New Neutronics Analysis of Heisenberg's B-VIII Reactor with the Total German Uranium Inventory

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I’m a physics senior doing MCNP

Reed College, B.A. Physics (2018-21)

Columbia U., B.S. App. Physics, History (2021-23)

- SRO at Reed Research Reactor (250 kW TRIGA Mk.I)
- MCNP work at Reed, Los Alamos, NIST
- Contacted for this B-VIII analysis from U Maryland (Luke Gilde, Prof. Tim Koeth)

Historiography

Goal: Quick background on German nuclear program

German Nuclear Program ("Uranverein") was Highly Dispersed

- Code-named "Uranverein," lit. "uranium club"
- Total 9 separate programs, of which 3 to reactor dev, rest to U+D_2O production
- Split on fuel design:

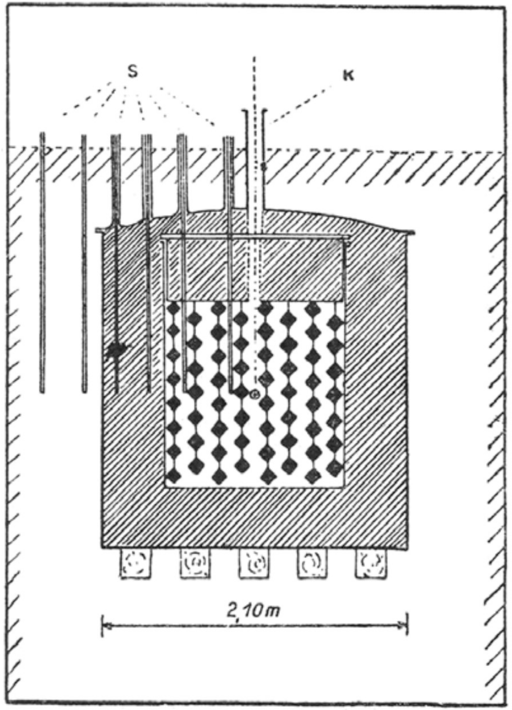
  Diebner: cubes > rods > plates

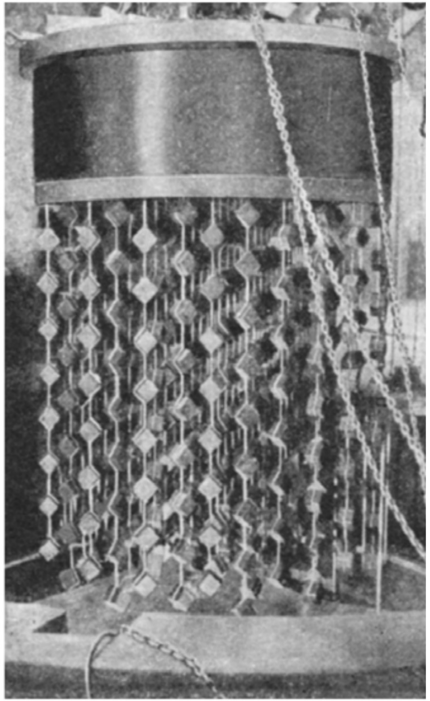
  Heisenberg: plates > rods > cubes → later agreement w Diebner

Director	Institute	Location (Codes)	1944 Fuel Allocation
Döpel + Heisenberg	Univ. of Leipzig	Leipzig (L1-4)	0
Kurt Deibner	*Heereswaffenamt* (Army Weapons Office)	Gottow (G1-3)	470 (~40%)
W. Heisenberg	**Kaiser Wilhelm Institute**	**Haigerloch (B1-8)**	**664 (~60%)**

Heisenberg's Haigerloch B-VIII was closest to criticality

- 664 cubes, 5 cm, nU
- Cubes hung in alternate Al chains of 8 vs. 9 cubes, 5.5 cm spacing per cube
- 1304 L heavy water moderator
- Tank radius 62 cm, height 120 cm
- Natural graphite reflector
- Heisenberg estimated peak criticality of $k_{eff} = 0.85$ via 1/M method





Aside: MCNP

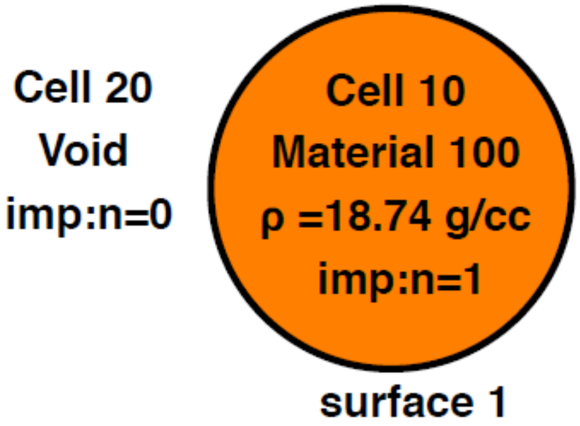
Goal: Make sure everyone can get a rough idea on what this “work” entailed re: this esoteric MCNP program

MCNP Reads in a Text File, Runs Calculations, and Prints out a Text File

```
Godiva critical
c   CELL CARDS
10    100 -18.74       -1   imp:n=1
20       0             +1   imp:n=0

c   SURFACE CARDS
1     so    8.741

c   DATA CARDS
kcode   1000    1.0    10    50
ksrc    0.0   0.0   0.0
m100    92235   -0.9473
        92238   -0.0527
```



MCNP Reads in a Text File, Runs Calculations, and Prints out a Text File

```
C:\Users\patri>mcnp6 i=test.i
```

MCNP Reads in a Text File, Runs Calculations, and Prints out a Text File

```
 ------------------------------------------------------------------------------------------------------------------------------
|                                                                                                                              |
| the final estimated combined collision/absorption/track-length keff = 0.95189 with an estimated standard deviation of 0.00017 |
|                                                                                                                              |
| the estimated 68, 95, & 99 percent keff confidence intervals are 0.95172 to 0.95206, 0.95155 to 0.95223, and 0.95143 to 0.95235 |
|                                                                                                                              |
| the final combined (col/abs/tl) prompt removal lifetime = 5.4287E-04 seconds with an estimated standard deviation of 6.0998E-07 |
|                                                                                                                              |
| the average neutron energy causing fission = 2.6361E-01 mev                                                                  |
| the energy corresponding to the average neutron lethargy causing fission = 3.0213E-07 mev                                    |
|                                                                                                                              |
| the percentages of fissions caused by neutrons in the thermal, intermediate, and fast neutron ranges are:                    |
|        (<0.625 ev):  85.03%         (0.625 ev - 100 kev):   6.28%           (>100 kev):   8.69%                             |
|                                                                                                                              |
| the average fission neutrons produced per neutron absorbed (capture + fission) in all cells with fission = 1.1062E+00         |
| the average fission neutrons produced per neutron absorbed (capture + fission) in all the geometry cells = 9.4838E-01         |
|                                                                                                                              |
| the average number of neutrons produced per fission = 2.460                                                                  |
|                                                                                                                              |
 ------------------------------------------------------------------------------------------------------------------------------
```

