THE FUTURE ROLE OF RESEARCH REACTORS

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1. Introduction

Since the first start of a reactor in 1942 at the University of Chicago (by Fermi and his collaborators) using nuclear fission and the chain reaction the technical design and development of research reactors has made considerable progress. Presently there are about 250 research reactors in the world. Nuclear fission of U235 is still the most effective and economic means to generate high intensities of neutron beams and neutron fields in a continuous way.

A large fraction of the capacity of these neutron sources is used for neutron scattering research and applied nuclear physics, like production of radioisotopes and activation analysis. There are also special problems in nuclear and particle physics which can be best solved with neutrons.

Neutron scattering techniques has developed in an important scientific and technologic tool that provides essential information about the microscopic and mesoscopic properties of condensed matter, living and non-living matter. An ever-growing scientific community (currently of the order of more than 6000 scientists) uses neutrons for research in physics and chemistry and, more recently, in materials science, engineering, earth sciences, biology and medicine .

2. Decline of neutron research capacity

The presently available and active sources of neutrons will not be able to supply the future demand for research. In fact, some time between the years 2010 and 2020 the presently installed capacity of neutron sources for beam research will decrease to a level below one third of that today because of shutting down of older reactors.

The likely decline in research capacity was analyzed in an OECD report in 1998. Fig. 1 lists existing continuous sources for beam research in OECD countries and Fig. 2 planned new sources and major upgrades.

Fig. 3 is an illustration of possible time evolution of the availability of neutron sources. This urges for the planning and construction of new sources at least to compensate for the predicted decline in current capacity.
(black and red are existing continuous and pulsed sources
green and blue are projects of continuous and pulsed sources)

3. Concepts for new research reactors

Technical means to improve and control the nuclear safety of a reactor facility have also made considerable progress. Here the consequent safety design of the temperature behavior of a reactor core, requesting negative temperature coefficients, training of reactor operators, automized and redundant reactor protection systems, minimizing operating failures, will assure a high reliability of modern research reactor facilities.

Finally also the protection of new research reactor facilities against external hazards like airplane crashes, earth quakes and high water floods is now generally accepted and will reduce the small probability of such unlike external incidences even further. The rest risk probability of a research reactor facility may be lowered to about 10^{-8} per year.

In the construction of the reactor building of the new reactor FRM II this protection against external hazards has been realized with a 1,8 m thick reinforced concrete wall of the building and a decoupled reactor block inside.

Considering reactor physics, the optimization of a research reactor may have different aims depending on the intended application priorities.

Certainly an economic aim could be to improve on the flux to power ratio of a research reactor without reducing the important safety requirements. This has been tried e.g. in the planning and design of the FRM II with the so called "compact core" concept, allowing to build a scientific attractive modern research facility with realistic investment requirements and operation costs. The effluence of fission neutrons from the compact core into a surrounding moderator is determined by its power density and the surface area of the core. Surface area and critical size of the core depend on the other side on the U235 - density in the core which can be optimized with highly enriched U235.

Fig. 4: Flux to power ratio Φ/P of FRM-II. Almost a factor of 2 is achievable with present techniques.

With the development of higher density fuel materials than presently available from a scientific point of view the figure of merit Φ/P (flux density/power) can be further optimized.

The compact core concept introduces additional safety features controlling the chain reaction because of the basically undermoderated core, which leads to longer reactor periods (~ 15 ms).

Improving the flux to power ratio may also help to reduce background problems for many applications.

The compact core because of its more compact biological shielding requirements of 8 m diameter for FRM II also allows a better optimization of beam ports and neutron beam cross sections taking full advantage of modern neutron optics techniques with neutron guides and supermirror techniques.

4. Broad range of applications of a research reactor

The available thermal neutron spectrum in a large D_2O moderator can be extended in an efficient way to lower and higher neutron energies by cold and hot neutron sources.

These extended neutron spectra at the FRM II are illustrated in Fig. 5.

Fast neutron spectra can be reconverted from thermal spectra with a fission converter to avoid high γ-background for medical and technical applications.

Such devices like cold and hot sources, neutron filters, optimized beam ports and irradiation facilities should be integrated already in the design and construction of a new research reactor.

For an effective and flexible use of the beam ports of a neutron beam tube reactor (the FRM II has 10 horizontal and 2 inclined beamports)the experimental floor around the source should be spacious and should offer the possibility of extension with neutron guide halls to eventually double the available space for the setup of beam experiments especially with cold neutrons.

Fig. 6: View of the space of a neutron guide hall (FRM II).

