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26.07.01 #24

Core Physics and Pebble Flow, Examples from THTR Operation

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1. Introduction

To introduce myself: for 7 years I have been working at the THTR plant, starting with the commissioning till the end of operation. I left shortly after the decision to definitely shutdown the plant.

I've been involved in the evaluation of physical properties of the THTR-Core, the comparison of calculated design features and measured effects during the commissioning phase. And in particular I was involved in refuelling the core, which did take more attention that expected.

Since this is a long time ago, I do not have nice drawings, but more or less sketches with hand writing. I appologies for this, but I think the idea is the main point and I take efforts to present it clearly.

There has been no concluside evaluation of the pebble flow within the THTR Core. There have been many experimental evidences on how and why the core moves, but an evaluation taking into account <u>all</u> the effects is missing. In fact the operation time of the THTR was too short to have definit evidence. We only had 423 full power days of load and where far away from the equilibrium core. This is really

a disadvantage, for the pebble flow is the central question of having command over the dynamic core of moving and flowing contents.

So far for the introduction.

There are only 2 items I want to talk about, these are the pebble flow and how to keep it going from the physical point of view and its connection to the resulting gas temperatures. I leave out influence on absorber rod values, not touching bypass effects of core bottom cooling and the rest of core physics.

2. Gas temperatures

Folie 1 reactor vessel and core as model in ~ 300 kg/sec He

Folie 2 flow lines and core rods, to have an impression

22 are control rods, exchanged from time to time to avoid bending because of the pebble flow.

Gas temperatures at the core outlett (mass flow downwards) are measured by NATO in bottom

Folie 3 reflector at symmetric positions.

The aim for the outlet gas temperature is to have a flat profile. This is best for passing into the hot gas duct – with cold bypass from below and above than – where the gas goes through the mixing plate ahead of the steam generator.

It takes some time to really have a "stationary" state (because of Xe and protactinium) with also similar rod positions in R2. But the conditions I used are rather stationary and there were repeated measurements.

A word how to characterize burnup and core in general: we used AVLT/BVLT (abgebrannte Vollastage or burned up full power days, bestrahlte Vollastage or refuelled full powerdays). A full power day is a good measure for the burnup of the core and usually there is a difference between the used power and the necessarily refilled pebbles. Which doesn't matter if the difference is not so large. It has influence on rod bending and in particular on the possibility of fast core rod insertion in emergency shut down. I leave that out.

Folie 4 So you see in the upper sketch at 40% power that the temperature profile is bending with increasing burnup; it gets colder at the side reflector and more hot at the inside.

Later as we reached 100% power, the same feature (lower sketch) showed up.

For each power level the rod positions were similar (they depend on the power level and refuelling), so the change of the temperature profile is a real fact.

3. Refilling and fuel circulation

Folie 5 A short view on the total fuel circulation — in principle and the loading pipes positions on top of the core Folie 6.

The first core was statically filled with only two mixtures, one in IC and one in AC. We used 1:6 refuelling, reactivity requirements asked for the daily fresh number Folie 7

To understand the moving core – bulk material in a silo – we used the channel flow model with rather straight vertical flow lines Folie 8 + 9, the velocity characterized by the amount of horizontal steps defined by the fixed time interval. Folie 9 is obviously faster in the outer region than Folie 8

One can define refuelling parameters α_i using 6 assumptions

1. volume conservation, numbers of discharged pebbles have to be replaced with refuelling ratio
   β = pebbles IC / pebbles AC
2. fuel ratio IC/AC
3. absorber ratio IC/AC
4. splitting age τ^* within the refilled fuel distribution Folie 10
5. more used fuel is only recycled to the IC
6. absorber are recycled to the IC (temperature reasons)

The resulting α_i are rather lengthy expressions. The difficulty is, that there is not always a solution with these 6 assumptions fixed <u>and</u> one has also to distribute into the core what is coming out of the core, without interim storage.

Well, we managed that. It was difficult, but by far not the most difficult task.

As I mentioned, the first core was build with two fuel mixtures. So being through first time with the innermost channel should be seen in the discharged fuel elements and there remaining fuel content.

We had this zero-power reactor to measure the discharged pebbles, where we could distinguish by the pebble signal what it is and how much fuel remained (Folie 11). Being through the first time one could recalculate the "measured" pebble flow which turned out to be much higher than designed.

β refilling ratio	=	0.83	WB1
		0.78	WB2
		0.76	WB3
		0.76	WB4

$\beta_{design} = 0.56$

(Folie 8+9 nodonal)

We then changed the flow model for recalculation of reactivity development from 0.56 to 0.78.

Later on we could verify – in looking at the discharged pebble distributions – that also

WB 5-8 (2nd time arrival of the innermost channel) and WB 9-11 moved with essentially $\beta = 0.78$. In fact this meant that fuel in the outer core is staying there for a very long time getting rather burned up, which in turn shows up a low integral temperature at the core bottom. This was evidently different from the design calculation with $\beta = 0.56$, and not the inserted core rods could be taken as explanation, because than they were only slightly inserted.

Unfortunately the refilling was made – due to decision of the manufacturer of the plant – with $\beta = 0.70$ and fuel ratio higher to IC than at the beginning. Due to calculations this was the direction to the equilibrium core. People were convinced the actual core would alike with the equilibrium core calculations. But the core did not. At least not than.

In fact this worsened the situation with the bottom temperatures because of the following fact: the friction coefficient of graphite in the increases with decreasing temperature (Folie 12), so the rather cold temperature at the side reflector hindered the pebble flow which in turn would increase β further and so on. A self-amplifying process.

The design β rested on many experiments done in models with different skales, 1:6 and 1:2 as far as I remember. But all experiments were done in air and without any temperature or even temperature distribution. So something was missed.

It took us as long as WB 16 (May 88) to convince the people to change the fuel ratio, thus loading more fuel elements to the AC. It had the effect of increasing the outer core temperatures. We finally succeeded to have the effect wanted.

But the decision for decommissioning the plant came soon afterwards (WB 23, AVCT = 423). And then this same very good idea turned out to be a bit of a problem for deloading the core! If nothing is refilled, the core behaves as an egg-clock. The inner core flows out and the upper side of the outer core plunges (strips) into the inner channel and makes a rather reactive assembly there.

But I want to mention another experiment we made for the pebble flow, we added a small amount of fresh absorber at a later time with only minor reactivity effects. With the zero power reactor we could definitely distinguish these fresh absorber being one through from others, which were mixed in the first core. The amount showing up at the bottom was a direct function of the integrated channel area on top of the core where we added the absorber. This was another clear proof for the flow channel model. Unfortunately the test was not finished because of the decision for decommissioning.