“Automating MCNP” means having Python “fill in the blanks”

- Jinja2 package
- Harder than it looks to set up properly, but immense payoff
- Python writes MCNP code → runs it → reads output file to copy relevant data to a spreadsheet

Ex: material densities

```
c --- 4111 - SS clad (T0S210D210) universe ---
c
411101   105 -7.85       312300 -312301 -311302
411102   102 {{h2o_density}}      312300 -312301
```

Ex: water material card (temperature-dependent)

```
m102    {{ h_mats }}
        {{ o_mat_lib }} 1.0000
c
mt102   {{ h2o_mt_lib }}
```

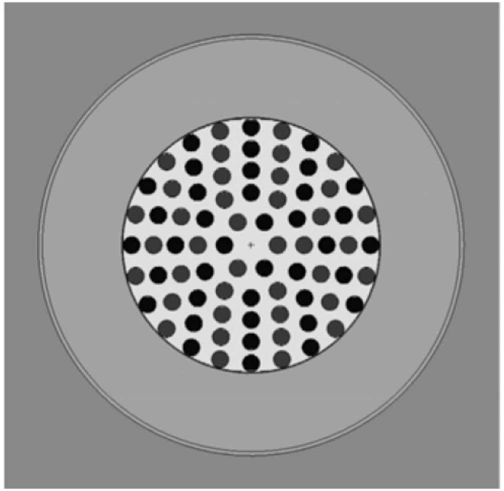
Analysis: Base Model B-VIII

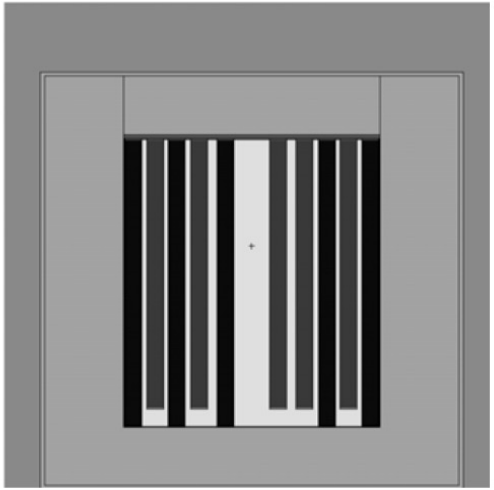
2009 Italian analysis set the wrong "consensus"

- 2009 Italian neutronics analysis of B-VIII became default source for most historiographies of the German nuclear program
- Italians' conclusions:
  - Neutron thermalization pathlength in heavy water should be 11 cm (B-VIII only had 5.5 cm spacing between cubes)
  - MCNP $k_{eff} = 0.86$
  - Graphite poisons largely irrelevant to final keff when used as reflector
  - **Germans had neither enough fuel NOR heavy water for criticality**

Heisenberg [k_{eff}]	Grasso et al. (2009) [k_{eff}]
0.85	0.86

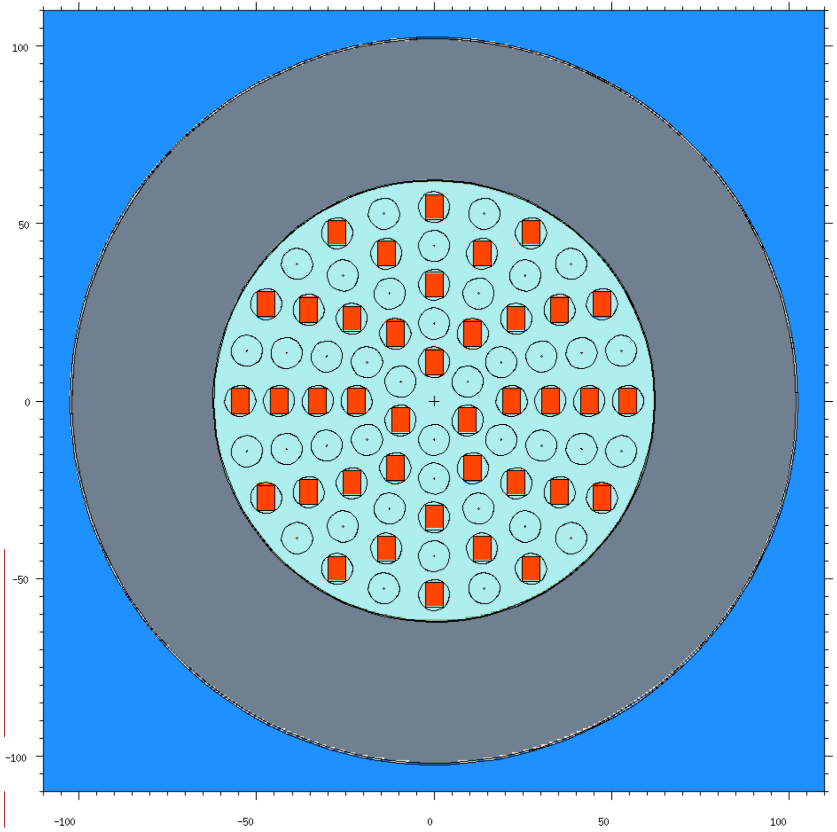
2009 Italian analysis: Unclear methodology

