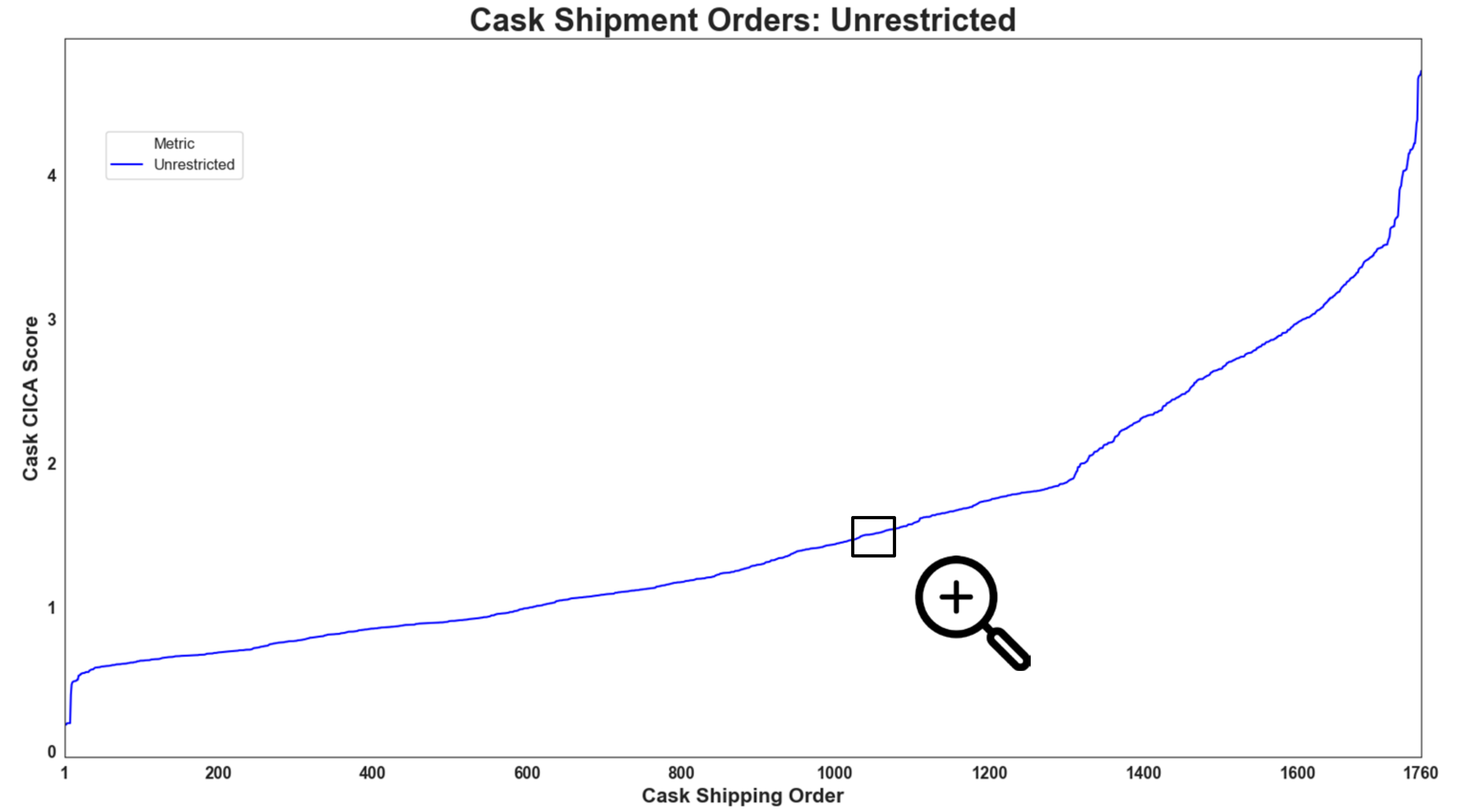
Unrestricted Cask Priority Order



- CICA values are estimated risk values for casks
- Ranking casks from the lowest to highest CICA is the safest shipping order
- Assumes no transportation restrictions
    - Refer to this priority ranking as “Unrestricted”

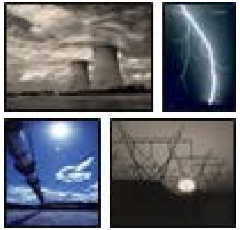

Cask Shipment Orders: Unrestricted
Metric
Unrestricted
Cask CICA Score
0
1
2
3
4
1
200
400
600
800
1000
1200
1400
1600
1760
Cask Shipping Order


Cask Shipment Orders: Unrestricted (Casks 1-50)
Cask CICA Score
0.6
0.5
0.4
0.3
0.2
Cask Shipping Order
1
10
20
30
40
50
10 Storage Facilities
HB Robinson 2, SC
Rancho Seco, CA
Haddam Neck, CT
Surry, VA
San Onofre, CA
Maine Yankee, ME
Arkansas Nuclear One, AR
Point Beach, WI
Calvert Cliffs, MD
Oconee, SC



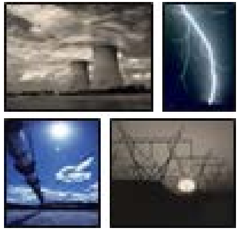
Cask Shipment Orders: Unrestricted
Metric
Unrestricted
Cask CICA Score
0
1
2
3
4
1
200
400
600
800
1000
1200
1400
1600
1760
Cask Shipping Order

Cask Shipment Orders: Unrestricted (Casks 1000-1050)
Cask CICA Score
1.51
1.50
1.49
1.48
1.47
1.46
1.45
1.44
Cask Shipping Order
1000
1010
1020
1030
1040
1050
19 Storage Facilities
Arkansas Nuclear One, AR
Palo Verde, AZ
Farley, AL
Byron, IL
Calvert Cliffs, MD
Cook, MI
HB Robinson 2, SC
Palisades, MI
Turkey Point, FL
Sequoyah, TN
Surry, VA
St. Lucie, FL
Waterford, LA
North Anna, VA
Seabrook, NH
Hope Creek/Salem, NJ
Oconee, SC
Dresden, IL
Susquehanna, PA



