Design of Ni-based Superalloys for Fusion Energy through Life Cycle Analysis

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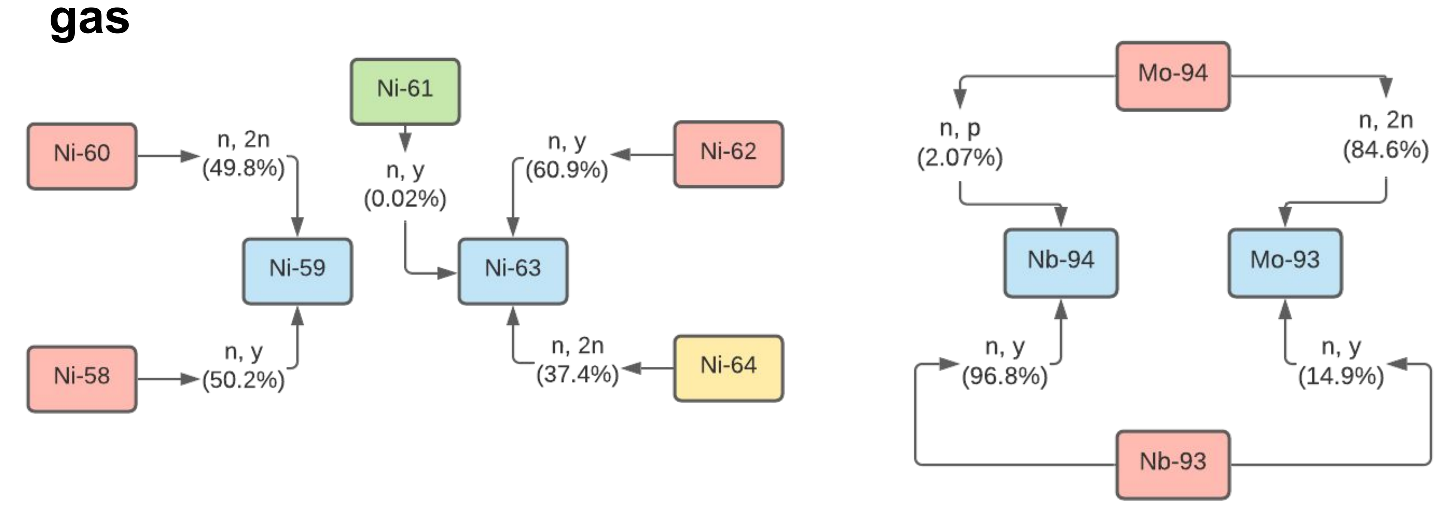
Background and Introduction

The Problem:

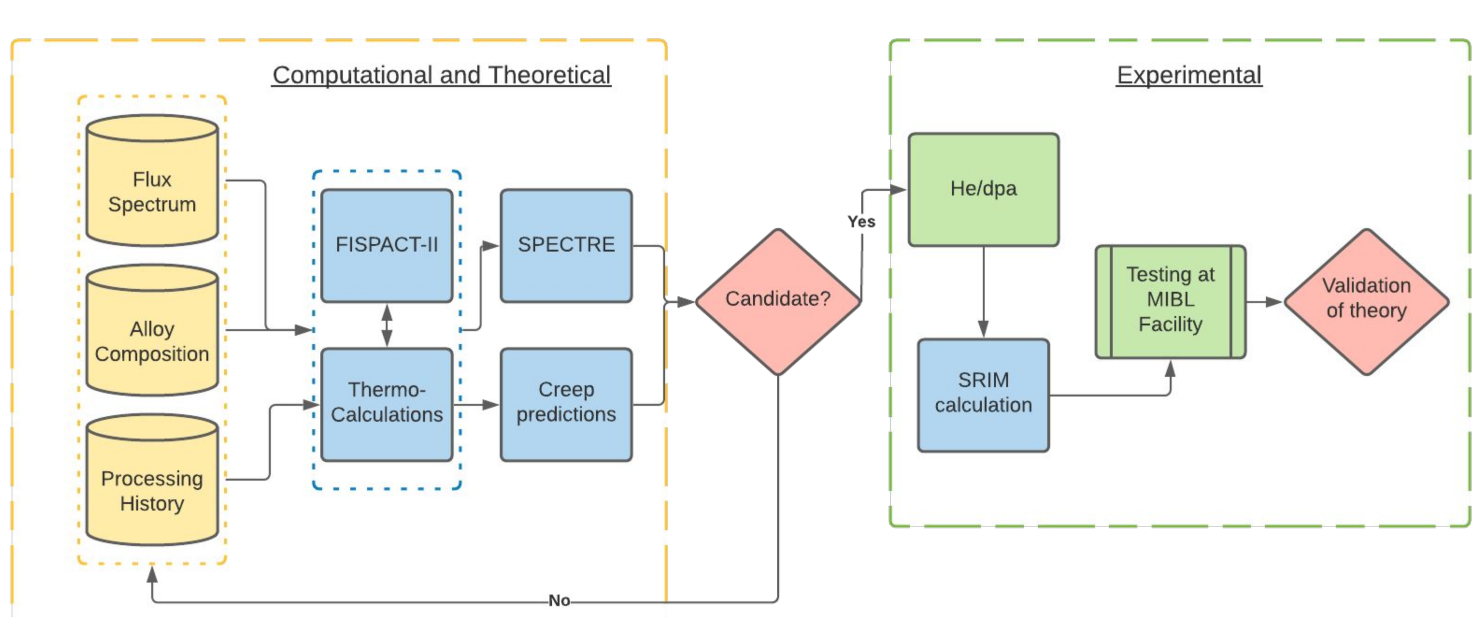
- Fusion neutrons can impart 4x more damage (DPA) than fission neutrons → **Currently, we have no way to experimentally verify material performance in a fusion environment**
- The fusion neutron spectrum produces large volumes of radioactive waste → **The Nuclear Regulatory Commission (NRC) has legal limits for specific radionuclide concentrations in materials for Class C waste disposal**
- Inconel-718 has been proposed as a structural material for a fusion reactor concept → **Elevated alloy constituents of Ni, Nb, and Mo all produce long-lived radionuclides and large amounts of He gas**