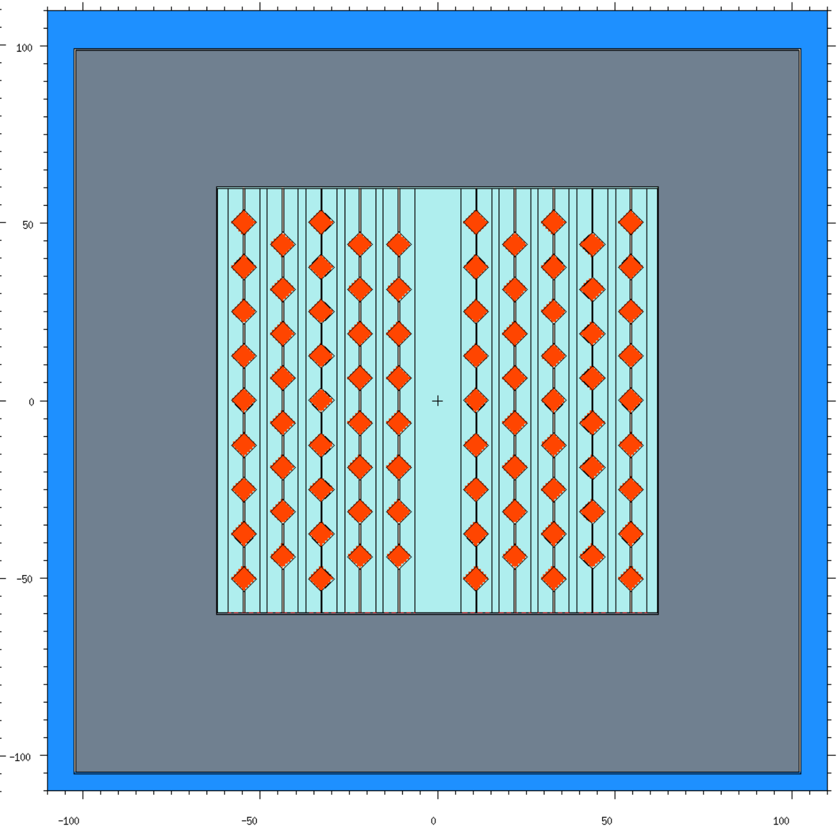




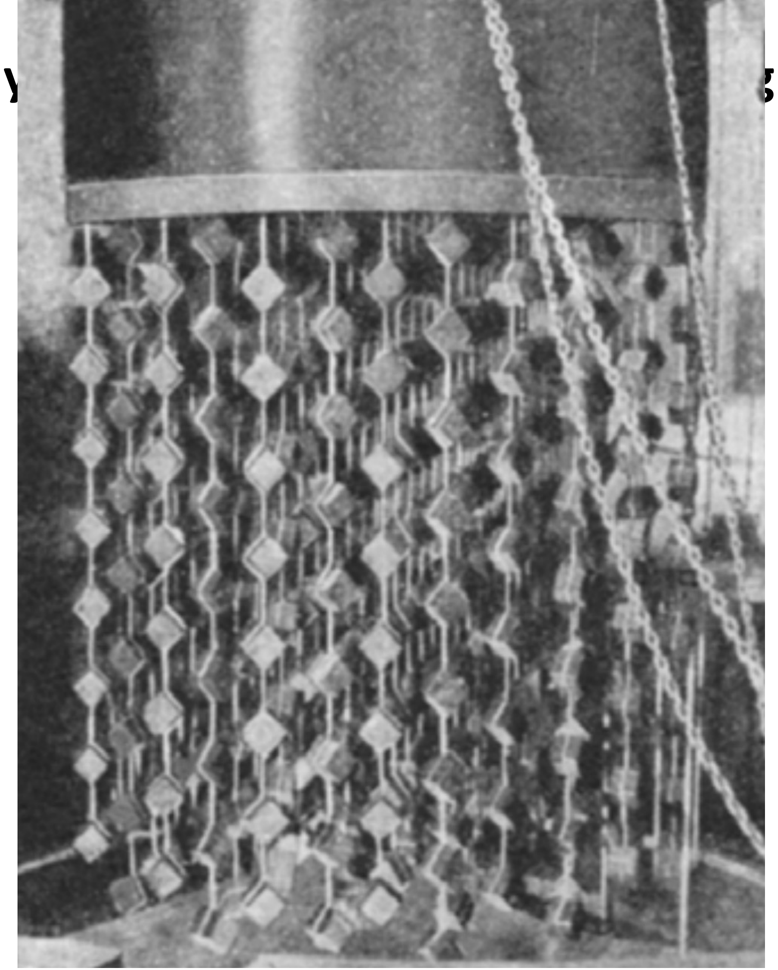
"We had to make some assumptions… to the necessity of **simplifying the system** for calculational purposes. First, we assumed that the uranium-fuel… were filled with **a uniform and homogeneous mixture** of uranium fuel, aluminium, and heavy water, with the known masses of these materials placed inside each cylinder. This introduced a **small underestimation** of the k_{eff}… because the uranium fuel in the B-VIII reactor was lumped in three directions, while in the MCNP simulation it is **lumped only in the radial direction.**" –Grasso, *Phys. Perspect.* (2009)

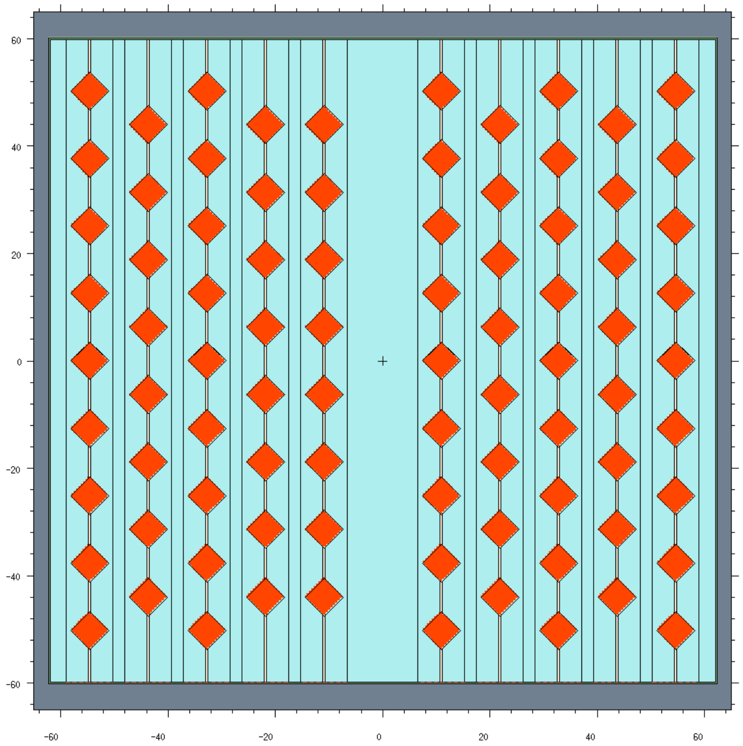
My 1st Improvement: Fully Modeling the B-VIII