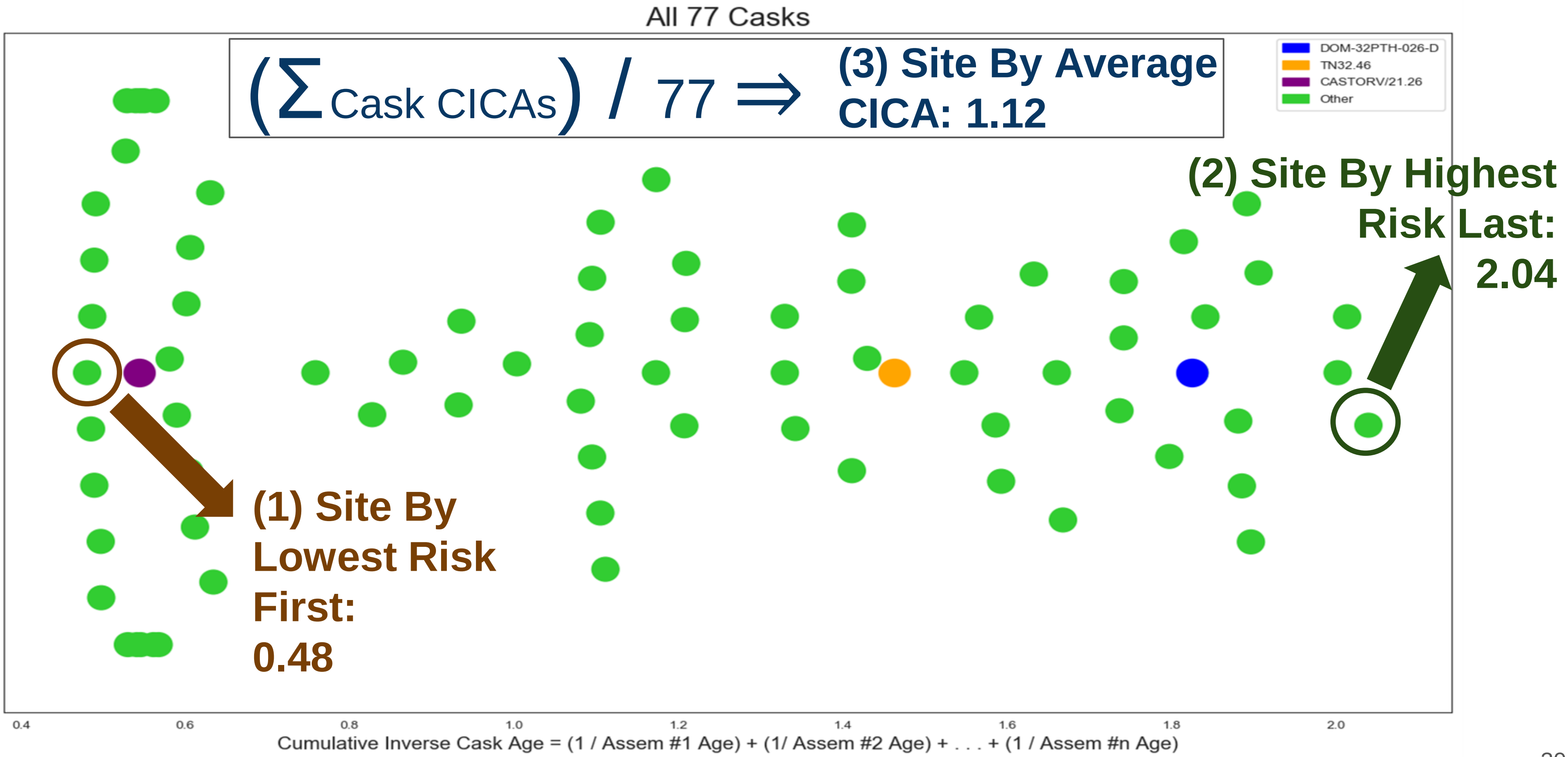
Determine Site Shipment Priority Order

Risk of Shipments from Sites

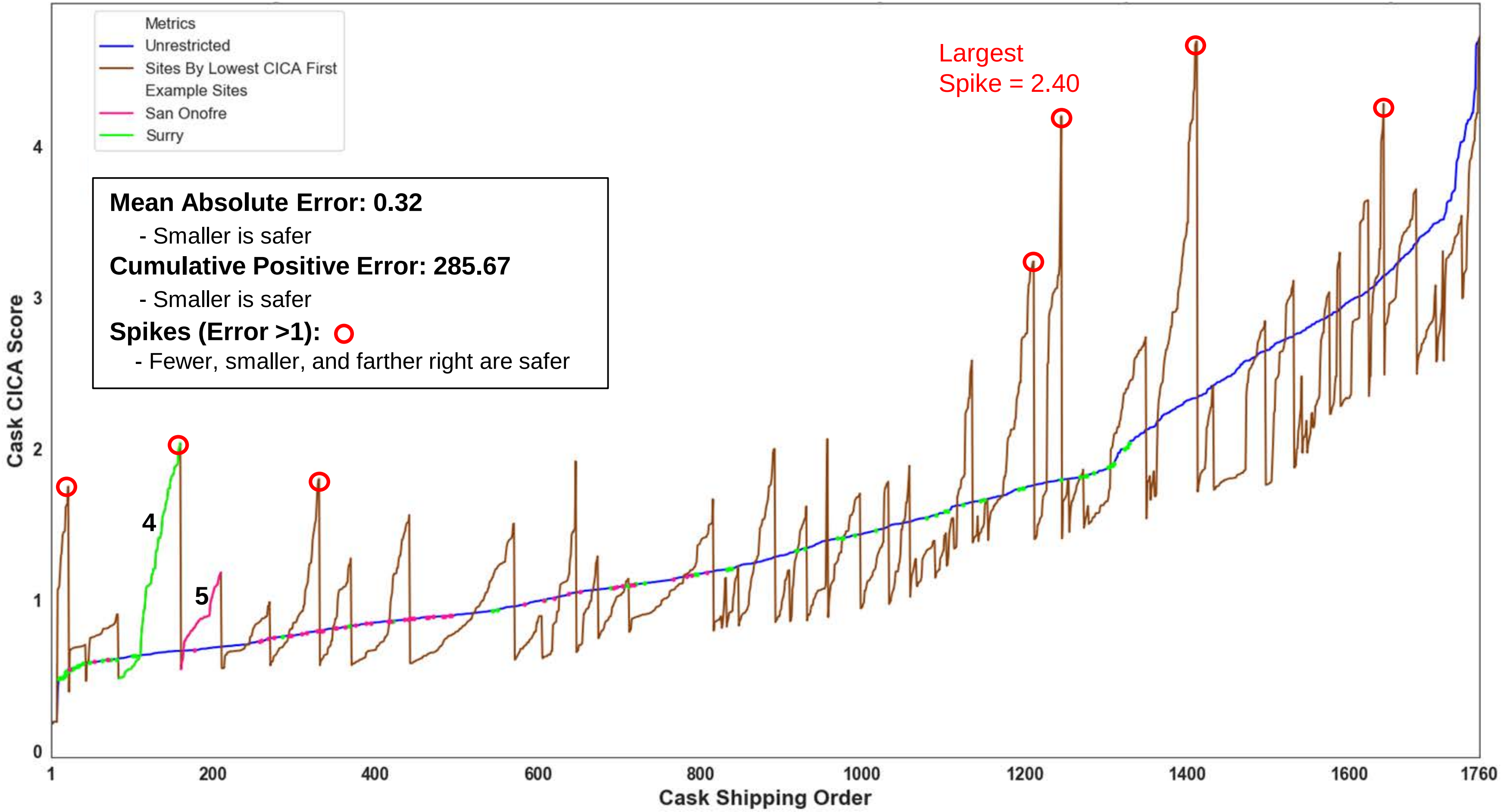


- Rank sites by risk of cask shipments
  - CICA scores vary within sites (Ex. CICAs at Surry range from .48 to 2.04)
- Methods for Site Ranking:
  1. Site by Lowest CICA Score (Lowest Risk Fuel First)
  2. Site by Highest CICA Score (Highest Risk Fuel Last)
  3. Site by Average CICA Score