The growing interest in the production of neutron induced radioisotopes for medical and many industrial applications requires the optimization of very versatile inpile irradiation facilities.
Tab. 1 lists the 6 vertical irradiation facilities realized at the FRM II

Facility	**Flux**	**Irradiation Time**	**Positions**	**Sample Size**
Fast pneumatic-tube	$4 \cdot 10^{14}$	0.5...2000s	1	1 cm^3
Pneumatic tube	$5 \cdot 10^{12}..10^{14}$	min...hours	2 x 3	12 cm^3
Pneumatic tube	$2 \cdot 10^{13}...2 \cdot 10^{14}$	min...hours	2 x 3	12 cm^3
Hydraulic tube	$4 \cdot 10^{14}$	min...weeks	2 x 5	30 cm^3
Silicon doping	$2 \cdot 10^{13}$	10 min... 1 day	1	4-8 inches
large volume	$2 \cdot 10^{13}$	10 min... 1 day	1	2,5 liters

Some of these irradiation facilities should also be available for the application of the neutron activation analysis technique, one of the most sensitive non-destructive analytic techniques presently known, e.g. for the characterization of highly purified materials, where now sensitivities of up to 10^{-17} g/g can be achieved

For the production of radioisotopes special irradiation reactors may be designed in a more effective way, but certainly high flux research reactors with optimized beam ports and irradiation facilities offer a much broader range and spectrum of possible applications.

5. Complementarity of spallation sources and reactors

Spallation sources: Concerning the predicted decline in currently available neutron source capacity in the next 10 - 20 years especially for neutron beam experiments presently a lively discussion takes place on the planning and construction of several high intensity pulsed spallation sources with up to 2 orders of magnitude higher peak fluxes compared to steady state reactors. These sources, when built, may indeed lead to progress in some fields of neutron scattering and promote also new areas of neutron research. The development of effective methods for the use of the short pulses and optimizing the beam lines of these sources is still a great challenge.

On the other side there are established techniques in neutron scattering which require high average intensities from neutron sources, such as e.g. triple axis spectrometers, single crystal diffractometers and small angle scattering techniques. These applications from present experience can be better served with high flux research reactors with optimized cold source installations. This may also be true for applied work with optimized irradiation facilities for radioisotope production and activation analysis techniques, where growing needs exists.

Because of the high investment and development costs for high flux pulsed spallation neutron sources and their more restricted advantage for desired high pulsed neutron intensities mainly for neutron scattering techniques, high and medium flux research reactors will also in the foreseeable future continue to play an important role in serving national requirements in applications of neutrons in a broader way and also in developing and testing new techniques in neutron science. E.g. intense radioactive beams, intense positron beams, tomography with neutrons, stress and strain analysis with neutrons.

Research reactors at universities will continue to play an important role in the education and training in basic and applied nuclear science and even more general with applications in the field of environmental science.

6. Summary

The decline of neutron source capacity in the next decades urges for the planning and construction of new neutron sources for basic and applied research with neutrons.

Modern safety precautions of research reactors make them competitive with other ways of neutron production using non-chain reactions for many applications.

Research reactors consequently optimized offer a very broad range of possible applications in basic and applied research.

Research reactors at universities also in the future have to play an important role in education and training in basic and applied nuclear science.

Figure 1

Tab. 1 Existing Continuous Sources

Source	Location	Weight factor	First operation	Power [MW]	Thermal flux [1014 n/cm2s]	Special moderators		Operating time [days/y]	Number of users	
						cold	hot		internal	external
Australia										
HIFAR	Lucas Heights	2.2	1958	10	1.4	0	0	300	10	62
Canada										
NRU	Chalk River	2.8	1957	120	3	0	0	300	10	100
Denmark										
DR3	Risø	2.3	1960	10	1.5	1	0	286	20	120
France										
HFR	Grenoble	4.2	1972	58	12	2	1	225	50	1200
Orphée	Saclay	2.8	1980	14	3	2	1	240	60	500
Germany										
BER-2	Berlin	2.5	1973	10	2	1	0	240	70	300
FRJ-2	Juelich	2.5	1962	23	2	1	0	200	50	150
FRG	Geesthacht	1.9	1958	5	0.8	1	0	200	27	68
Hungary										
BNC	Budapest	2.3	1959	10	1.6	1	0	200	20	60
Japan										
JRR-3	Tokai	2.5	1962	20	2	1	0	182	192	387
Korea										
Hanaro	Taejon	2.7	1996	30	2.8	0	0	252	16	not yet open
Netherlands										
HOR	Delft	1.2	1963	2	0.2	0	0	160	25	15
Norway										
JEEP2	Kjeller	1.3	1966	2	0.22	1	0	269	8	7
Russia										
IR8	Moscow	2.3	1957	8	1.5	0	0	100	35	10
IWW-2M	Ekaterinburg	2.0	1966	15	1	0	0	250	50	-
WWR-M	Gatchina	2.2	1960	18	1.4	1	0	200	60	13
Sweden										
R-2	Studsvik	2.0	1960	50	1	0	0	187	10	60
Switzerland										
SINQ	Villigen	2.5	1996	1000 KW Spall. Source	2	1	0	250	30	?
USA										
HFBR	Brookhaven	3.0	1965	30	4	1	0	260	54	223
HFIR	Oak Ridge	4.2	1966	85	12	1	0	210	37	139
NBSR	Washington	2.5	1969	20	2	1	0	250	36	650