My[...]g the B-VIII





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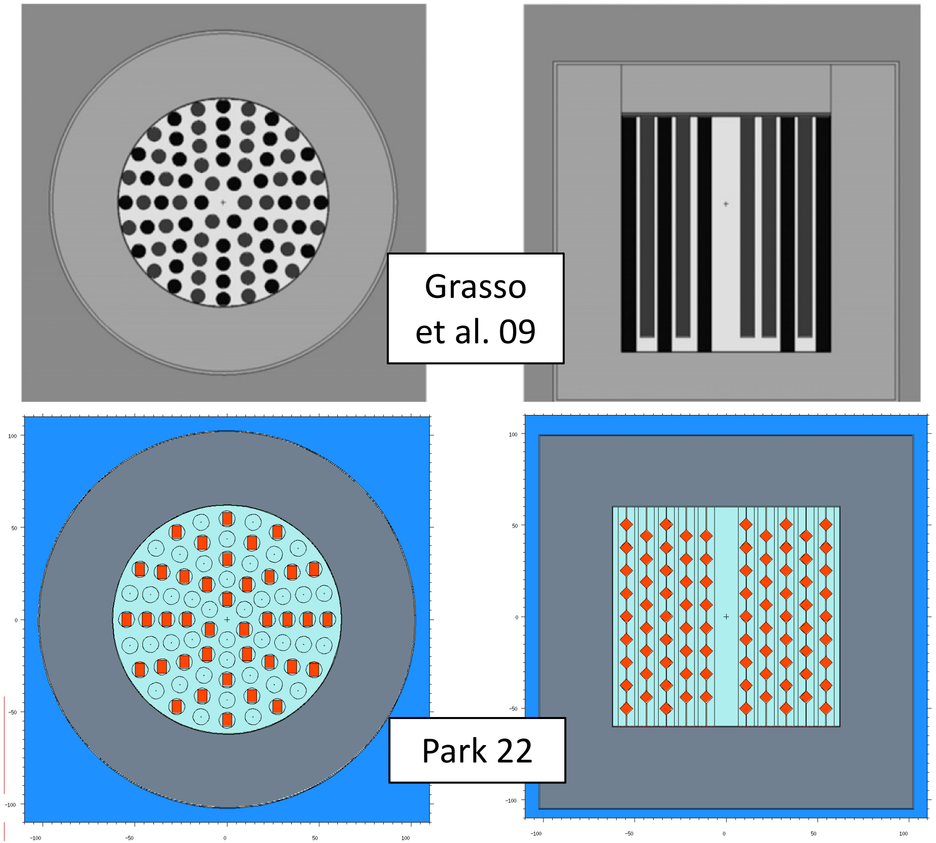

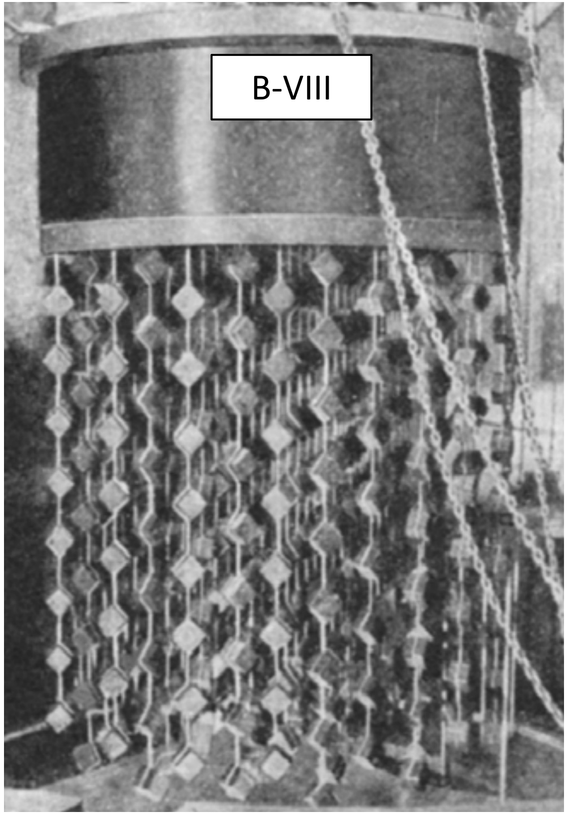

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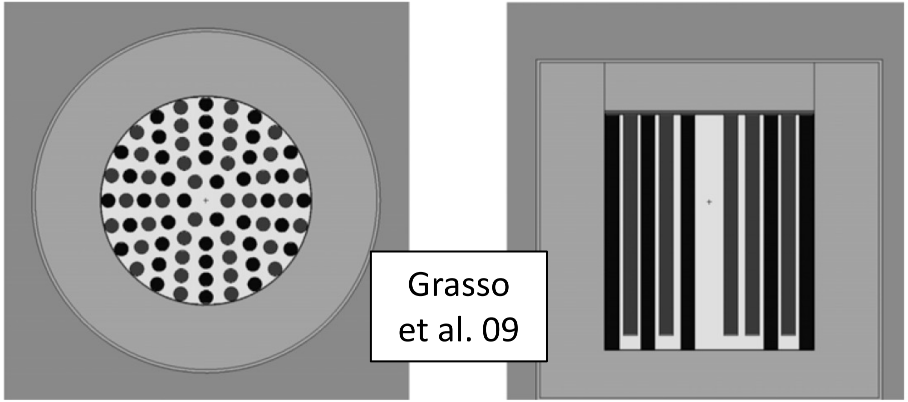
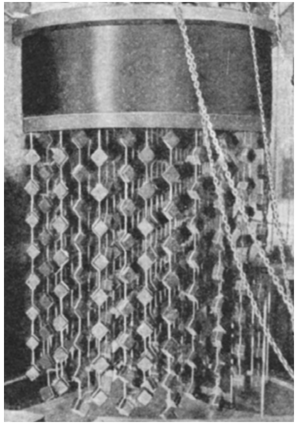
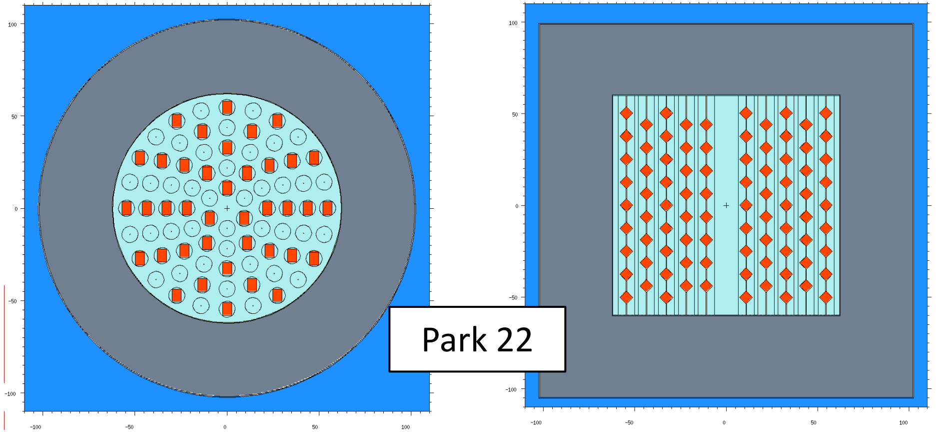