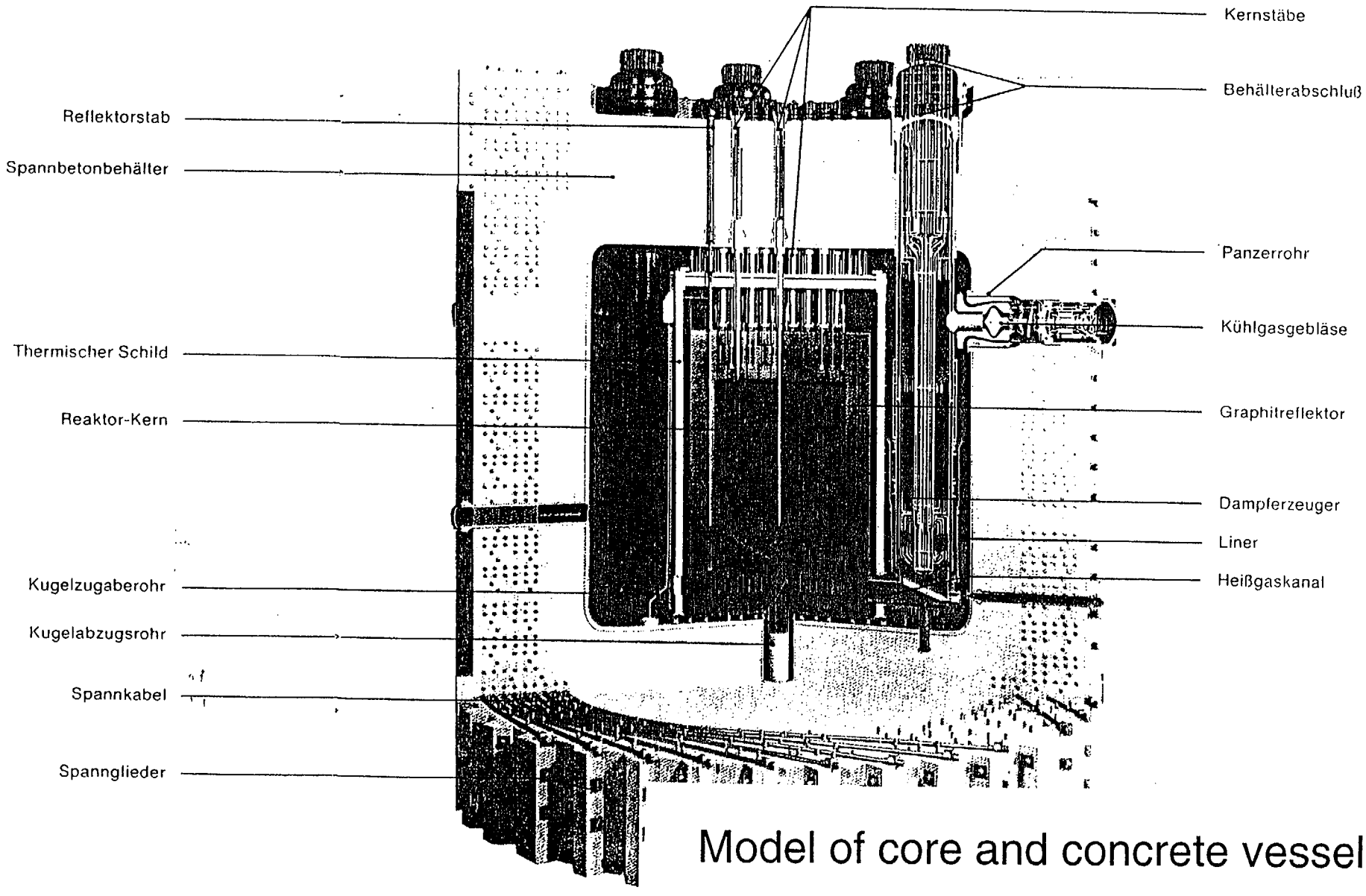
4. Conclusion

So what is the point I want to make?

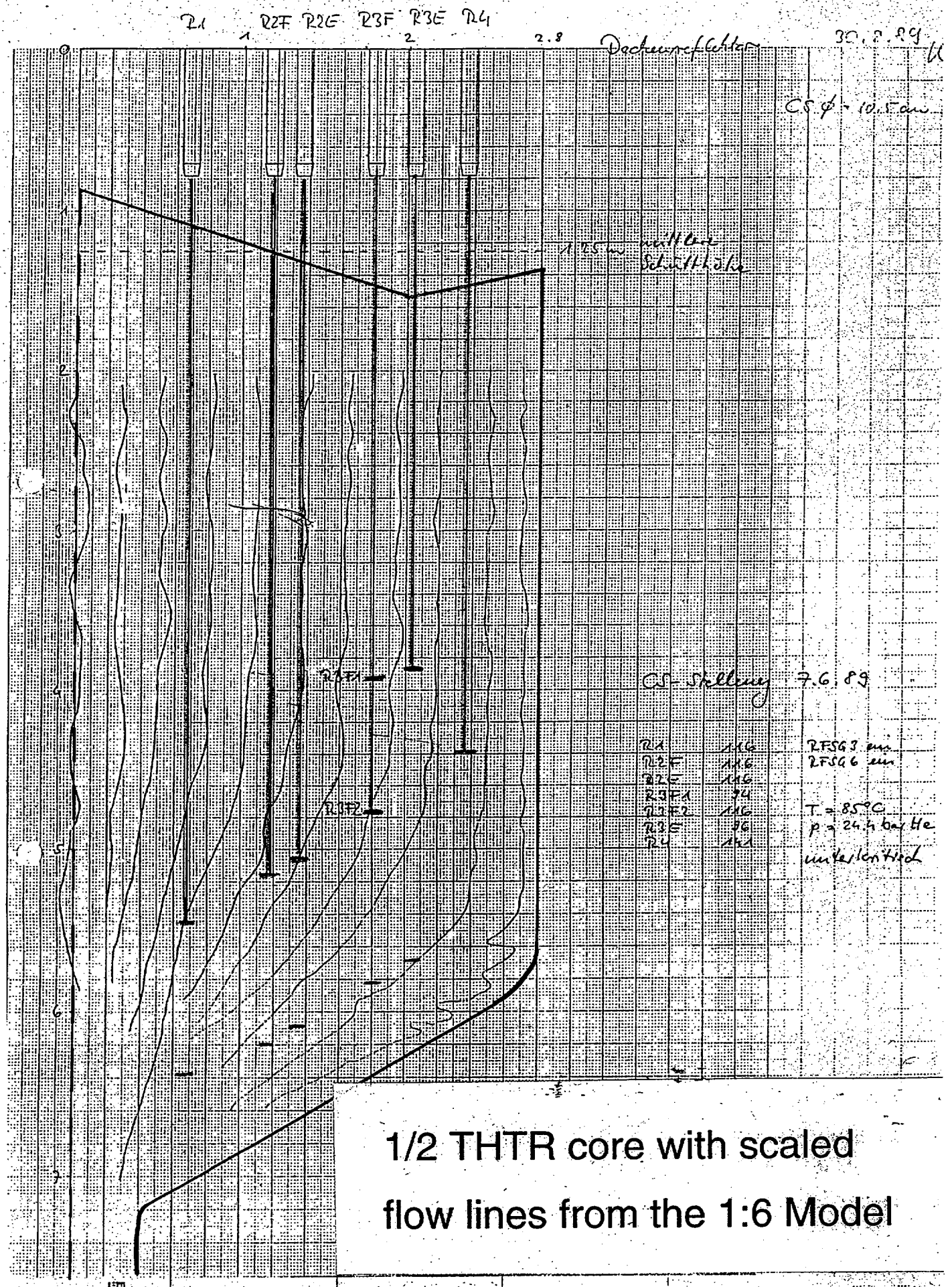
To have a moving assembly like the core of a pebble bed reactor one should have a thorough look at several physical properties from time to time to confirm that you have the core you thought. It is not sufficient to believe in model calculations even if they pretend to have included all the experiments that are available. There may be aspects missing, as we have seen. The verification of the core by means of measurements of the physical properties is absolut essential. It is more essential than in the common water reactor. (But these water reactors have many other difficulties a gas cooled graphit reactor will never have).

