Understanding Early Reactor Programs: Nuclear Archaeology of Heisenberg's B8 Pile

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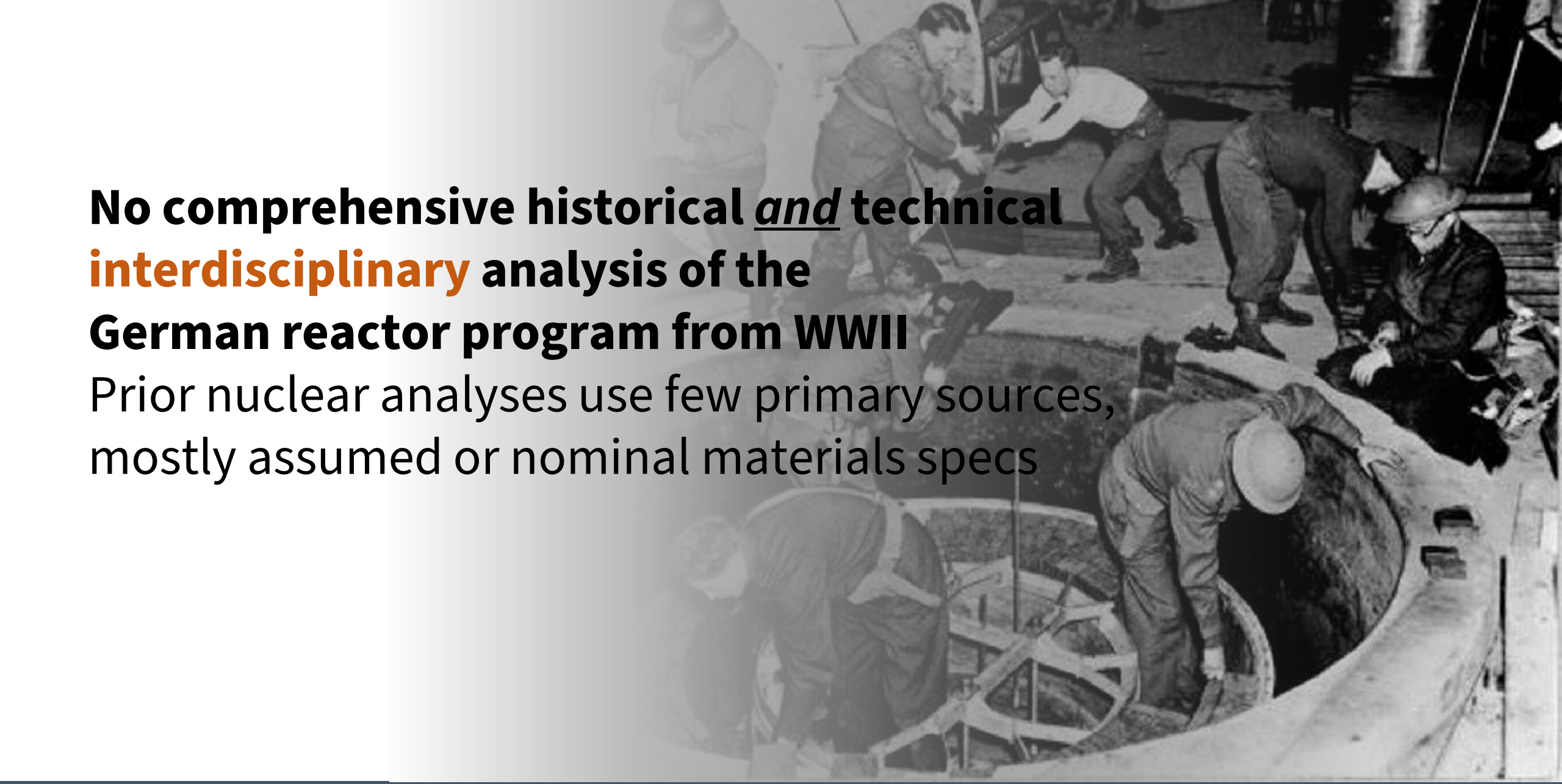
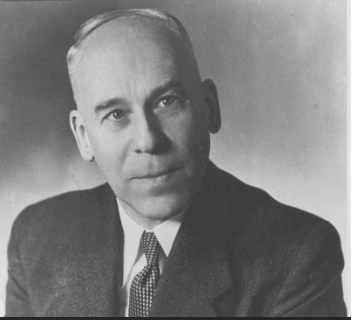
NB for peer-reviewers: Preferably view as PowerPoint slideshow.