Grasso et al. 09



B-VIII



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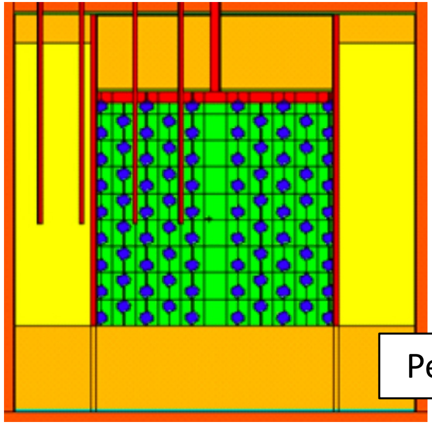


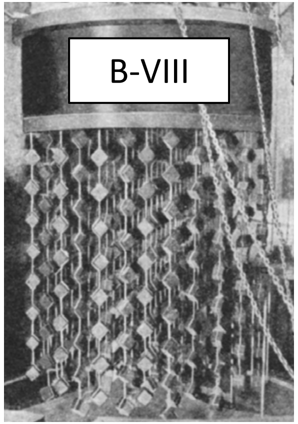
Pesic 19

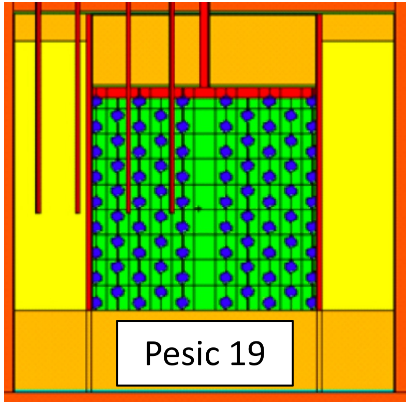
My 2nd Improvement: Better nU density + D_2O purity data

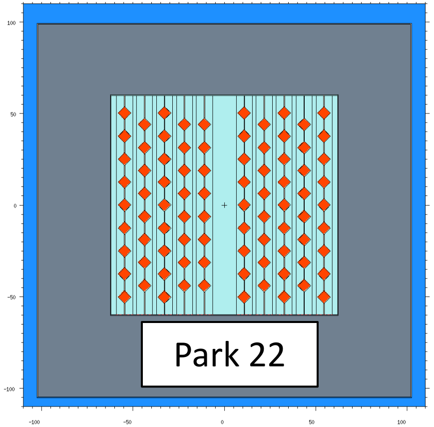
- Extant cubes sent to Pacific NW Nat'l Lab (PNNL) for mass spectroscopy
  - Natural uranium nominally is 19.05 g/cc (Grasso + Pesic this assumption)
  - PNNL measured **18.53 g/cc**

- Samples of B-VIII heavy water kept at NIST
  - B-VIII D_2O purity guessed as 95 at% (Grasso + Pesic use this assumption)
  - NIST measured **96.8 at%** in 1947 analysis

Different k_{eff} between Heisenberg + Grasso v Pesic + Park







Heisenberg [k_{eff}]	Grasso (2009) [k_{eff}]
0.85	0.86

Pesic (2019) [k_{eff}]	Park (2022) [k_{eff}]
0.953	0.958

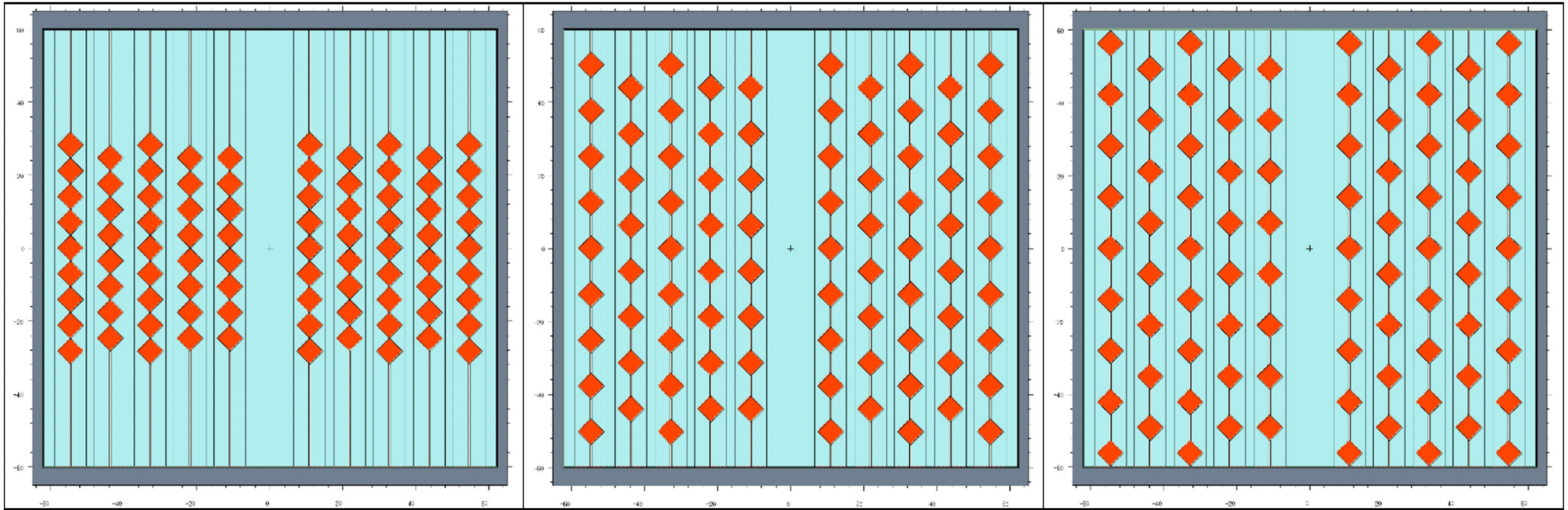
- My decrease in nU density (19.05 $\longrightarrow$ 18.53 g/cc) and increase in D_2O purity (95 $\longrightarrow$ 96.8 at%) balance out results with Pesic
- Why different from Heisenberg?