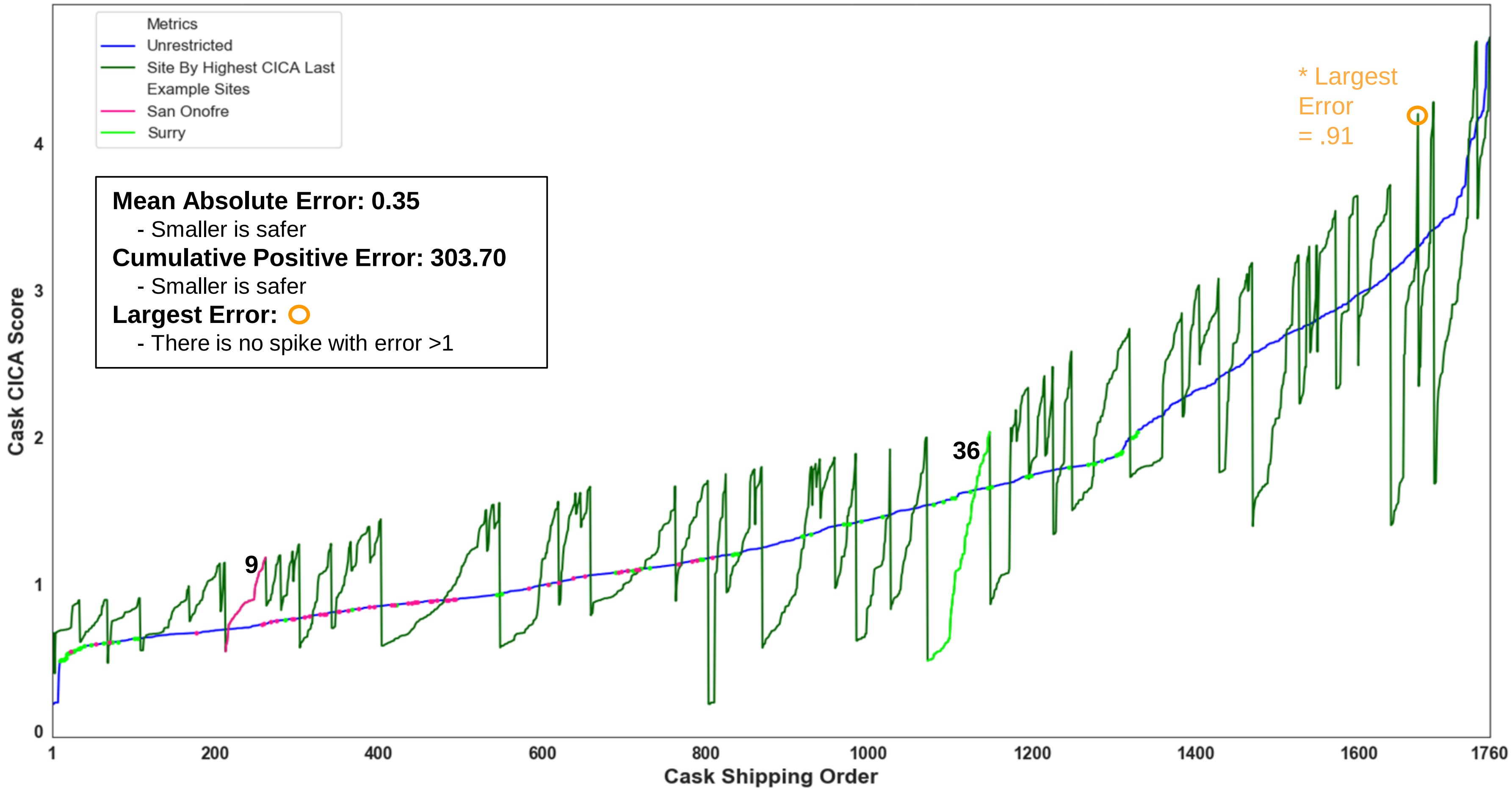
Surry: Determining Site Safety Values



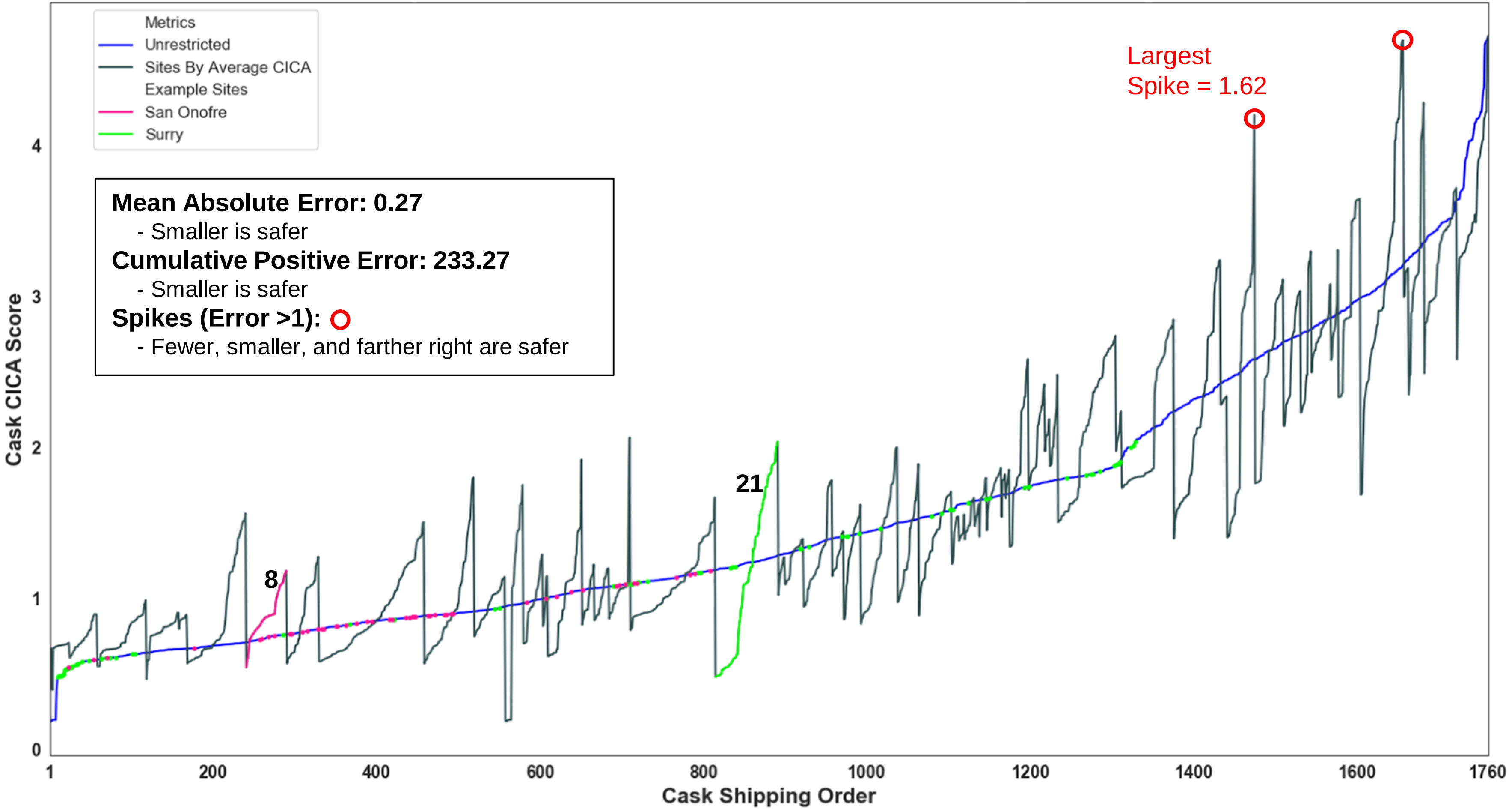
Cask Shipment Orders: Lowest Risk First



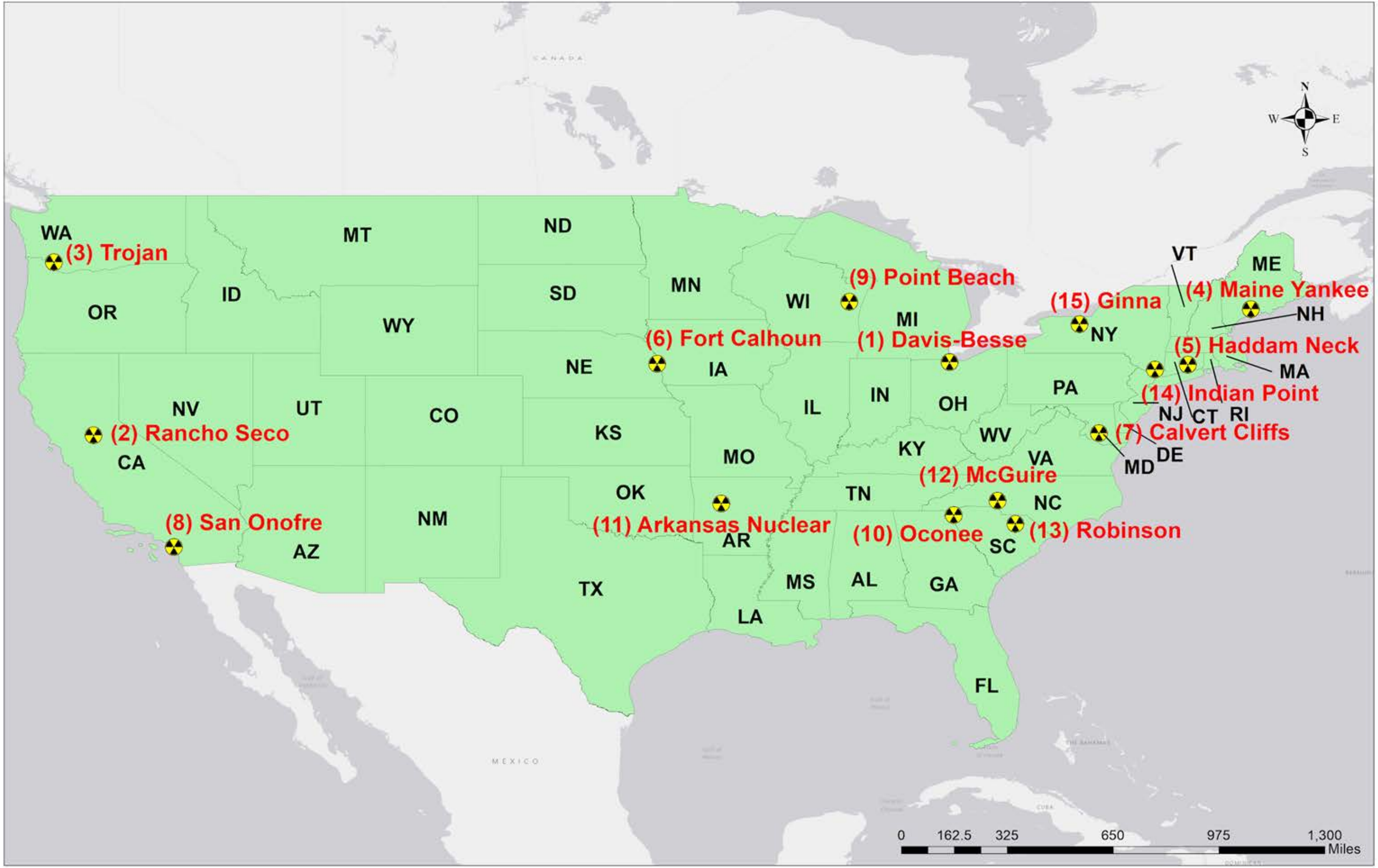
Cask Shipment Orders: Highest Risk Last



Cask Shipment Orders: Average CICA Score

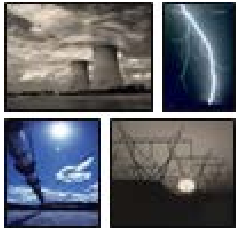


Cask Ranking Method	Method Safety Implication	Mean Absolute Error * Smaller is Safer	Cumulative Positive Error * Smaller is Safer	Largest Error * Smaller is Safer	Earliest Spike (Shipment Number) * Larger is Safer	Number of Spikes * Smaller is Safer
(1) Site by Lowest CICA	Sites With Lowest Risk Fuel First	0.32	285.67	2.40	21	7
(2) Site by Highest CICA	Sites With Highest Risk Fuel Last	0.35	303.70	0.91	N/A	0
(3) Site by Average CICA	Sites by Average CICA Score	0.27	233.27	1.62	1473	2

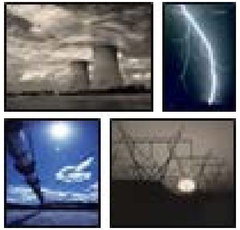


CANADA
WA
(3) Trojan
MT
ND
OR
ID
WY
SD
MN
WI
(9) Point Beach
MI
(15) Ginna
VT
ME
(4) Maine Yankee
NH
NY
(6) Fort Calhoun
(1) Davis-Besse
NE
IA
(5) Haddam Neck
MA
NV
UT
CO