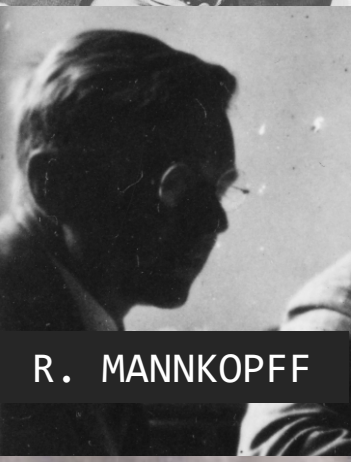


No comprehensive historical *and* technical interdisciplinary analysis of the German reactor program from WWII

Prior nuclear analyses use few primary sources, mostly assumed or nominal materials specs

THE GERMAN NUCLEAR PROGRAM WAS CALLED THE *URANVEREIN*

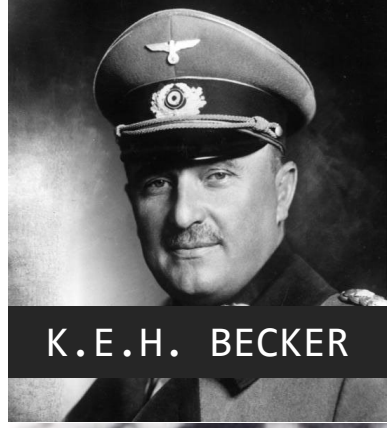

W. HANLE

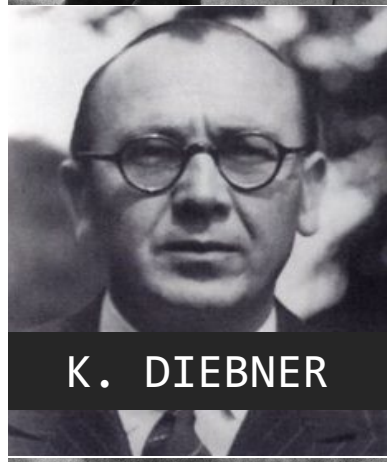

R. MANNKOPFF

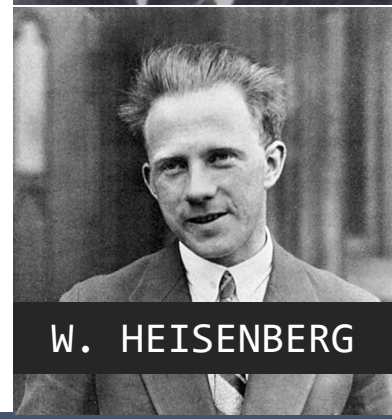

G. JOOS

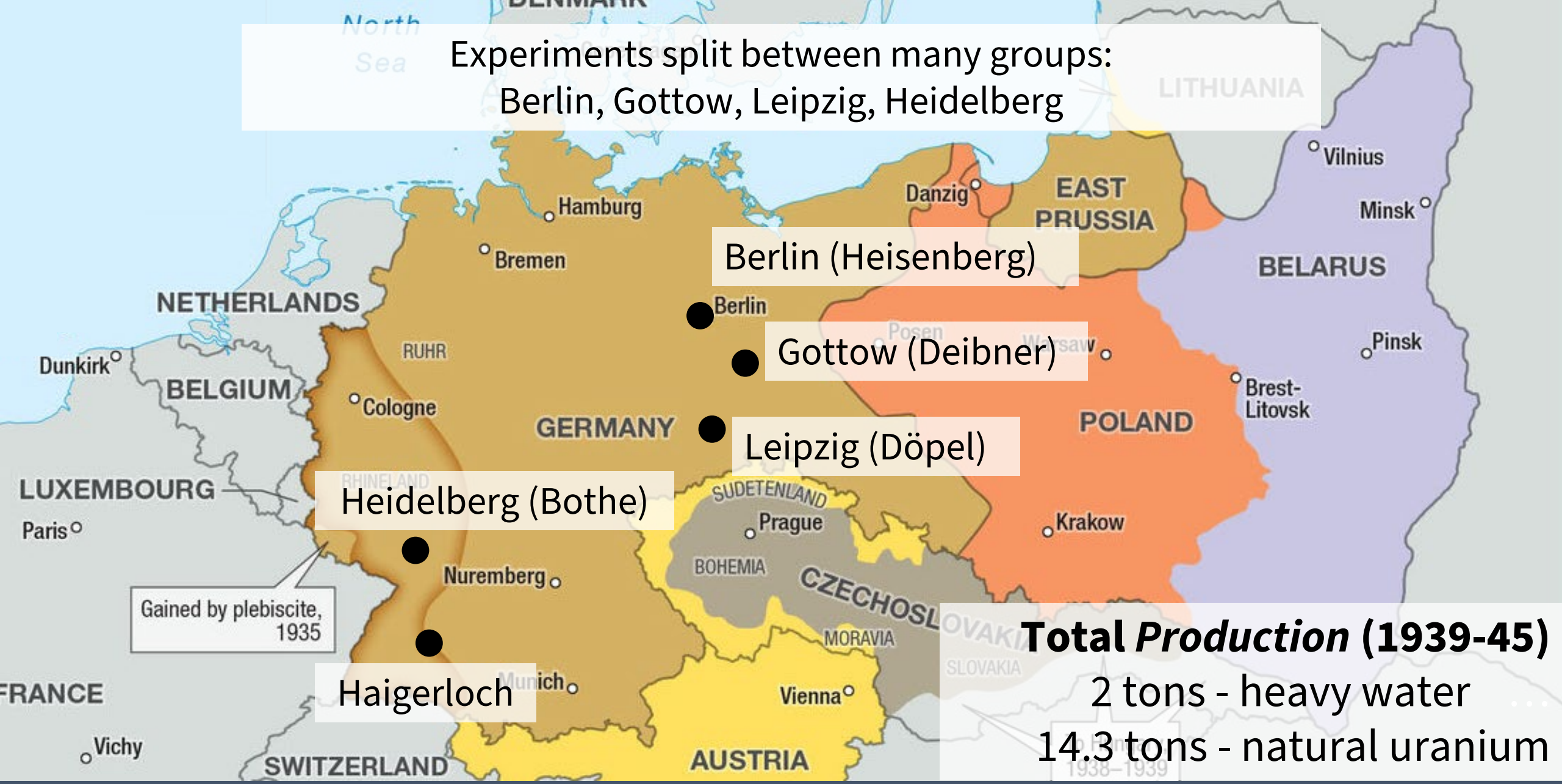
Generally marked by

cut-throat competition,
personal rivalries, and
fighting over limited resources


K.E.H. BECKER


K. DIEBNER


W. HEISENBERG


Experiments split between many groups:
Berlin, Gottow, Leipzig, Heidelberg
Berlin (Heisenberg)
Gottow (Deibner)
Leipzig (Döpel)
Heidelberg (Bothe)
Haigerloch
Total Production (1939-45)
2 tons - heavy water
14.3 tons - natural uranium
Gained by plebiscite, 1935
Hamburg
Bremen
Danzig
EAST PRUSSIA
Vilnius
Minsk
BELARUS
Pinsk
Brest-Litovsk
POLAND
Krakow
Berlin
Posen
Warsaw
RUHR
Cologne
GERMANY
NETHERLANDS
Dunkirk
BELGIUM
LUXEMBOURG
Paris
RHINELAND
SUDETENLAND
Prague
BOHEMIA
MORAVIA
CZECHOSLOVAKIA
SLOVAKIA
Nuremberg
Munich
Vienna
AUSTRIA
SWITZERLAND
Vichy
FRANCE
LITHUANIA
North Sea
DENMARK