Analysis: Optimizing the B-VIII

Italians were right in that B-VIII neutron path lengths were too short

- I wrote automation scripts in Python to test & optimize B-VIII cube intervals **both axial and radial**

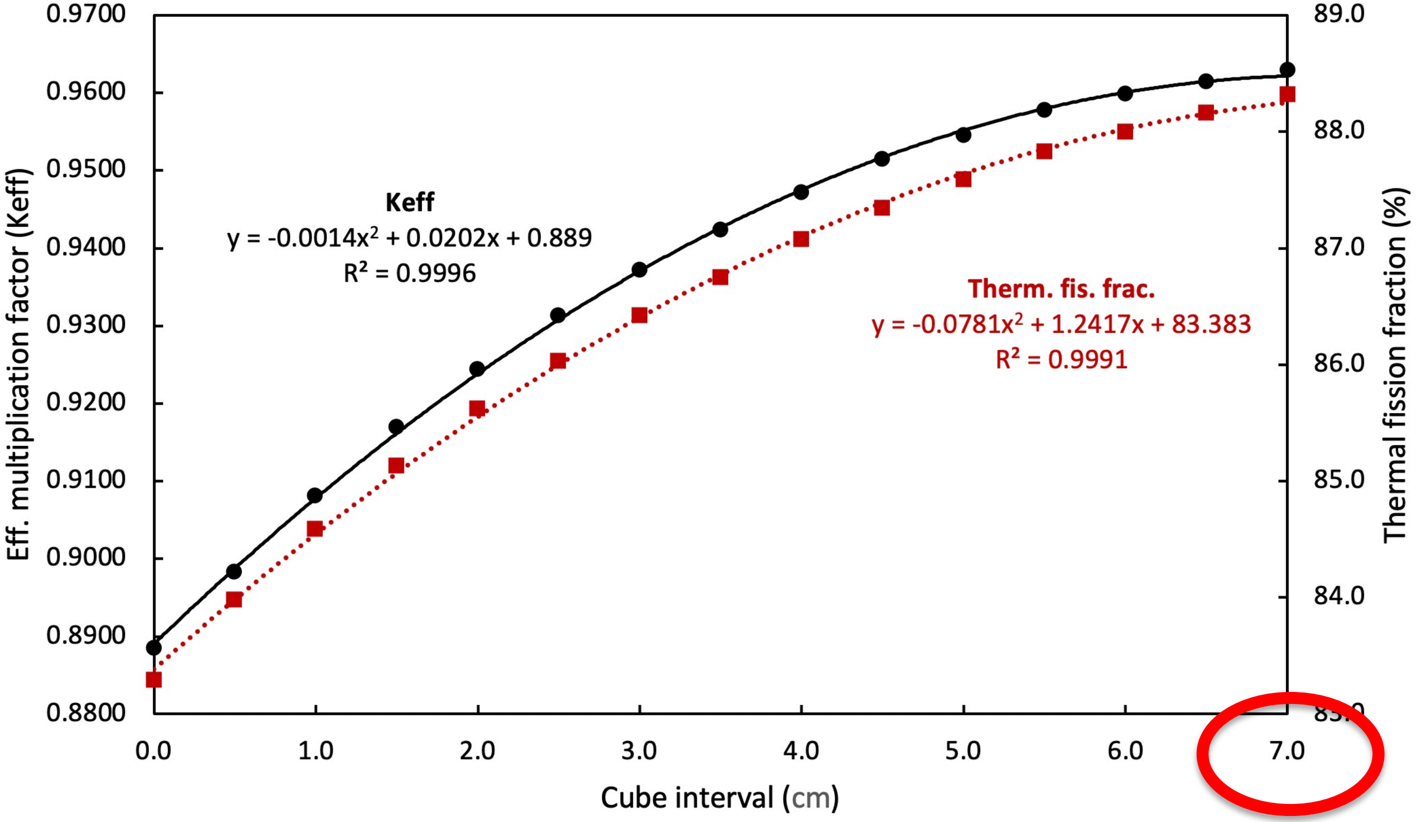
Original axial interval: 5.5 cm | Peak possible k_{eff} at: 7 cm



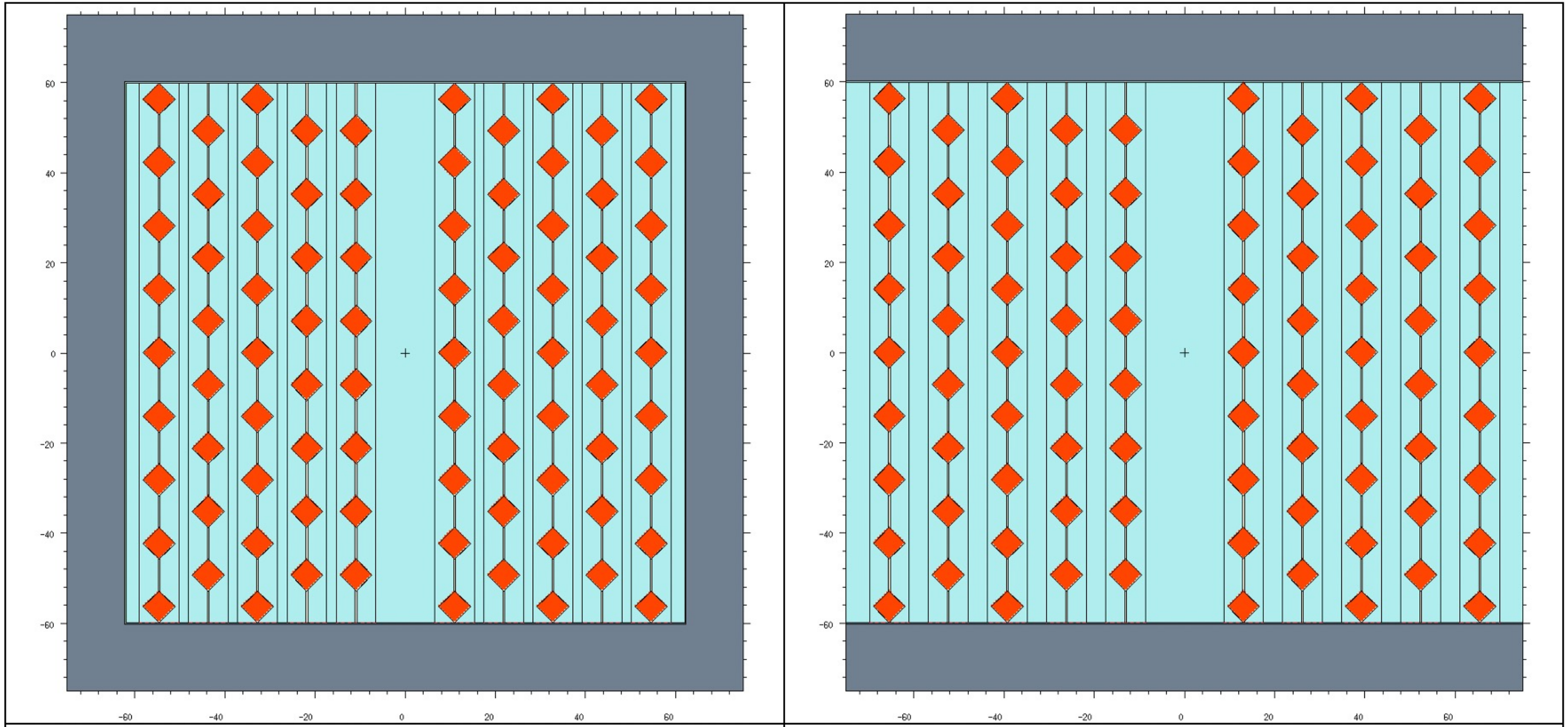
(a) 0 cm	(b) 5.5 cm, original	(c) 7.0 cm, max