IL
IN
OH
PA
(14) Indian Point
NJ
CT
RI
(2) Rancho Seco
KS
MO
KY
WV
(7) Calvert Cliffs
DE
MD
CA
VA
(12) McGuire
OK
TN
NC
(8) San Onofre
NM
(11) Arkansas Nuclear
AR
(10) Oconee
(13) Robinson
SC
AZ
TX
MS
AL
GA
LA
FL
MEXICO
N
W
E
S
0
162.5
325
650
975
1,300
Miles

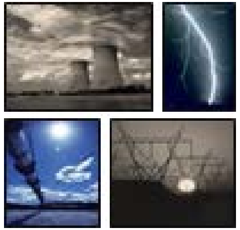
Shipment Assumptions



- Estimated 2 weeks transport to and from storage/disposal site (round trip)
  - A dedicated train would likely carry up to 5 casks per shipment
  - Assume back-to-back shipments and no transportation delays
- Timeline to clear dry storage for unrestricted shipping order
  - 1,447 shipments
  - 55 years and 8 months
- Timeline to clear dry storage for any clear-by-site shipping orders
  - 374 shipments
  - 14 years and 5 months



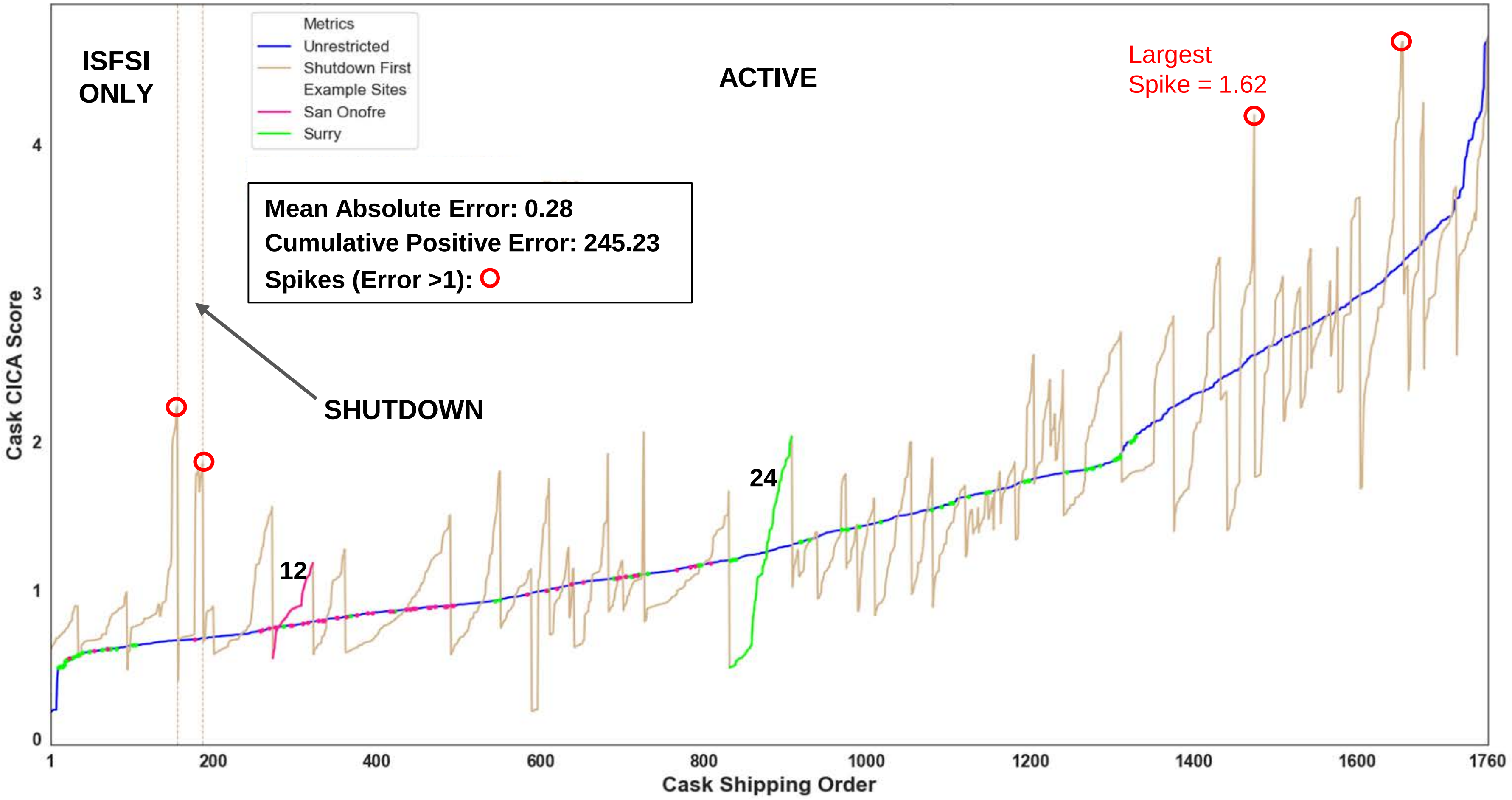
Other Shipment Considerations

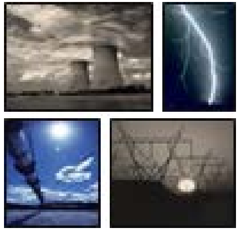


Prioritize by Reactor Status

- Clear ISFSI only sites first
  - ISFSI: Independent Spent Fuel Storage Installation
- Then other shutdown sites
- Then active sites