Physical properties to be looked at are beside the temperatures in the core bottom, the rod values (total and differential), reactivity (in rod equivalents), rod insertion time in case of core rods and, most important, discharged pebbles distributions including test charges to measure the pebble flow.

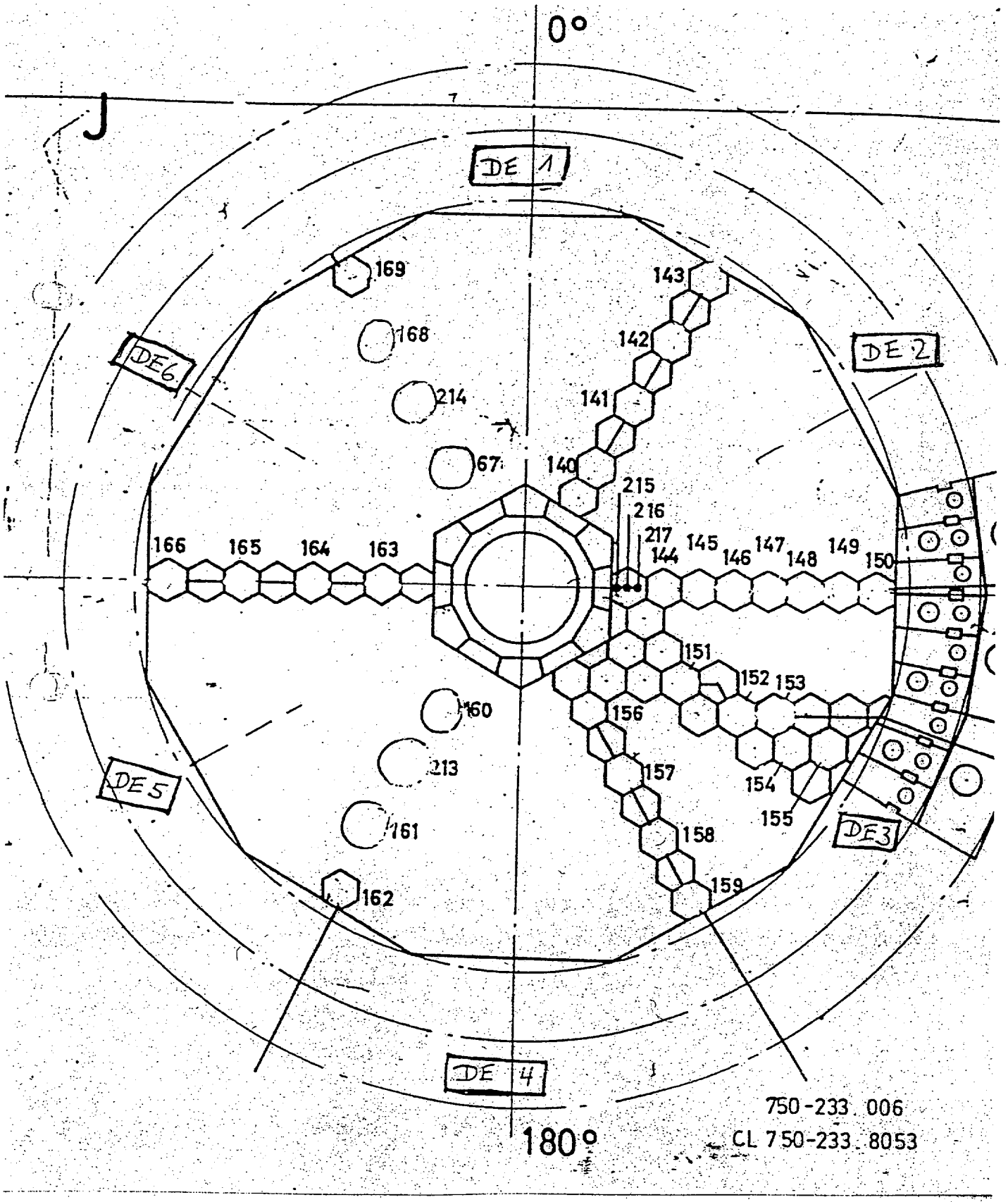
Thank you for listening



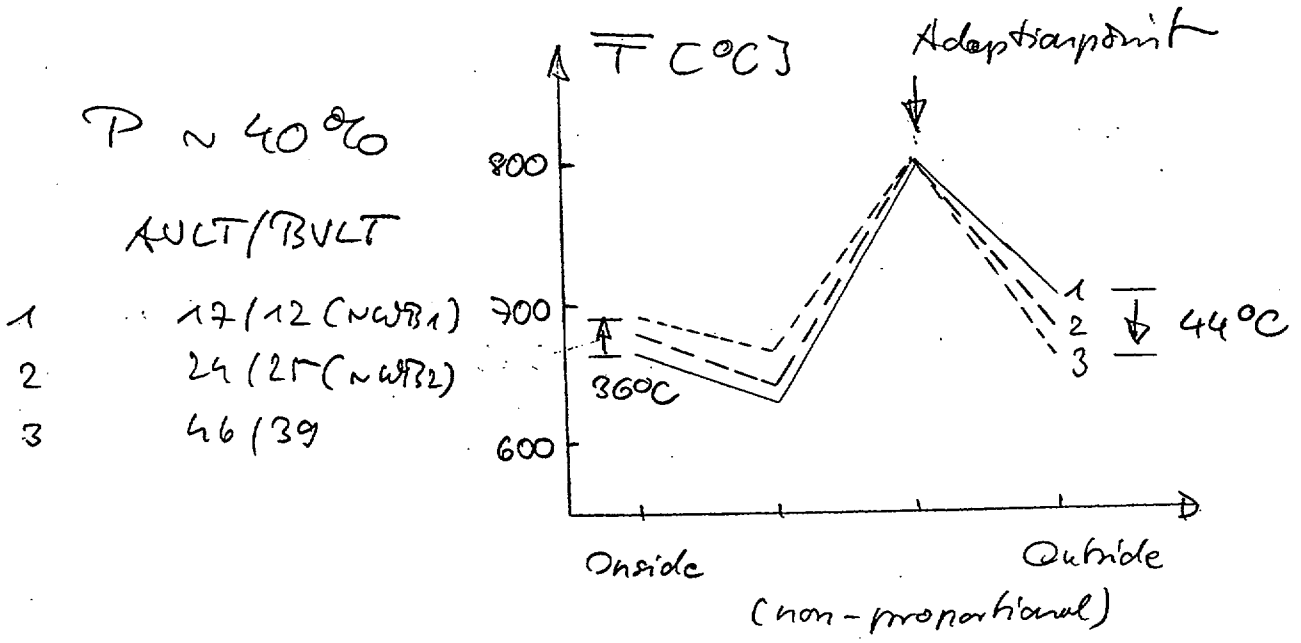
Model of core and concrete vessel

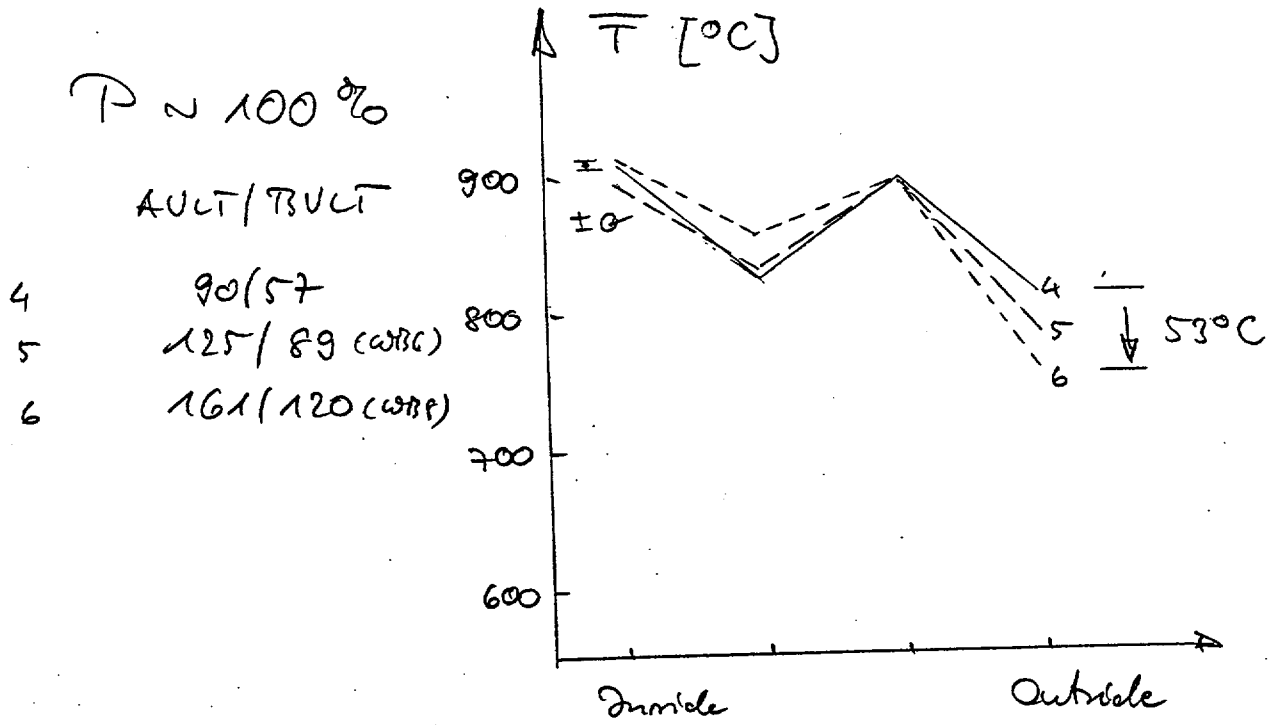


1/2 THTR core with scaled flow lines from the 1:6 Model



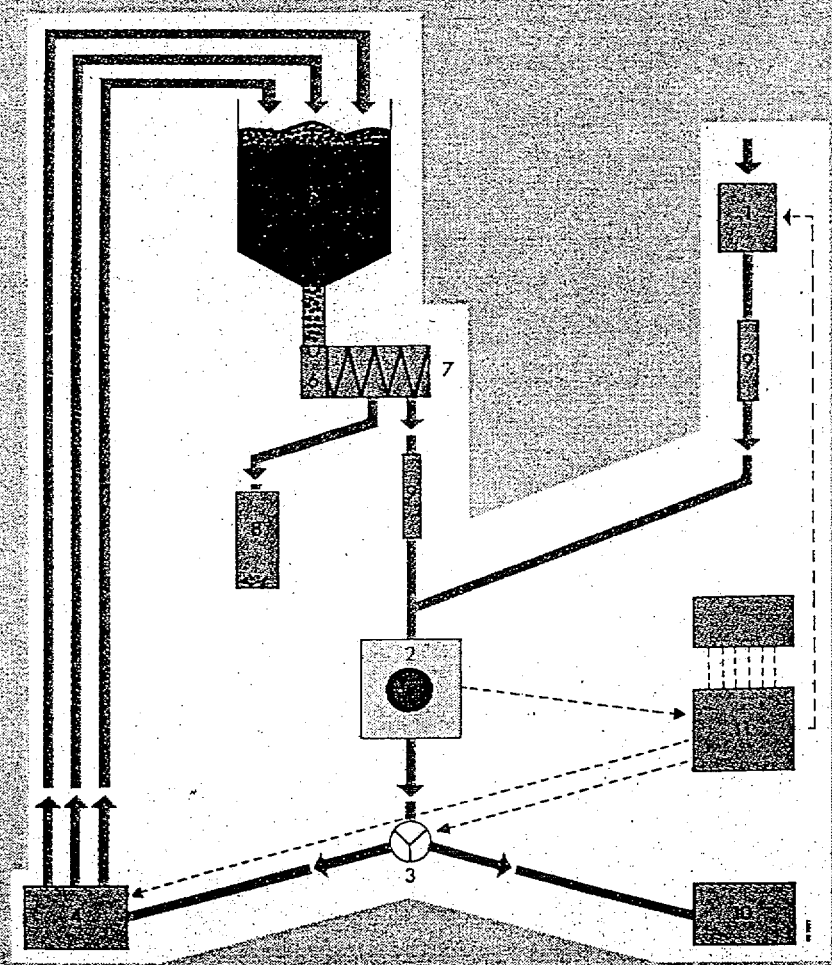
Position of NATE in corebottom reflector