Figure 8. Sample plots of the 0, 5.5, and 7.0 cm cube interval cases in this test.

Original axial interval: 5.5 cm | Peak possible k_{eff} at: 7 cm



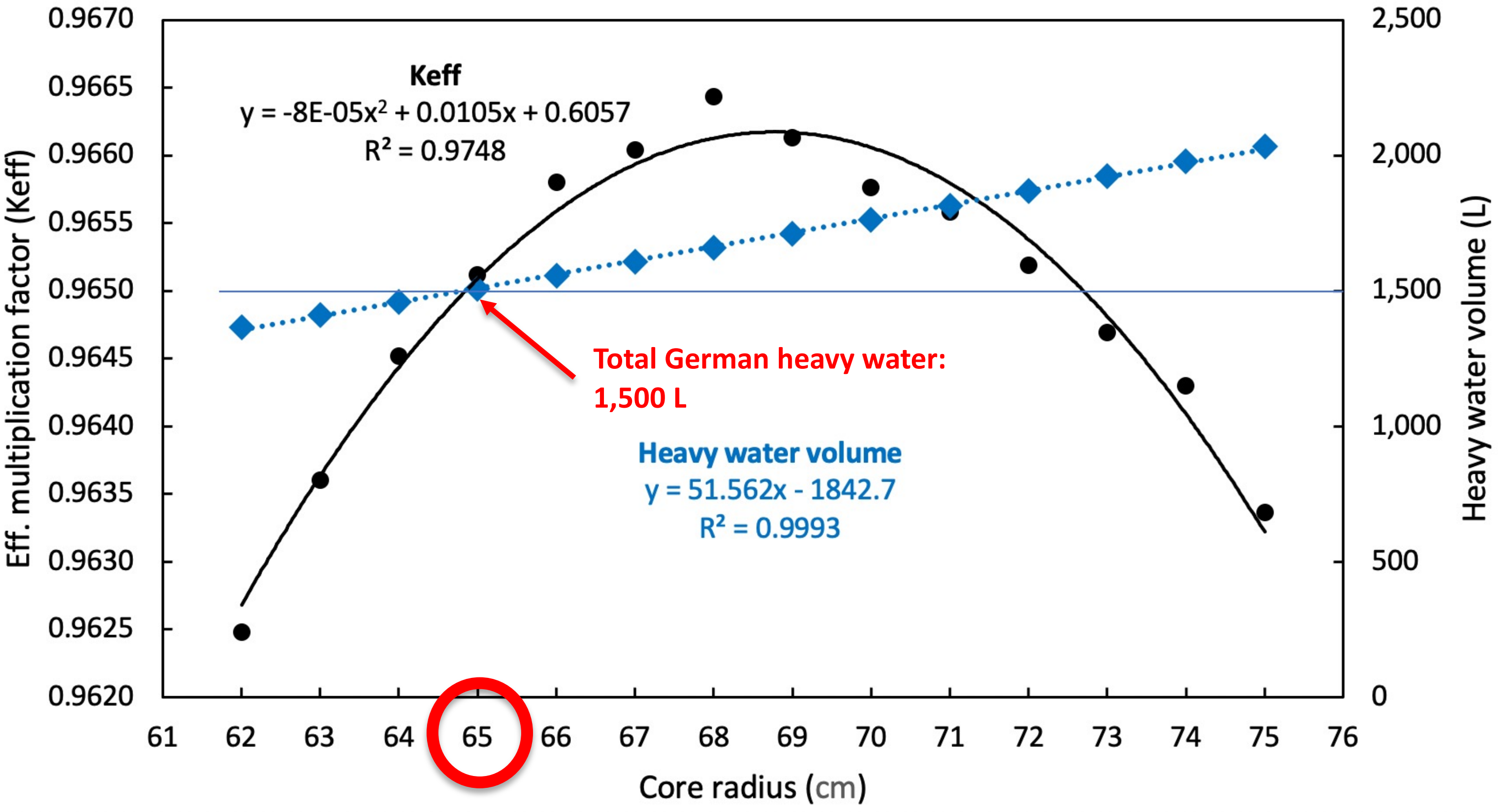
Original tank radius: 62 cm | Peak possible k_{eff} at: 65 cm



(b) r = 62 cm | (c) r = 75 cm

Figure 10. Sample plots of the 62 and 75 cm radial expansion cases in this test.