Proposed Solution:

- Engineer current alloys to mitigate the effects of the fusion environment
  - Reduce/eliminate long-lived radionuclide production through **element replacement of Nb for Ta, Mo for W, and Al for Be**
  - Reduce He and H gas production through **isotopic-tailoring of Ni**

Impact and Future Work



- **Revolutionize materials selection** for nuclear reactor concepts
- Optimize selection based on operational needs, **while minimizing their impact on waste management**
- Could result in an overall cost reduction by **reducing the amount of waste produced in the first place**

Results and Discussion

Inconel-718	Inconel-718, Nb → Ta	Inconel-718, Ta and Mo → W	Inconel-718, Ta, W, and Al → Be
Nb-94 (2884.0)	Tc-99 (13.6)	Ni-63 (1.86)	Ni-63 (1.86)
Tc-99 (13.6)	Nb-94 (7.38)	Ni-59 (1.58)	Ni-59 (1.58)
Nb-91 (4.79)	Nb-91 (4.64)	Al-26 (0.46)	Ho-166m (0.04)
Ni-63 (1.86)	Ni-63 (1.86)	Ho-166m (0.04)	Nb-94 (0.03)
Time @ WDR = 1	**Time @ WDR = 1**	**Time @ WDR = 1**	**Time @ WDR = 1**
2.63 hours	19.5 days	3.0 months	3.4 months

Table 1a: Shows the fractional isotopic contribution to the WDR at 1 FPY from radioactive daughter isotopes produced through transmutation and/or activation. Tc-99 comes from Mo-99 and Nb-91 comes from Mo-92. Al-26 comes primarily from impurity levels of Al-27 and Ho-166m comes from impurity levels of Er-164.

Table 1b: Shows the time it takes for various theoretical compositions of Inconel-718 to exceed WDR = 1. ***The alloying elements of Nb, Mo, and Al have large impacts on the WDR and thus component lifetime if Class C waste requirements are the determining factor.***

Inconel 600**	Inconel 706	Incoloy 721**	Incoloy 800	Incoloy 800H**	Incoloy 800HT	Incoloy 801**	Incoloy 802	Nimonic 75
Ni-63 (2.77)	Ni-63 (1.44)	Ni-63 (2.50)	Ni-63 (1.11)	Ni-63 (1.12)	Ni-63 (1.14)	Ni-63 (1.13)	Ni-63 (1.15)	Ni-63 (2.70)
Ni-59 (2.38)	Ni-59 (1.23)	Ni-59 (2.16)	Ni-59 (0.95)	Ni-59 (0.97)	Ni-59 (0.95)	Ni-59 (0.95)	Ni-59 (0.96)	Ni-59 (2.32)
Ho-166m (0.04)	Al-26 (0.18)	Ho-166m (0.04)	Al-26 (0.34)	Ho-166m (0.04)	Al-26 (0.35)	Ho-166m (0.04)	Al-26 (0.52)	Al-26 (0.14)
Nb-94 (0.03)	Ho-166m (0.04)	Nb-94 (0.03)	Ho-166m (0.04)	Nb-94 (0.03)	Ho-166m (0.04)	Nb-94 (0.03)	Ho-166m (0.04)	Ho-166m (0.04)
Time @ WDR = 1	**Time @ WDR = 1**	**Time @ WDR = 1**	**Time @ WDR = 1**	**Time @ WDR = 1**	**Time @ WDR = 1**	**Time @ WDR = 1**	**Time @ WDR = 1**	**Time @ WDR = 1**
2.3 months	4.1 months	2.5 months	4.8 months	5.6 months	4.8 months	5.6 months	4.4 months	2.3 months