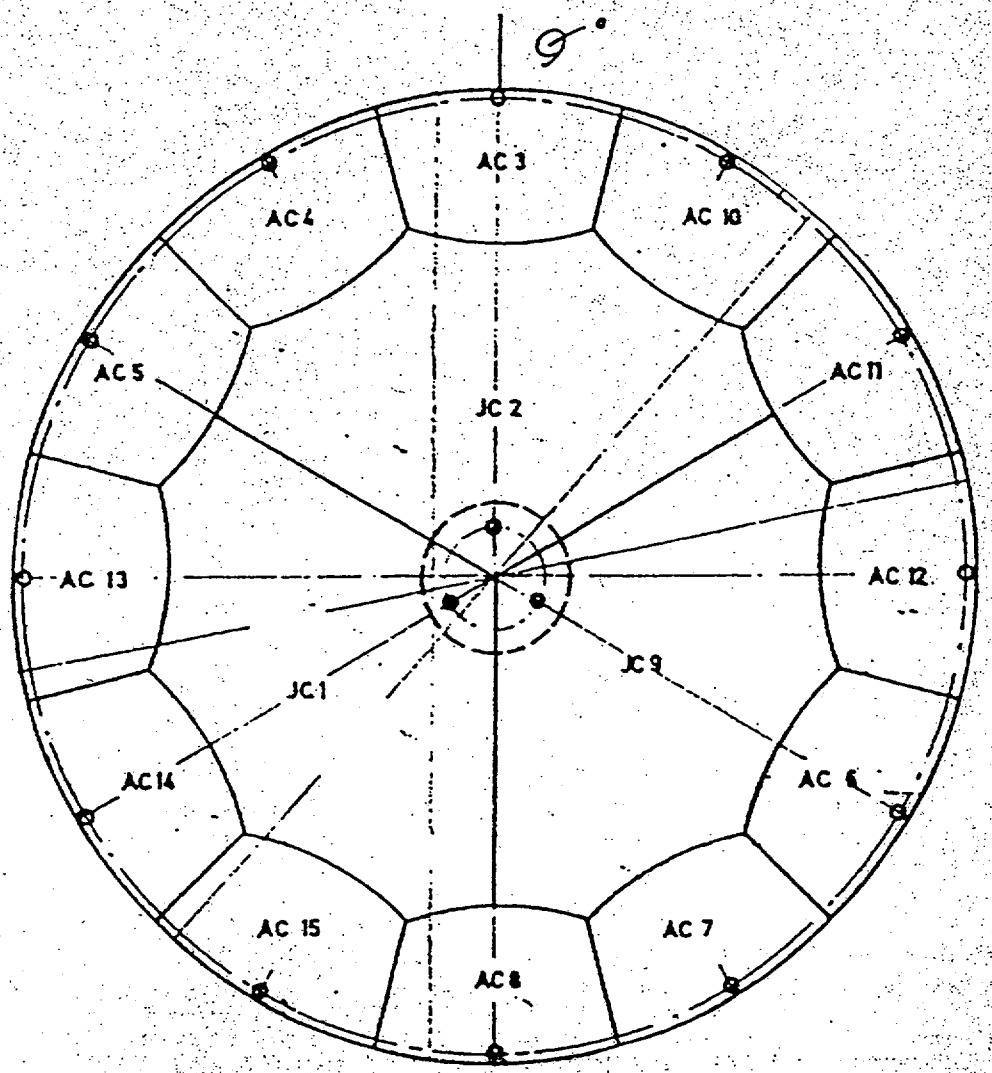
Temperature profile in bottom reflector

at 40 % and 100 % power and increasing burn up

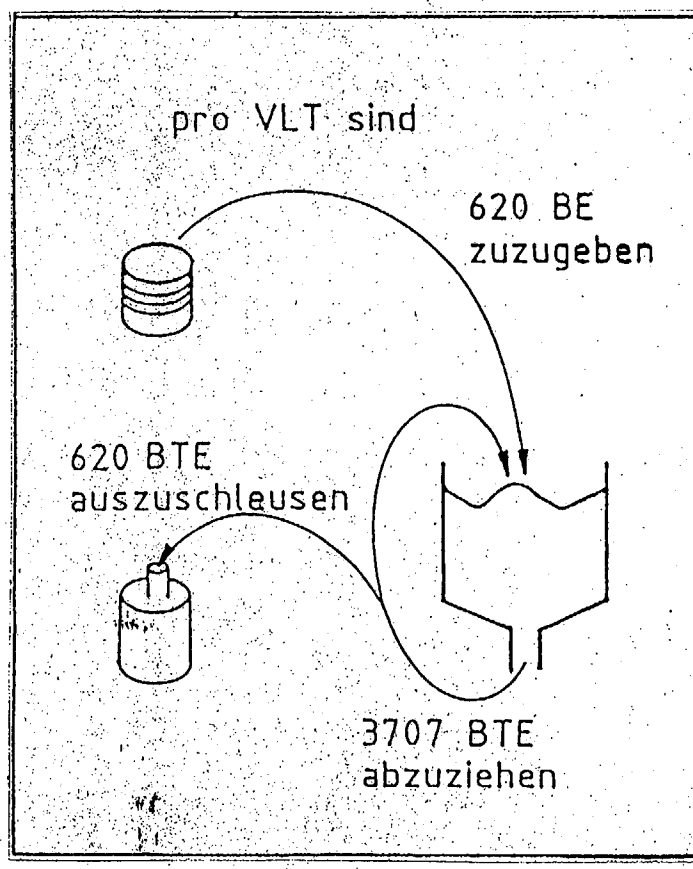


1 Fuel loading facility
2 Distinguishing and burn-up Measurement device
3 Switch
4 Elevation pipes
5 Reactor core
6 Singulizer
7 Damaged spheres separator
8 Damaged spheres container
9 Buffer line
10 Fuel element discharge facility
11 Process computer