URANVEREIN WAS “AHEAD” OF MANHATTAN UNTIL EARLY 1942

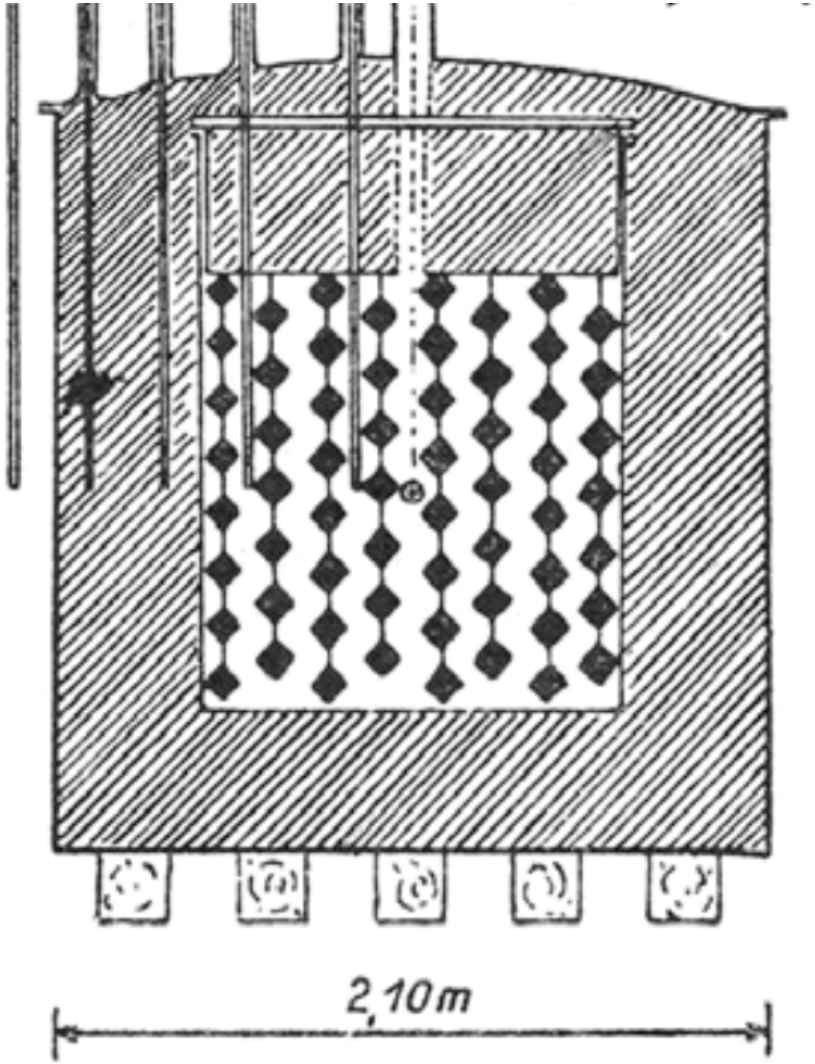
1 ton per month U metal

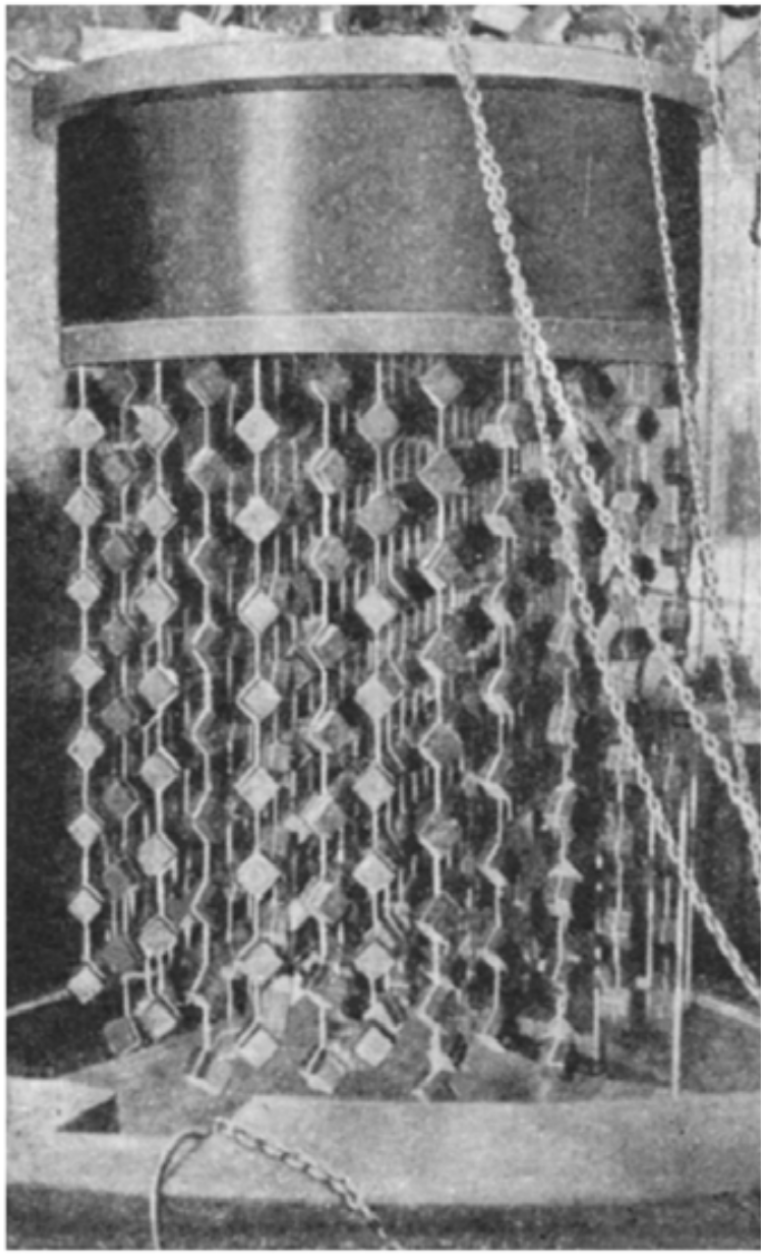
Produced by Degussa AG, Frankfurt using forced laborers

URANVEREIN WAS "AHEAD" OF MANHATTAN UNTIL EARLY 1942

919.6 kg D_2O

Norsk Hydro
Vemork, Norway





B8 Pile (1945)

1.54 tons
natural U
664 cubes

1.51 tons
heavy water

0.85
measured k_{eff}

“

The material available was just insufficient to attain $k = 1$. A relatively small amount of uranium would have probably sufficed.