Original tank radius: 62 cm | Peak possible k_{eff} at: 65 cm



Original B-VIII k_{eff}=0.958 can be optimized to 0.965 using existing 1945 materials

Case A: original B-VIII as built

Case B: optimization of B-VIII with constraints of materials on-site in 1945

Case	k_{eff}	nU cubes	Cube axial intrv. (cm)	D_2O (L)	Tank R (cm)	Tank H (cm)
A	0.958	664	5.5	1,304	62	120
B	0.965	664	7.0	1,500	65	120

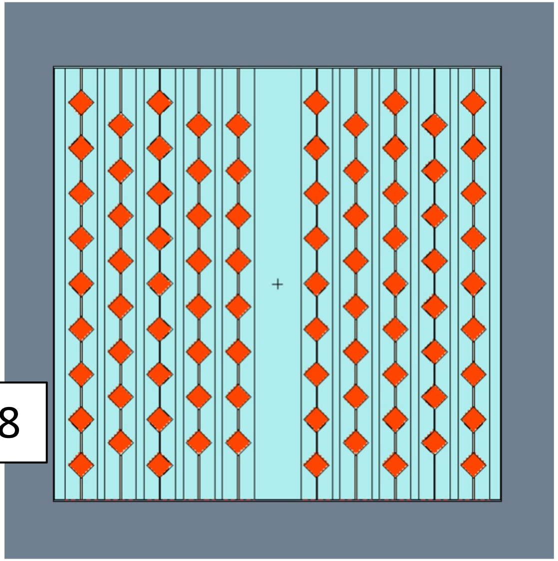
Analysis: Adding More Fuel from Gottow

If you just add 470 extra cubes into original dimensions, k_{eff} goes DOWN

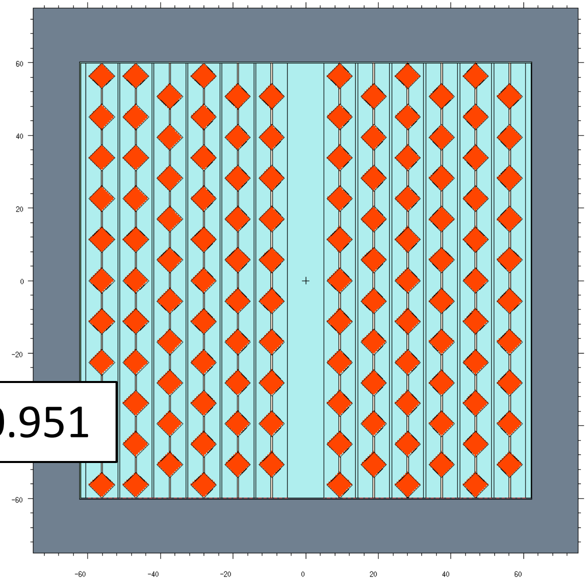
It’s not about the fuel– it’s about the thermalization

B-VIII original with 664 cubes (left).

B-VIII with +470 cubes in original tank dimensions (right).



0.958



0.951

With 664+470=1134 cubes and limited heavy water, max possible k_{eff} = 0.968

Case A: original B-VIII as built

Case B: optimization with heavy water constraint on-site in 1945

Case C: optimization of 664+470 cubes with heavy water constraint

Case	k_{eff}	nU cubes	Cube axial intrv. (cm)	D_2O (L)	Tank R (cm)	Tank H (cm)
A	0.958	664	5.50	1,304	62	120
B	0.965	664	7.00	1,500	65	120
C	0.968	1134	5.75	1,500	62	138

What did Heisenberg need for the minimum critical core?

Case A: original B-VIII as built

Case B: optimization with heavy water constraint on-site in 1945

Case C: optimization of 664+470 cubes with heavy water constraint

Case D: minimum critical core – needs +1,009 L heavy water

Case	k_{eff}	nU cubes	Cube axial intrv. (cm)	D_2O (L)	Tank R (cm)	Tank H (cm)
A	0.958	664	5.50	1,304	62	120
B	0.965	664	7.00	1,500	65	120
C	0.968	1134	5.75	1,500	62	138
D	1.001	1134	8.50	**2,509**	72	163

UMD Prof. Koeth: What's the max possible critical core you can make?

Case A: original B-VIII as built

Case B: optimization with heavy water constraint on-site in 1945

Case C: optimization of 664+470 cubes with heavy water constraint

Case D: minimum critical core – needs +1,009 L heavy water

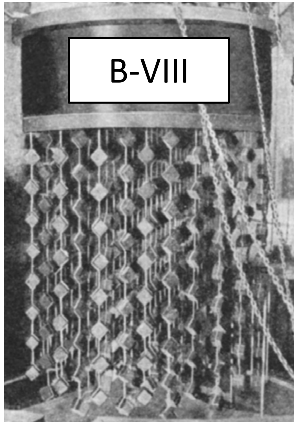
Case E: max critical core Patrick could make w given fuel – needs +1,330 L heavy water

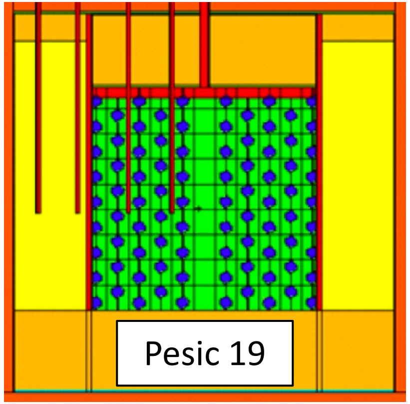
Case	k_{eff}	nU cubes	Cube axial intrv. (cm)	D_2O (L)	Tank R (cm)	Tank H (cm)
A	0.958	664	5.50	1,304	62	120
B	0.965	664	7.00	1,500	65	120
C	0.968	1134	5.75	1,500	62	138
D	1.001	1134	8.50	**2,509**	72	163
E	1.003	1134	7.00	**2,830**	80	148

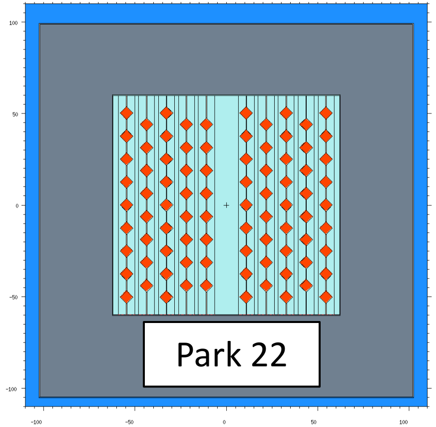
The consensus that the Germans did not have enough fuel NOR heavy water is not totally true.

German nuclear program could have combined Gottow and Haigerloch fuels to make their only criticality constraint be heavy water.

The Germans were at most 1,009 L of heavy water off from a critical assembly.







My unsolved mystery:

What could have made Heisenberg calculate k=0.85 when Pesic and I calculated 0.96?