Fuel circulation facilities (very simplified)



Position of fuel loading pipes on top of the THTR core



Seit Beginn abbrandabhängiger Beschickung am 26.10.85 wurden insgesamt bisher

zugegeben	248 055	Brennelemente
	5 200	Absorberelemente
abgezogen	1327 493	Betriebselemente
ausgeschleust	250 690	Betriebselemente

Refuelling THTR

BF 3517
Blatt 24

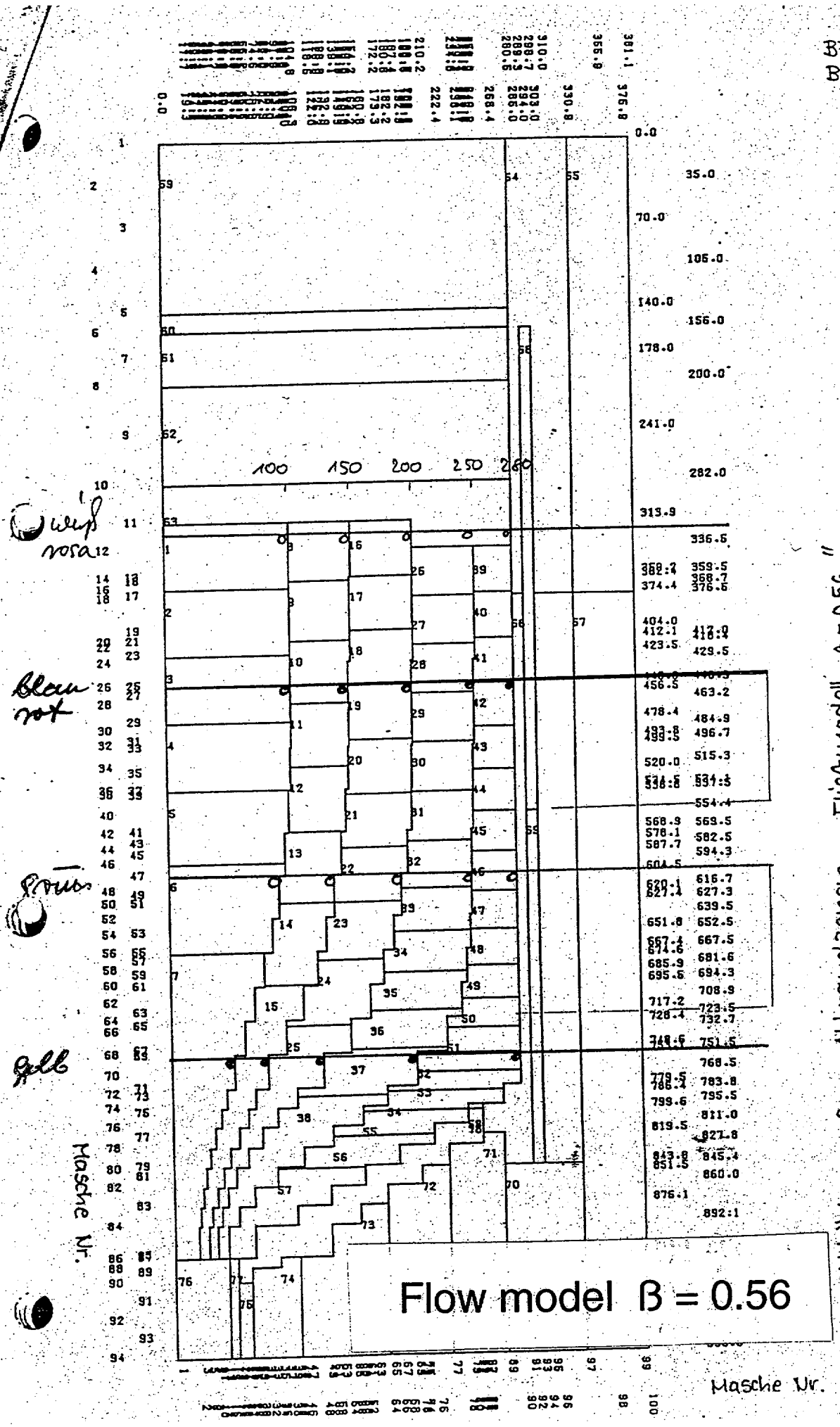


Abbildung 2 Abbrandzonen „Fließmodell β = 0.56"