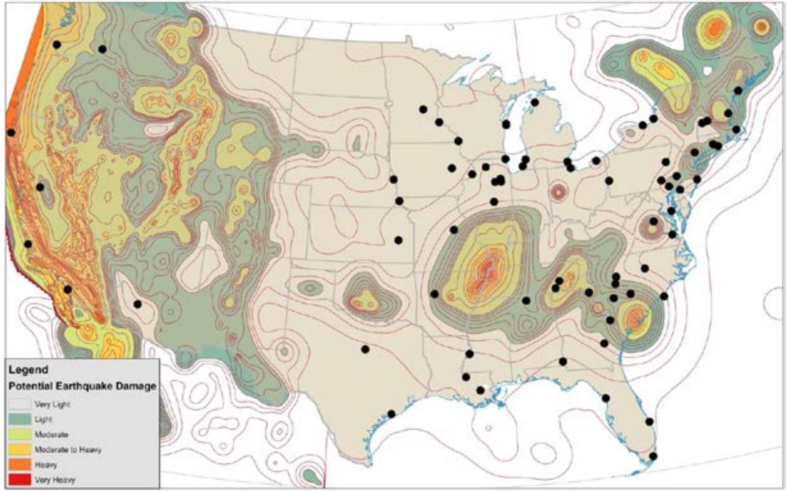
Cask Shipment Orders: Prioritize ISFSI-Only and Shutdown Sites





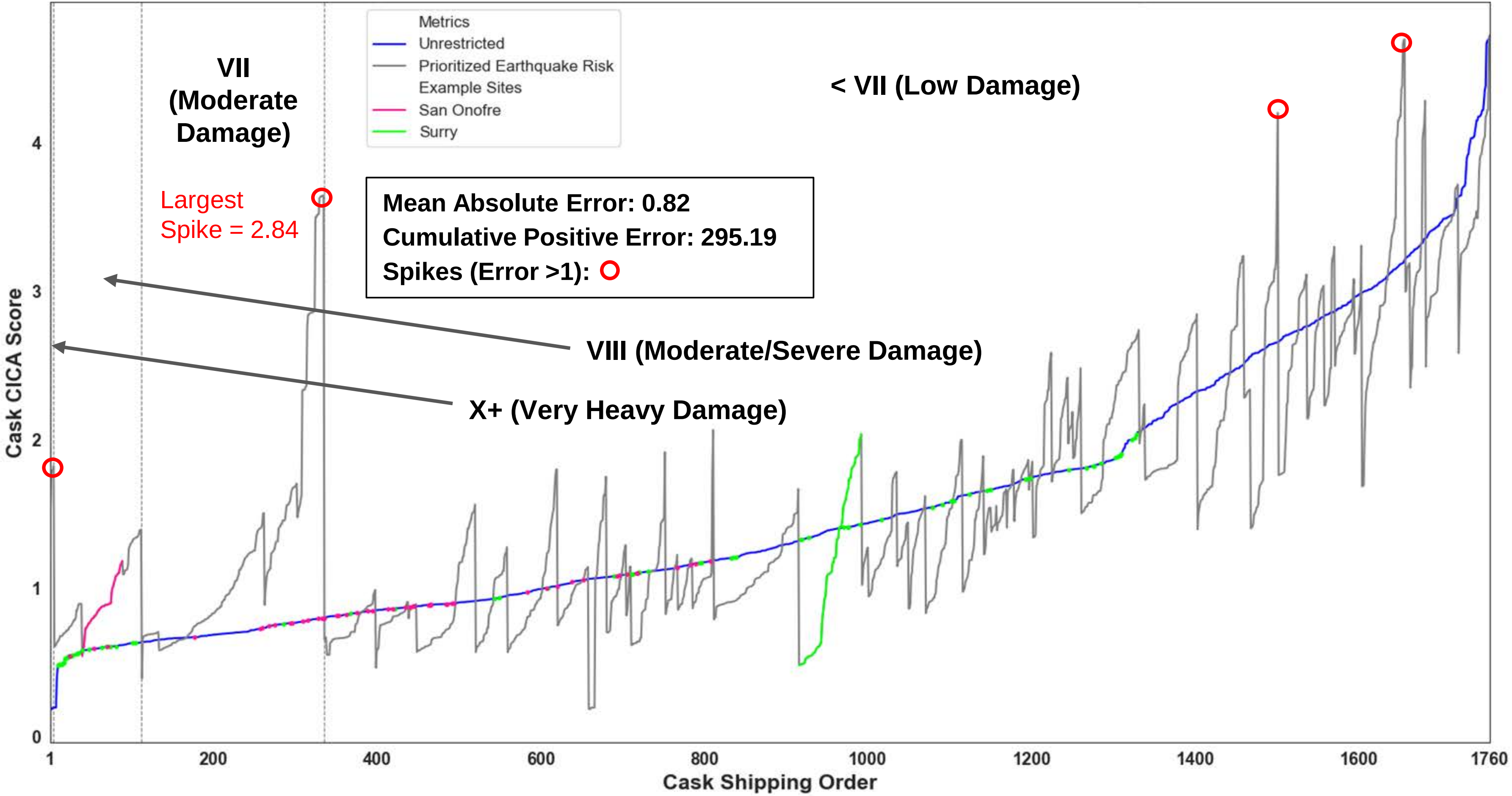
Prioritize by Potential Earthquake Damage

- Used peak ground acceleration (PGA) to determine potential risk
- First clear sites with predicted intensity X+
- Then sites with predicted intensity VIII (there's no site with intensity IX)
- Then sites with predicted intensity VII
- Lastly sites with predicted intensity I - VI (site-damage unlikely)

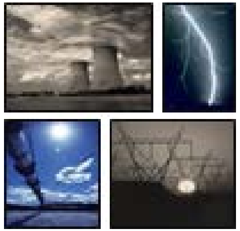


* Seismic hazard prediction data obtained from the United States Geological Survey, using 2014 Long-term Model (PGA, 2% in 50 years)