Table 2a: Shows the fractional isotopic contribution to the WDR at 1 FPY from radioactive daughter isotopes produced through transmutation and/or activation. *** Alloys were included as they are designed without Nb, Mo, or Al. We find that the WDR scales nearly linearly with the Ni content.*

Table 2b: Shows the time it takes for various Ni-based superalloys to exceed WDR = 1. ***Currently, none of the evaluated Ni-based superalloys can achieve the minimum 6 month component lifetime requirement.***

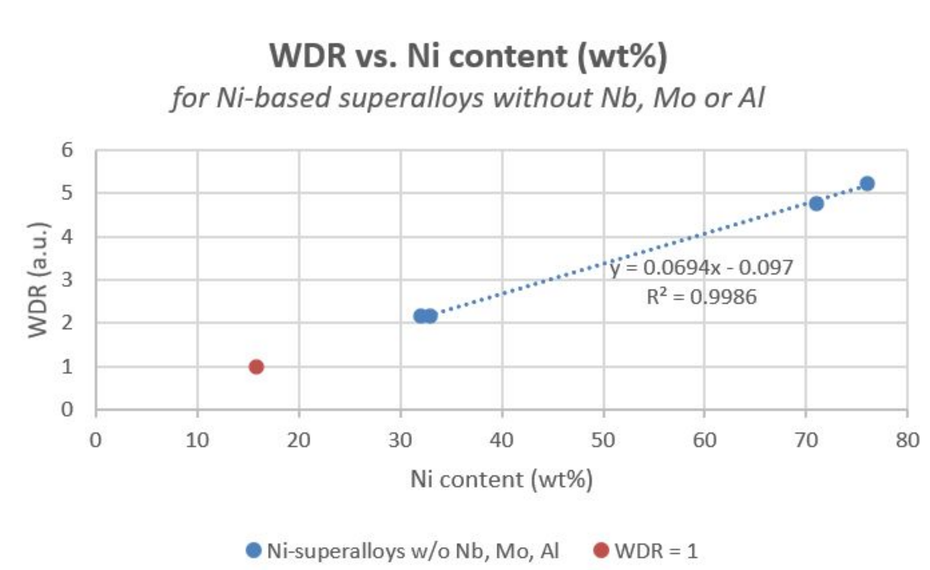
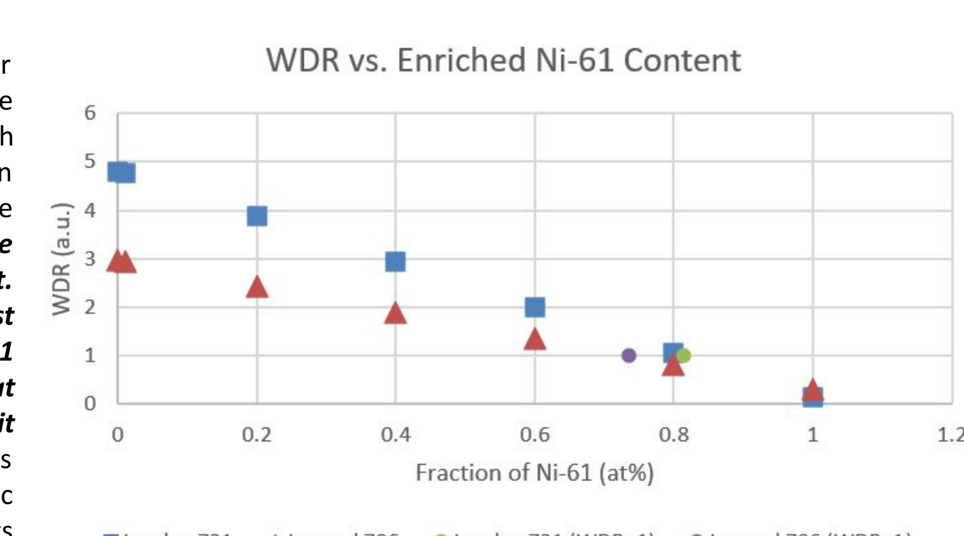
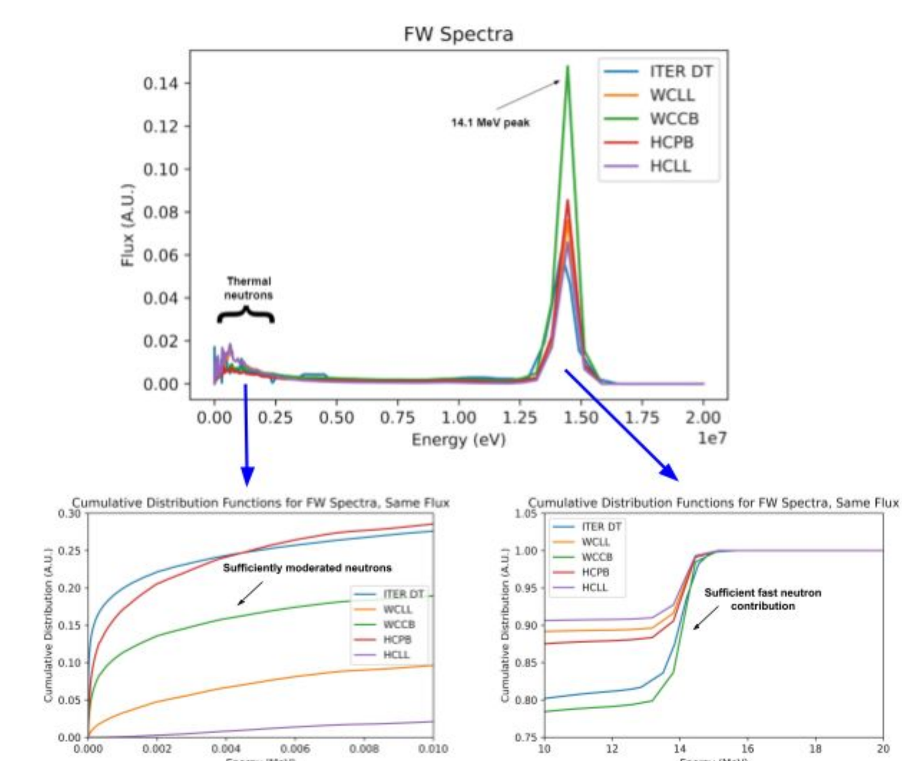