Schadhafte 7 8 10 13 19, 57

BF 3517
Blatt 23

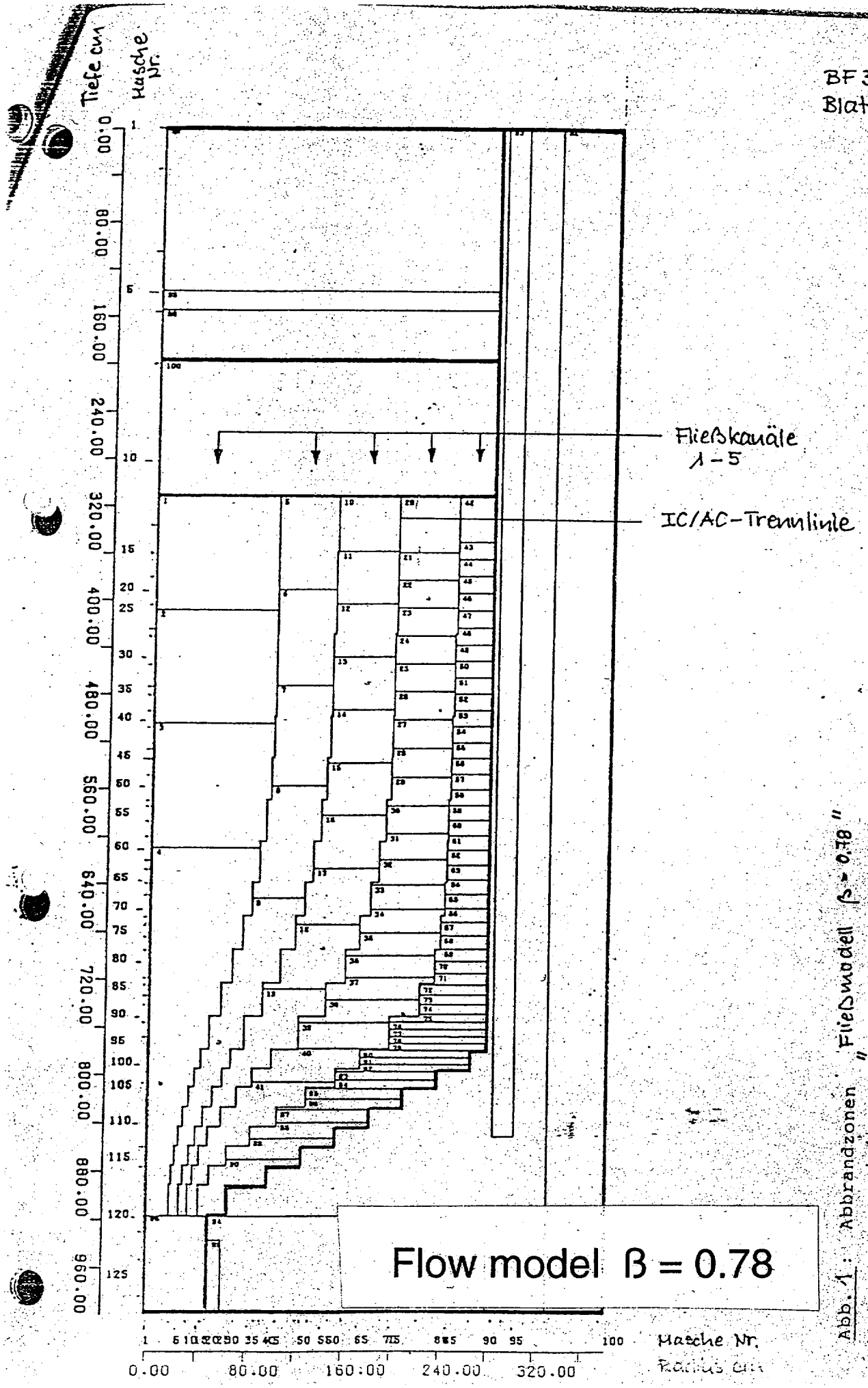
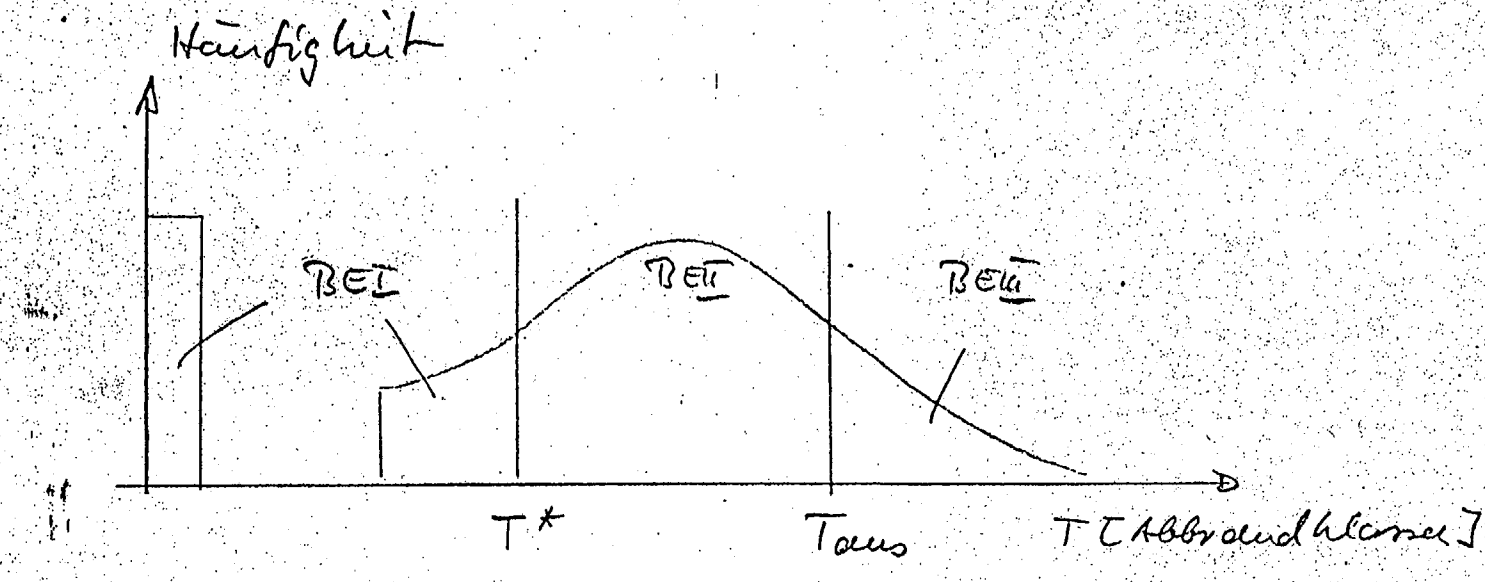


Abb. 1: Abbrandzonen "Fließmodell ß = 0.78"
(Benutzt in Standard-Nachrechnung THTR 03)

Mit fortschreitendem Abbrand ergibt sich die Notwendigkeit, zwischen frischeren und älteren BE zu unterscheiden, das Trennalter T^* wird eingeführt mit BEI jünger als T^* und BEII älter als T^*.