Nature (1947)

”

Post-war, Heisenberg claimed B8 was almost critical

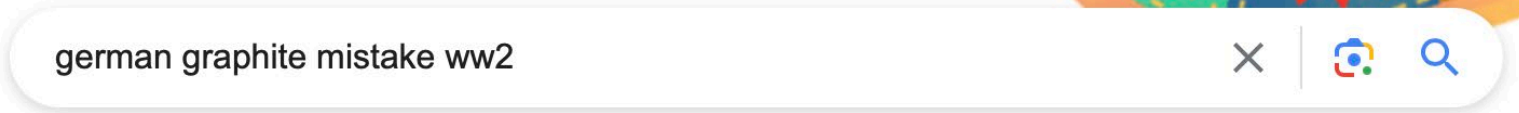
"The fission process with uranium discovered by Hahn and Strassmann may also be used, according to the data obtained so far, to produce energy on a large scale. The safest method of constructing a machine suitable for that

"One can also use natural uranium with another substance that slows down neutrons without absorbing them. Water is not suitable. Heavy water **and very pure carbon** satisfy the requirements."

can, however, also use natural uranium without enrichment of uranium-235,

far, heavy water and very pure carbon satisfy the requirements."

Also discusses uranium enrichment, plutonium breeding, thorium fuel, negative temperature feedback
No xenon, samarium, delayed neutrons
Discusses bomb only wrt power excursion



Graphite (carbon) as an alternative was not considered, because the neutron absorption coefficient value for carbon calculated by Walther Bothe was too high, probably due to the boron in the graphite pieces having high neutron absorption.

Wikipedia
https://en.wikipedia.org › wiki › German_nuclear_prog...

German nuclear program during World War II - Wikipedia

Reddit · r/askscience
300+ comments · 7 months ago

Why was "making heavy water" a mistake? : r/askscience

Graphite (relatively cheap and easy to come by) was tested, but the French and **Germans** both found that **graphite** didn't work in practice…it ...

TheArticle
https://www.thearticle.com › why-did-the-germans-fail-...

Why did the Germans fail to build a nuclear bomb?

Jun 20, 2023 — **German physicists dismissed graphite as the moderator, and vastly overestimated the** critical mass of uranium needed for the explosion. These ...

Wiley Online Library
https://onlinelibrary.wiley.com › abs › andp.202000121

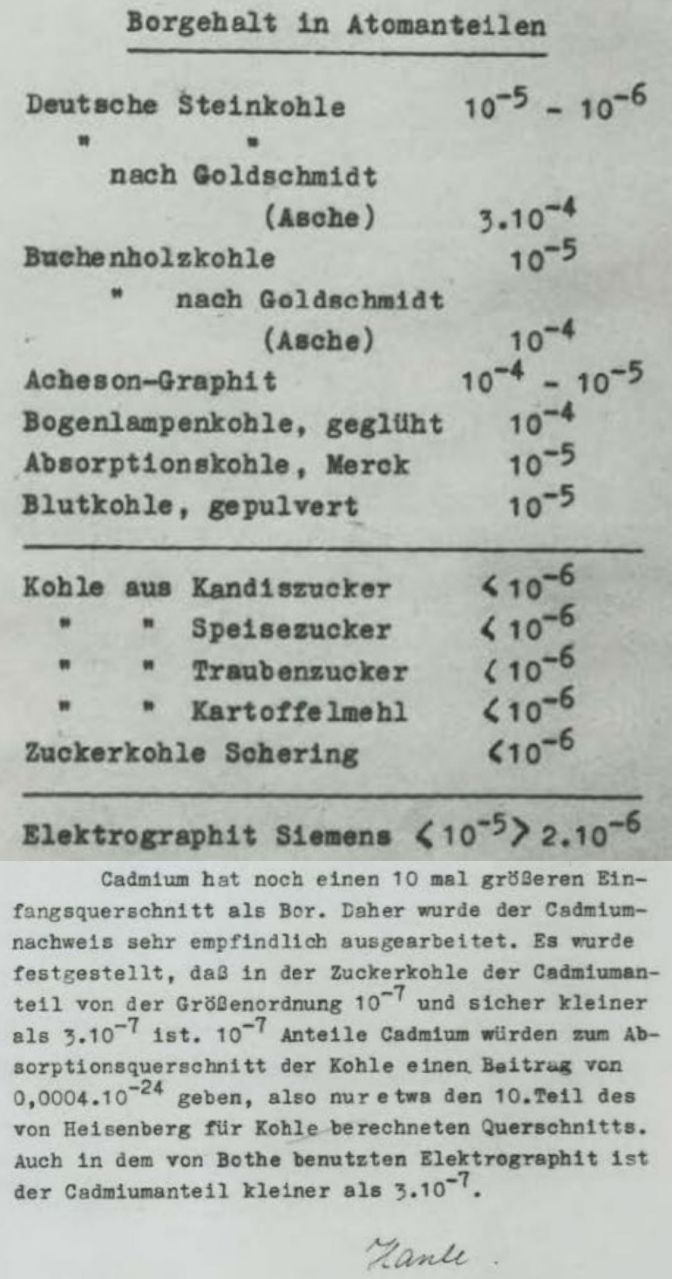
Walther Bothe's Graphite: Physics, Impurities, and Blame in ...