Cask Shipment Orders: Prioritize Earthquake Risk

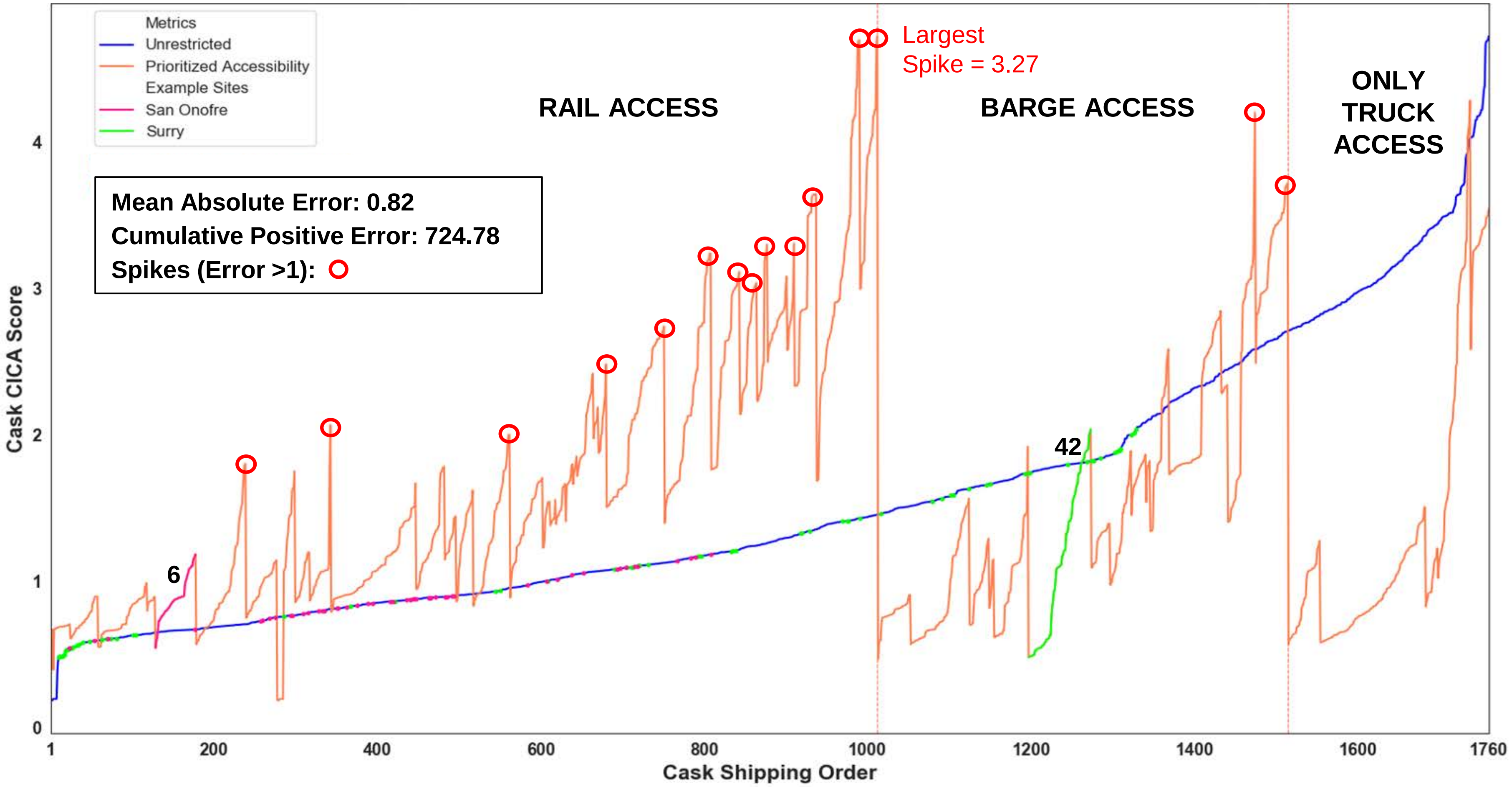


Prioritize by Site Accessibility

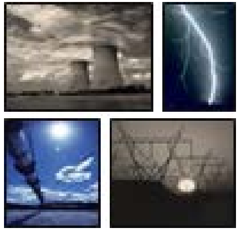


- Clear sites with railroad access first
- Then sites without railroad but with barge access
- Lastly those which only have truck access

Cask Shipment Orders: Prioritize Site Accessibility

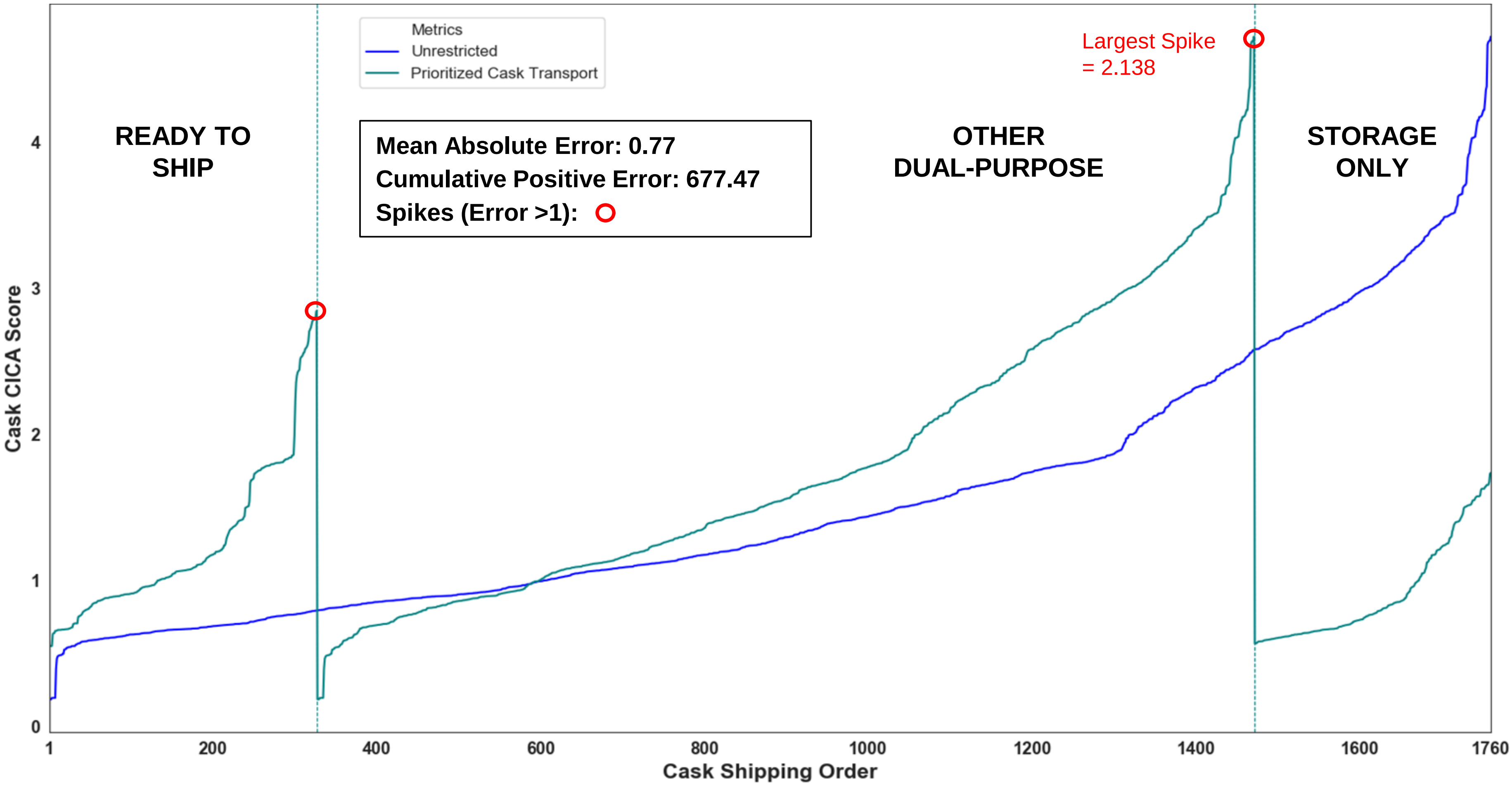


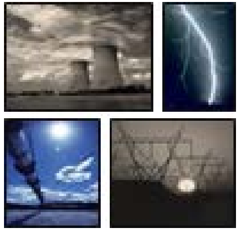
Prioritize by Cask Model for Transportation



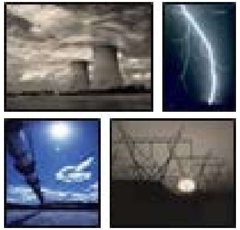
- Ship cask models that don't require transportation casks
  - Ready to ship
- Then other dual-purpose casks
  - Will require transportation casks
- Then storage only casks
  - May require repackaging

Cask Shipment Orders: Prioritize Ease of Cask Transportation





Pool Storage: Age Based Proxy for Radioactivity and Shipment Orders



Pool Storage: Explanation of Methods

- Different method from dry storage
  - Assemblies are currently stored in pools but may be packed into casks before shipping
  - Therefore, we assigned “predicted casks” to the sites
- Average