Figure 2 (left): Shows a linear fit (blue dots) for Ni-based superalloys with the lowest currently achievable impurity levels of Nb, Mo, and Al. In order of increasing Ni-content: Incoloy-801 (32 wt%), Incoloy-800H (33 wt%), Inconel-721 (71 wt%), Inconel-600 (76 wt%). ***If we want to use a Ni-based superalloy for fusion applications, we should aim for alloys with Ni content less than or equal to 15.80 wt% (red dot).***

Figure 3 (right): Shows the decreasing linear trend of WDR for both Incoloy-721 (blue squares) and Inconel-706 (red triangles) with isotopically-tailored Ni content based on varying ratios of Ni-61 to natural Ni in these alloys. ***This shows that we can further reduce the WDR by isotopically-tailoring Ni content. In these cases, Incoloy-721 requires at least 81.5 wt% enrichment of Ni-61 as it contains 71 wt% natural Ni and Inconel-706 requires at least 73.6 wt% enrichment of Ni-61 as it contains 41.5 wt% natural Ni.*** A cost analysis must be completed to determine the economic feasibility of isotopic-tailoring as Ni-61 costs ~$75/mg and Ni-58 costs ~$1/mg.



Materials and Methods

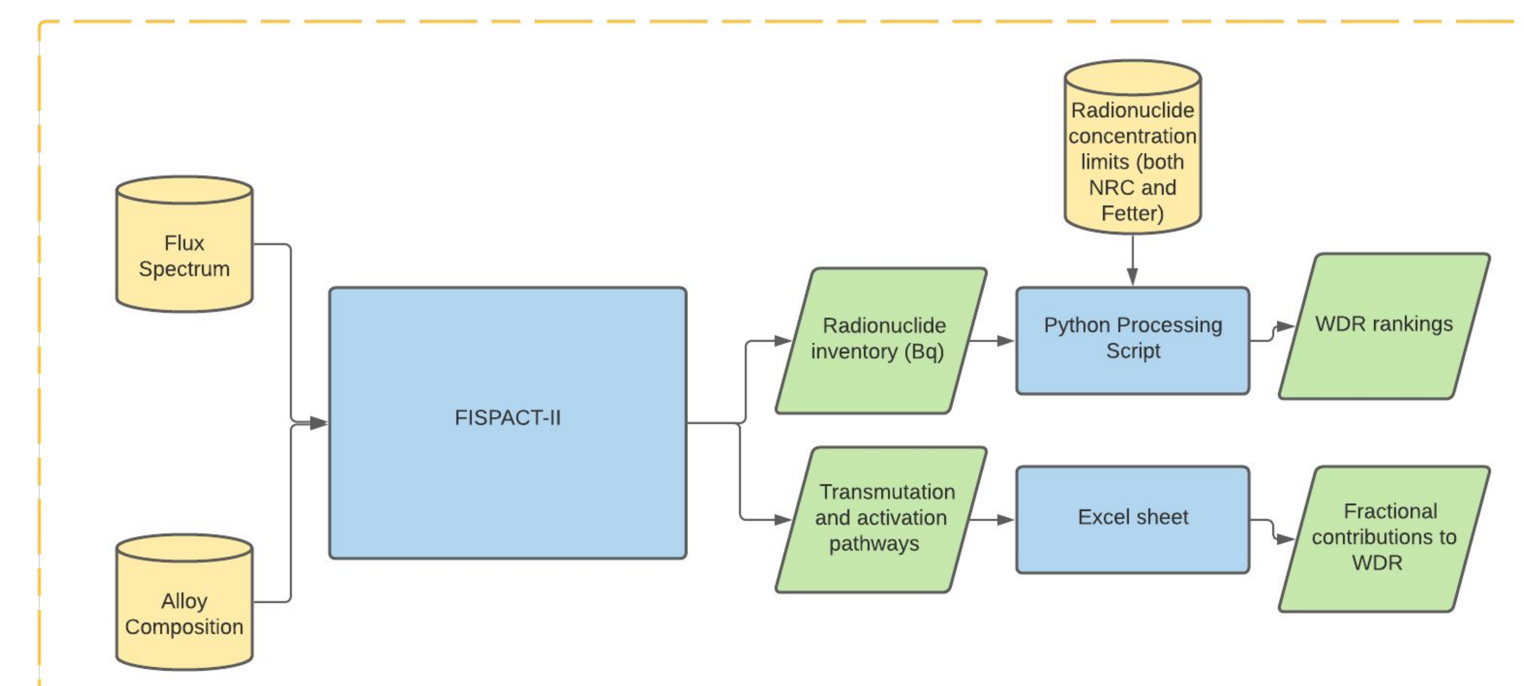


Fusion Neutron Spectrum Selection

Figure 4 (left): Shows various neutron spectra for five fusion reactor concepts: ITER-DT, water-cooled lead-lithium, water-cooled ceramic-breeder, helium-cooled pebble-bed, and helium-cooled lead lithium. Since ARC doesn't have experimental data, we needed to select a similar neutron spectrum. The WCCB spectrum includes sufficient thermal neutrons from the water moderator and sufficient fast neutrons to achieve threshold (n,2n) reactions.