by BC Reed · 2020 · Cited by 3 — This erroneous measurement was crucial as it prompted a decision by German military administrators to abandon **graphite** as a possible moderator ...

'Oppenheimer' and the path of heavy water

The Germans had investigated **graphite** but incorrectly concluded otherwise – that it absorbed too many neutrons – and so they stuck with the ...

In 1941, G. von Droste & Wilhelm Hanle fix Bothe's "mistake" and correctly calculate thermal absorption in reactor graphite



Borgehalt in Atomanteilen

Deutsche Steinkohle	10^{-5} - 10^{-6}
" " nach Goldschmidt (Asche)	3.10^{-4}
Buchenholzkohle	10^{-5}
" nach Goldschmidt (Asche)	10^{-4}
Acheson-Graphit	10^{-4} - 10^{-5}
Bogenlampenkohle, geglüht	10^{-4}
Absorptionskohle, Merck	10^{-5}
Blutkohle, gepulvert	10^{-5}
Kohle aus Kandiszucker	$< 10^{-6}$
" " Speisezucker	$< 10^{-6}$
" " Traubenzucker	$< 10^{-6}$
" " Kartoffelmehl	$< 10^{-6}$
Zuckerkohle Schering	$< 10^{-6}$
Elektrographit Siemens	$< 10^{-5} > 2.10^{-6}$

Cadmium hat noch einen 10 mal größeren Einfangsquerschnitt als Bor. Daher wurde der Cadmiumnachweis sehr empfindlich ausgearbeitet. Es wurde festgestellt, daß in der Zuckerkohle der Cadmiumanteil von der Größenordnung 10^{-7} und sicher kleiner als 3.10^{-7} ist. 10^{-7} Anteile Cadmium würden zum Absorptionsquerschnitt der Kohle einen Beitrag von $0{,}0004.10^{-24}$ geben, also nur etwa den 10.Teil des von Heisenberg für Kohle berechneten Querschnitts. Auch in dem von Bothe benutzten Elektrographit ist der Cadmiumanteil kleiner als 3.10^{-7}.

Hanle

Boron content in atomic parts	
German black coal	$10^{-5} - 10^{-6}$
...according to Goldschmidt (ash)	$3 \cdot 10^{-4}$
Beechwood carbon	10^{-5}
...according to Goldschmidt (ash)	10^{-4}
Acheson graphite	$10^{-4} - 10^{-5}$
Arc lamp carbon, incandescent	10^{-4}
Absorption carbon, Merck	10^{-5}
Blood charcoal, powdered	10^{-5}
Graphite from candy sugar	10^{-6}
...Edible sugar	10^{-6}
...Dextrose	10^{-6}
...Potato flour	10^{-6}
Sugar coal Schering	10^{-6}
Electrographite Siemens	$< 10^{-5} > 2 \cdot 10^{-6}$

Siemens electrographite

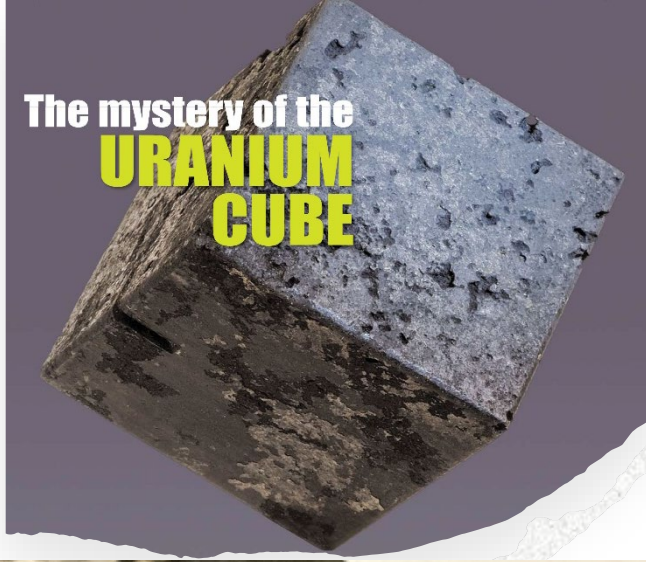
[a]Bothe's "mistake":	7.5±1 mb
[b]Droste & Hanle:	4.2 mb
[c]Lamarsh accepted:	4.8 mb