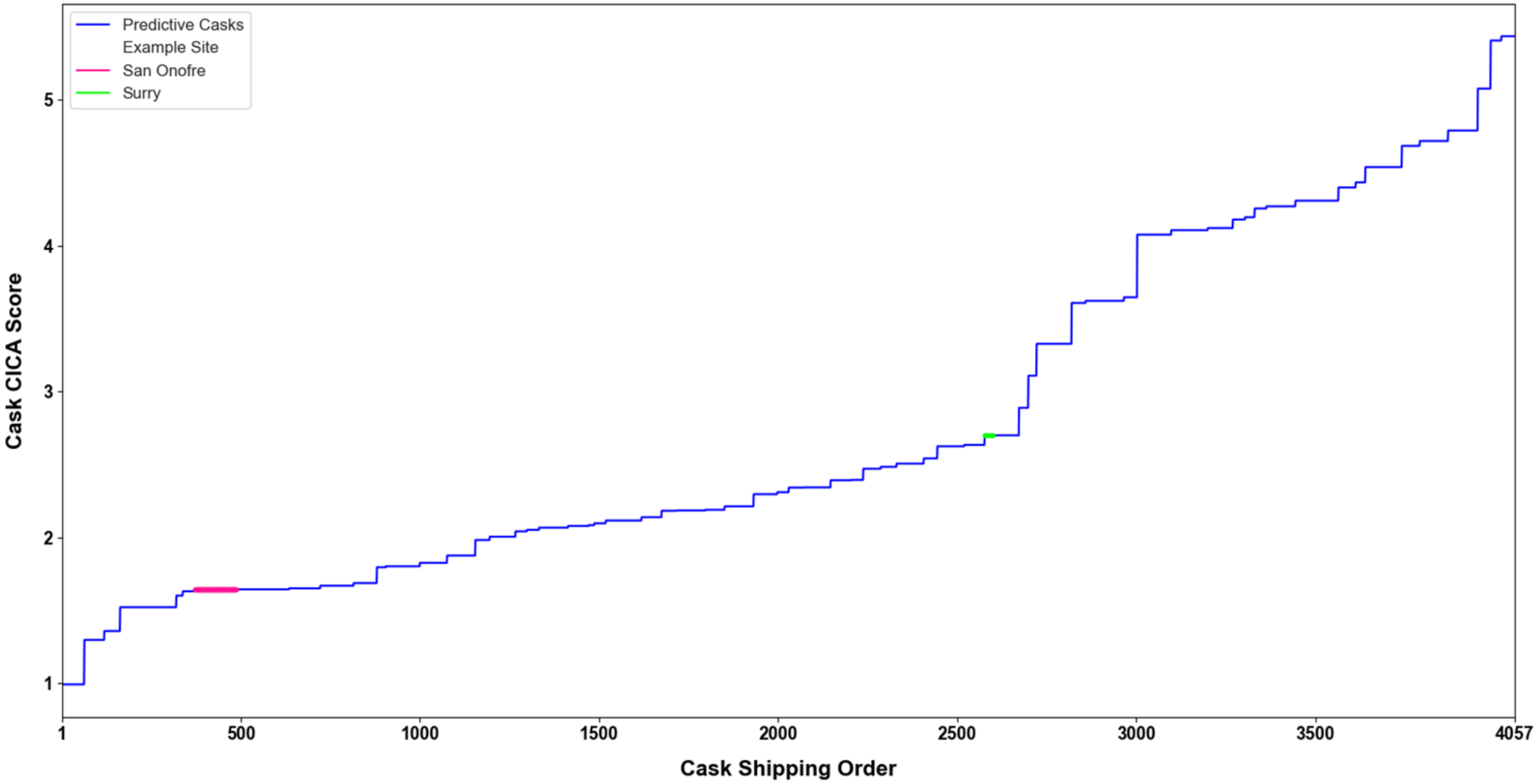
$$\text{Total Site Age} = \sum_{n=1}^{N} 1/T_n$$

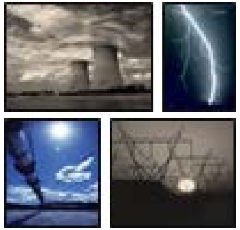
$$\text{Site Cask \#} = \frac{\text{Total \# of Assembly}}{\text{Average Cask Size at the Site}}$$

$$\text{Site Average CICA Score} = \frac{\text{Total Site Age}}{\text{Site Cask \#}}$$

* N is the total number of assemblies at the site, and Tn is the age of the nth assembly
** Cask size is estimated as the average size of the casks stored at the dry storage section of the same site

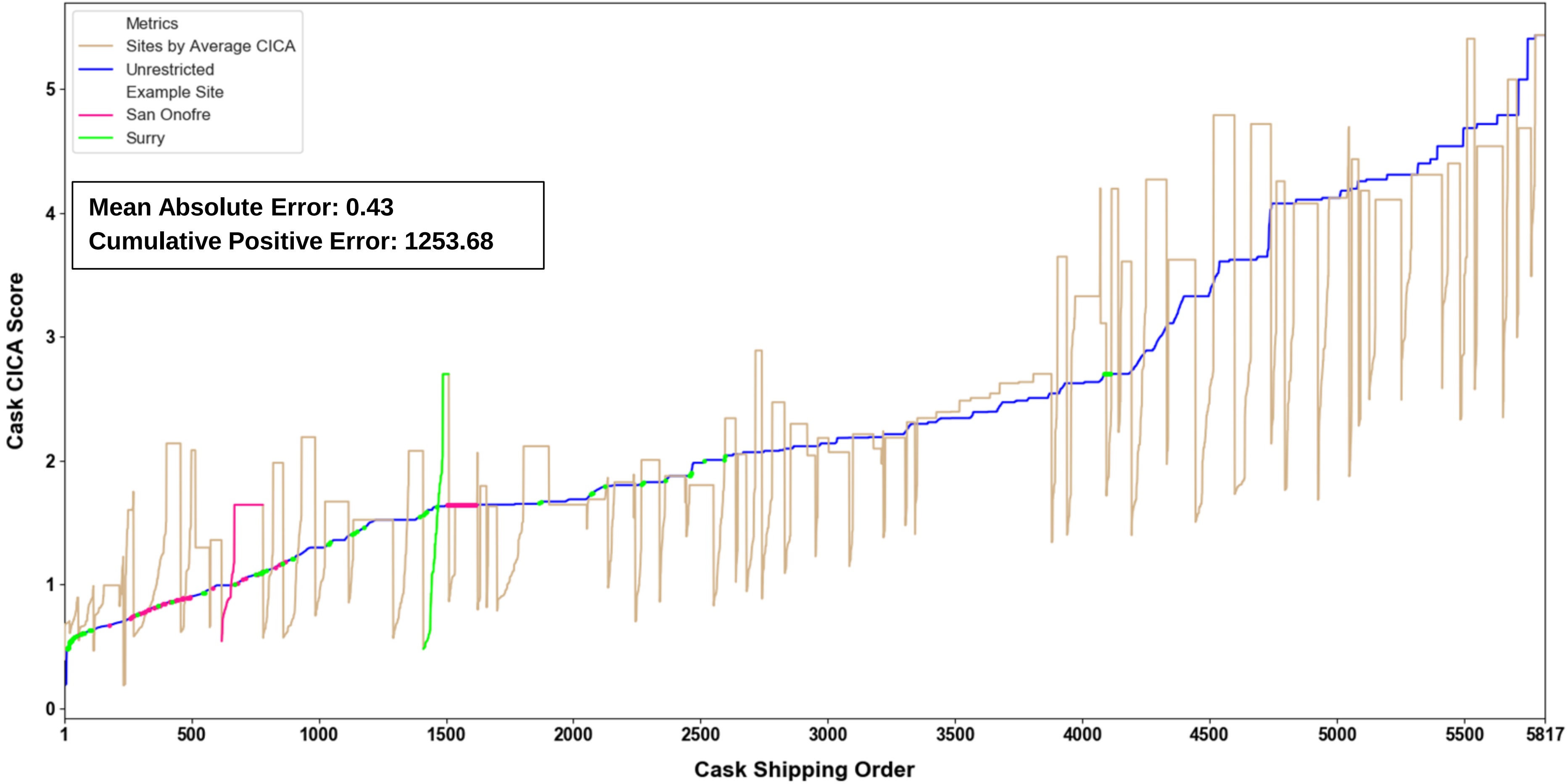
Cask Shipment Orders: Wet Storage



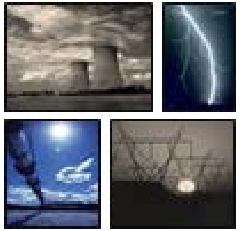


Combined Dry and Wet Site Shipment Order

Cask Shipment Orders (Wet and Dry): Site by Average CICA



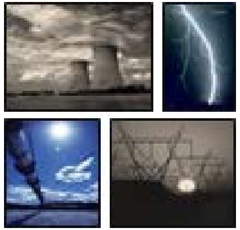
Wet and Dry: Unrestricted vs Clear by Site