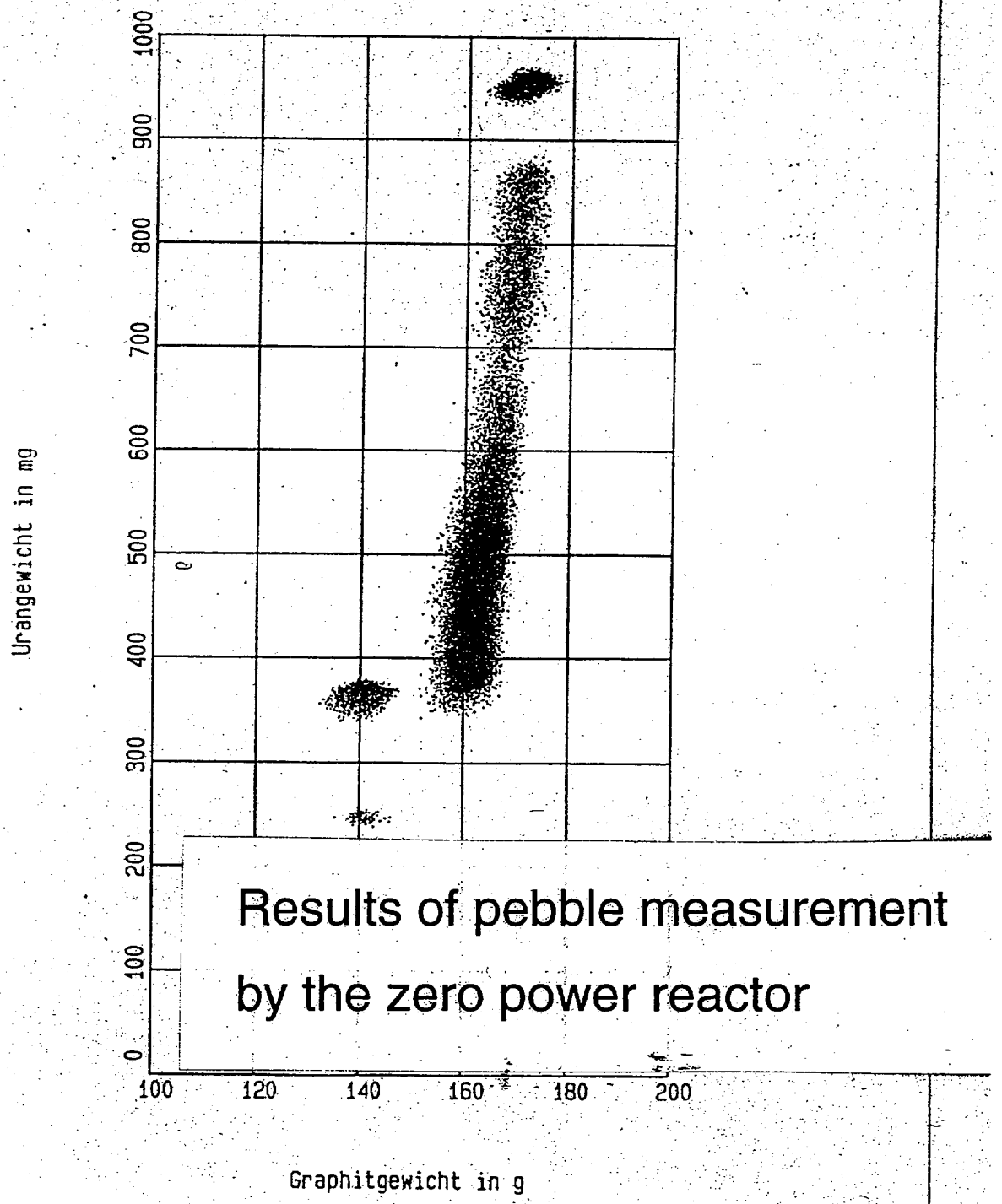


Age distribution for burned fuel

Uran-und Graphitgewichte der abgezogenen bzw. zugegebenen BE und GE

WOLKE 88/36 30.08.88 13.50 UHR NACH UB 240/1

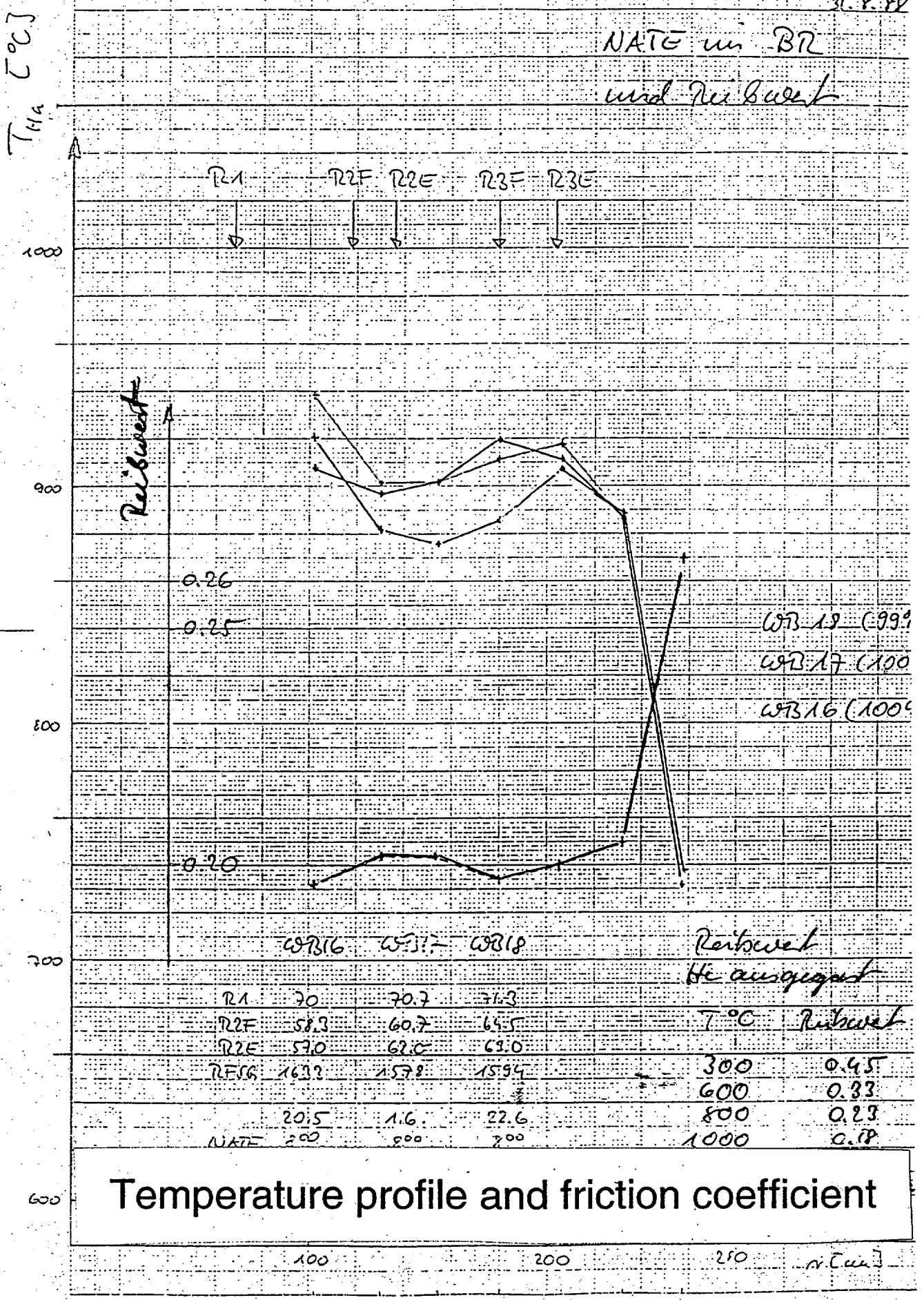
ausgewertet wurde jedes 1te BTE; Anzahl BE : 31284, Anzahl GE : 2838



Results of pebble measurement by the zero power reactor

31. 8. 84

NATE in BR und Reibwert



	WB16	WB17	WB18
R1	70	70.7	71.3
R2F	58.3	60.7	64.5
R2E	57.0	62.0	63.0
R3G	1632	1578	1594
	20.5	1.6	22.6
NATE	200	800	800

Reibwert He ausgegast

T °C	Reibwert
300	0.45
600	0.33
800	0.23
1000	0.18

Temperature profile and friction coefficient