Computational Workflow

Figure 5 (below): Shows the computational workflow for all the simulations. The spectral data was used as an input under "Flux Spectrum". Alloy compositions were input as total number of atoms of each isotope in a one cubic meter sample as an input under "Alloy Composition". FISPACT-II is an activation and transmutation software that we used for these simulations.



Class C Waste Disposal Rating (WDR)

Waste Disposal Rating (WDR) was our comparison metric. For waste to be classified as Class C by the NRC, our WDR must be less than 1. The minimum anticipated component replacement time is 6 months, but we simulated irradiation data for 1 full-power year (FPY). The WDR is calculated using the sum of fractions rule where:

$$WDR = \sum \frac{NWC}{Waste\ Limit} \leq 1$$

NWC = nuclide waste concentration (FISPACT output)
Waste Limit = nuclide waste concentration set by the NRC

Conclusions

1. For a one-year component lifetime, a WDR < 1 is not achievable with alloying elements of Nb and Mo. Only small amounts of Al may be permissible.

2. Ni content becomes the main contributor to WDR > 1 after Nb, Mo, and Al have been reduced to presently achievable impurity levels. We found that the WDR scales with the Ni content in the alloy.

3. Presently, there are no Ni alloys comparable to the performance of RAFM steels. These could be competitive through the isotopic-tailoring of Ni itself.

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