Von Droste calculated boron σ_{abs} = 545 b
(accepted σ_{abs} = 749 b)
yields boron contribution of **3.8 mb**
in Siemens eletrographite

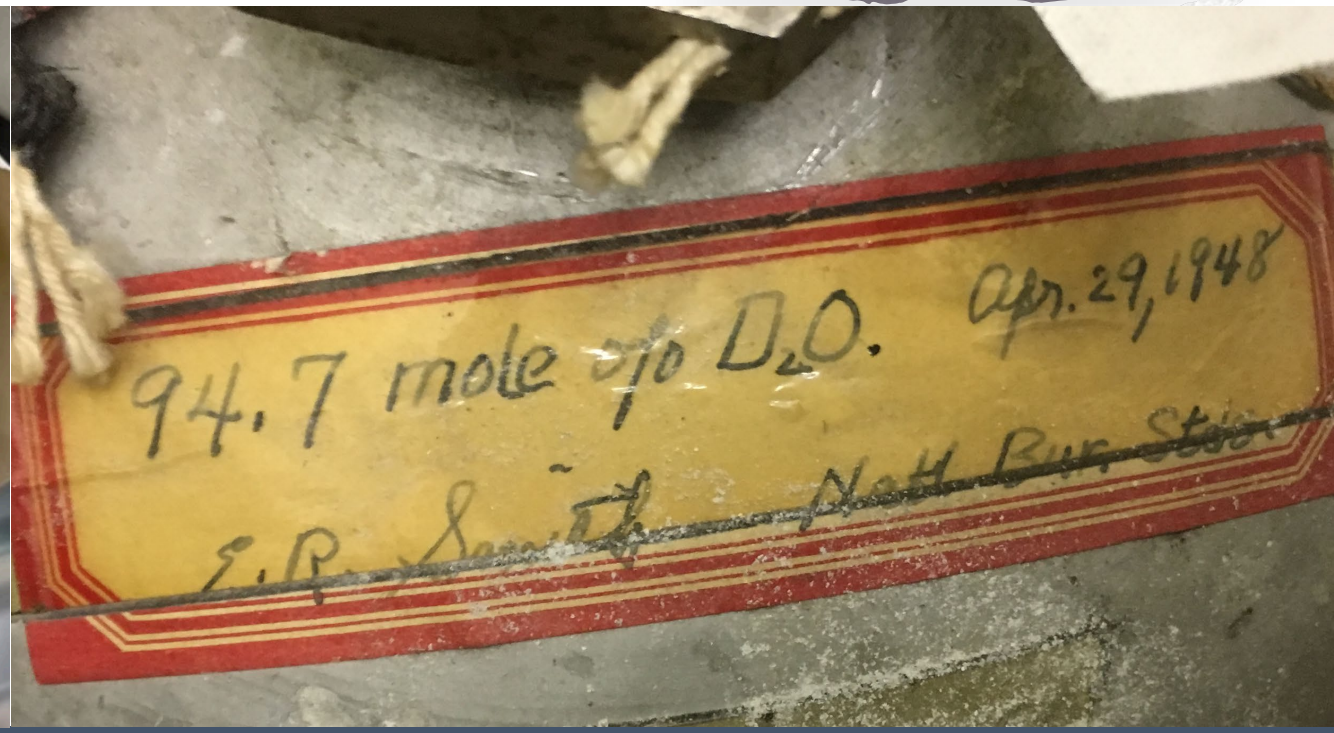
"…in the electrographite used by Bothe, the cadmium fraction is smaller than $3 \cdot 10^{-7}$… A 10^{-7} proportion of cadmium would give the total absorption cross section of the coal a contribution of **$0.0004 \cdot 10^{-24}$**." –Hanle