- 5,817 total casks (1,760 dry + 4,057 wet)
- Unrestricted
  - 2,271 shipments to clear all current fuel
  - Estimated 87 years and 4 months
- Clear by site
  - 1,194 shipments to clear sites
  - Estimated 45 years and 11 months

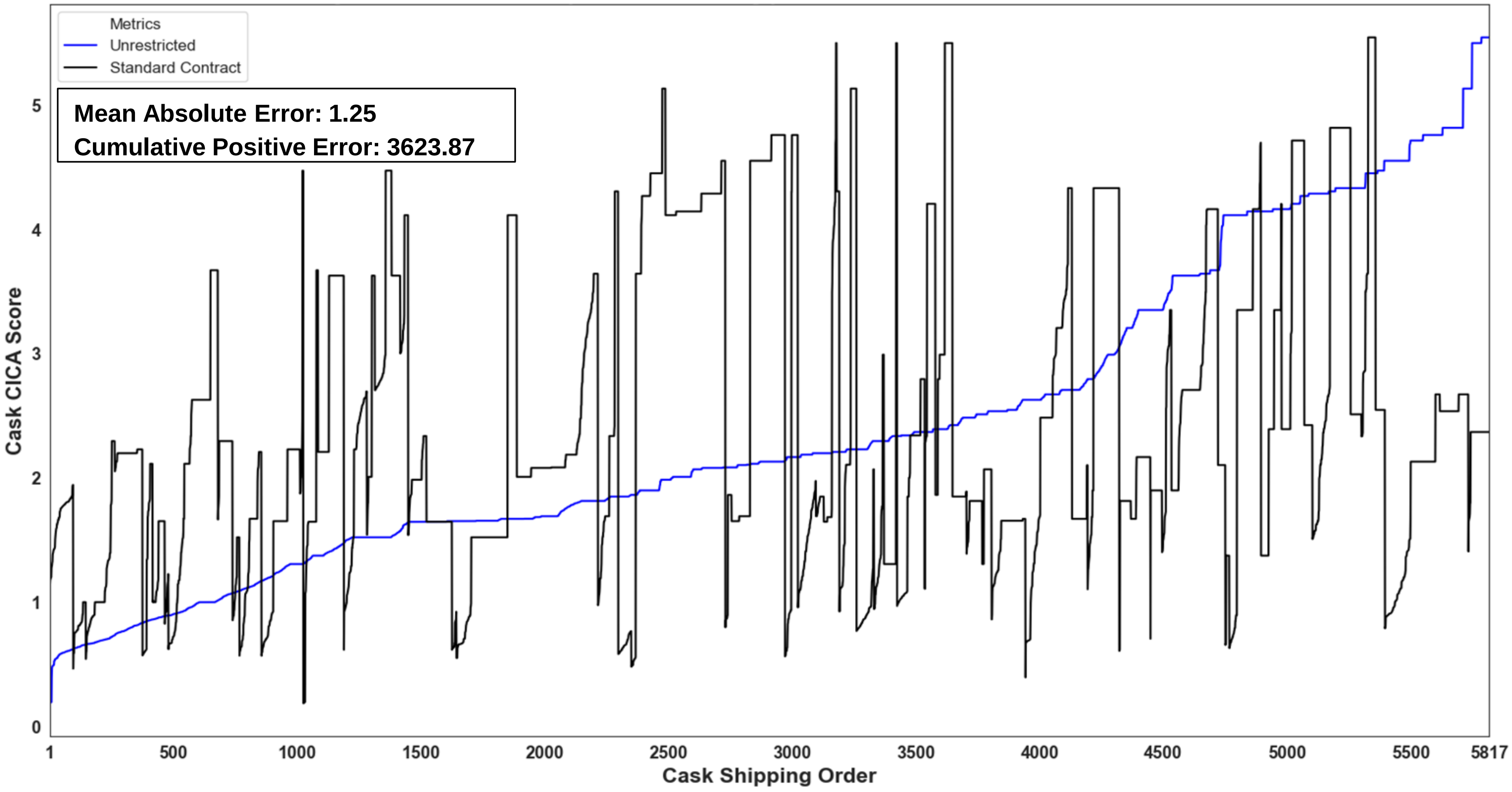
Top 15 Site Shipment Order (Wet and Dry)

Prioritize by Standard Contract

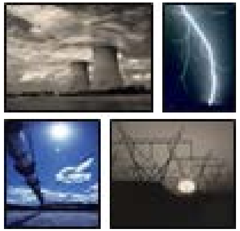


- *Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (10 CFR Part 961)*
  - A contract between the U.S. Department of Energy and utilities allowing DOE to take possession and dispose of the nuclear waste in exchange for a fee
- Ordered assemblies oldest to youngest
  - Each assembly represents a shipment slot for the utility which owns it
  - For each shipment slot, the utility transports its least risky cask
  - Continue until all casks and predicted casks are shipped

Cask Shipment Orders (Wet and Dry): Prioritize Standard Contract

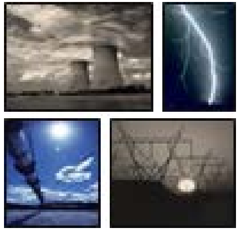


Key Findings



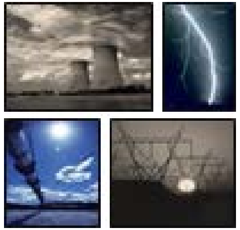
- 29% of discharged assemblies in dry casks, 71% in pools
- Age-based metrics can work as proxies for radioactivity
    - Actual cask radioactivity is preferable
- Actual 1,760 casks in dry storage
    - ~55 years, 8 months to clear dry storage by unrestricted plan
    - If clear by site, reduced to ~14 years, 5 months
- Predicted 4,057 casks required for pool storage
    - Therefore, 5,817 total casks must be shipped
        - ~45 years, 11 months to clear all commercial sent fuel by site

Key Findings (cont.)



- Methods for site and cask ranking have safety and efficiency trade-offs
  - Unrestricted is least risky but inefficient
  - Sites by “Highest Risk Fuel Last” and “Average CICA Score” are less risky
    - Either avoid individual risky casks or reduce overall shipment risk
    - “Lowest Risk Fuel First” is actually riskier overall than these site ranking methods
- Other observations from our data analysis
  - There are high-risk casks at some ISFSI only and other shutdown sites
  - Many low-risk sites do not have railway access
  - Many of the low-risk casks are storage-only
  - Preliminary analysis of the Standard Contract indicates early shipping of high risk casks and inefficient transportation

Future Study



- Conduct analysis with more up-to-date data
    - Next GC-859 survey is expected in 2020
- Calculate the actual radioactivity level for all of the casks and sites using the ORIGEN model
- Assess the radiation shielding capability of casks using the MAVRIC model
- Rank the cask and site shipping orders according to the actual radioactivity level
- Include other considerations: e.g., cask erosion, population near the site, potential transportation routes, interim storage, etc.

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