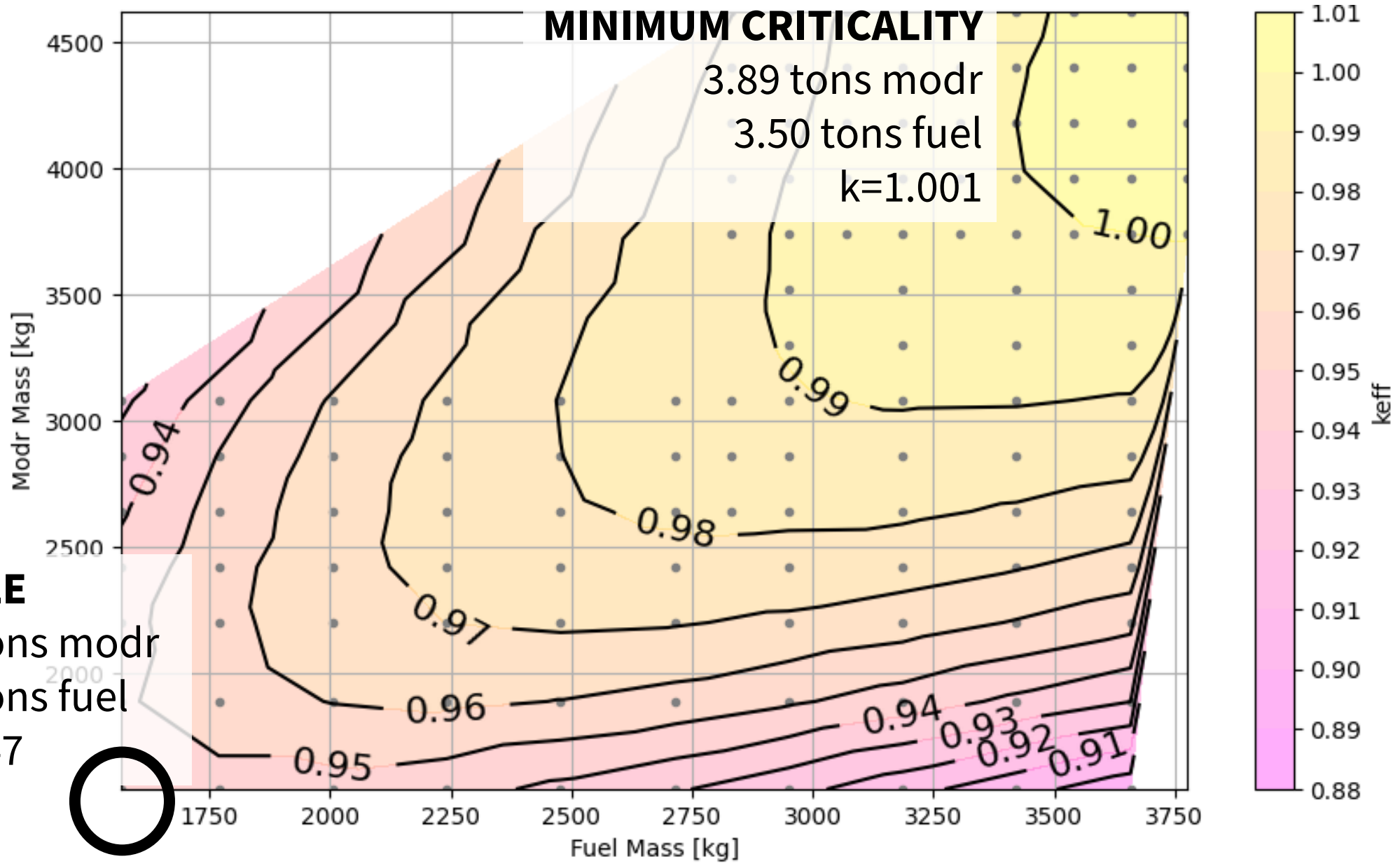
[a] Bothe G-71, Deutsches Museum Item FA-002-544
[b] von Droste G-76, Hanle G-85, G-153
[c] Lamarsh, *Nuclear Reactor Theory,* Tb.I-4

B8 cube density 18.53 g/cm^3, not nominal 19.01 g/cm^3



B8 heavy water analyzed by NIST in 1948




MINIMUM CRITICALITY
3.89 tons modr
3.50 tons fuel
k=1.001
B8 PILE
1.51 tons modr
1.54 tons fuel
k=0.947
Modr Mass [kg]
Fuel Mass [kg]
keff
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.94

There was theoretically enough uranium in Germany, but not enough moderator for criticality.

Bombing & sabotage of the Norsk Hydro plant made the difference in Uranverein's success.

Available	**B8 Pile**	**Minimum Criticality**
1.84 tons modr	1.50 tons modr	3.89 tons modr
5.50 tons fuel	1.54 tons fuel	3.50 tons fuel
	k=0.947	k=1.001

Heisenberg's *Nature* prediction:
"a small amount of uranium" and
increase in moderator "volume by not quite half"

> My opinion is that the cause of [the Germans'] failure is the continental system of education with its sharp distinction between science and engineering. It was no accident that a big machine like the cyclotron was designed in America.
>
> Every American student of my generation was well-familiar with engineering practices, large-size enterprises, and cooperative team work. The American project, from the very start, had the cooperation of industry's engineering skill… and team work among the scientists. Both facts were essential for the rapid growth of the project beyond mere academic capabilities, no matter how great a physicist [one] might have been.

S. A. Goudsmit

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