Figure 2

Tab. 7 Instruments on Planned Continous Sources and Upgrades

Source	Weight factor	Scatt. Instr.	Fig. of merit	Type of Instruments											
				Diffractometers				SANS + Reflect.		Inelastic Instr.				Polarised Instr.	Others
				Powder	Single crystal	Diffuse	Engi-neering	SANS	Reflect.	TOF	Triple axis	Back-scattering	Spin echo		
Australia															
HIFAR1	2.8	11	30.8	3	2	1		1			2			2	
Canada															
IRF	2.8	8	22.4	1	1	1*	1	1	0.01					1	2
Germany															
FRM II	3.6	17	61.2	1	2	2	1	2	2	2	2	1	2	5*	6
Russia															
PIK	4.2	21	88.2	4	3	1		3	3	2	3	1	1	6*	30
USA															
HFBR upgrade*	3.7	21	77.7	2	3	1	1	3	2	2	5	1	1*	1 + 1*	4
HFIR upgrade I*	4.2	12	50.4	1	1	1	1*	2	1		5			1	2
HFIR upgrade II*		14	58.8	3	2	1	2				6				

*replaces existing instrument portefeull

Figure 3

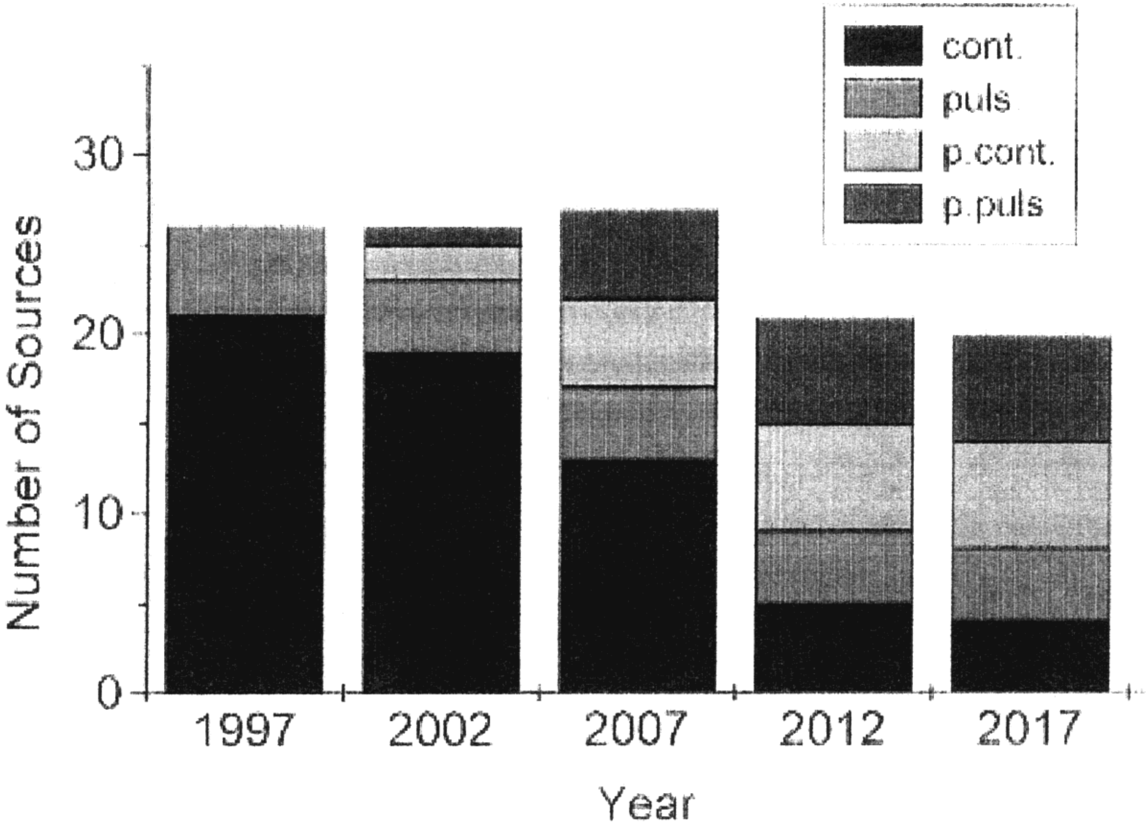

cont.
puls
p.cont.
p.puls
30
20
10
0
Number of Sources
1997
2002
2007
2012
2017
Year

Figure 4

$$\phi \sim \frac{P}{S} \sim \frac{P}{V^{2/3}}; \quad \longrightarrow \quad \underline{\frac{\Phi}{P} \sim V^{-2/3}};$$

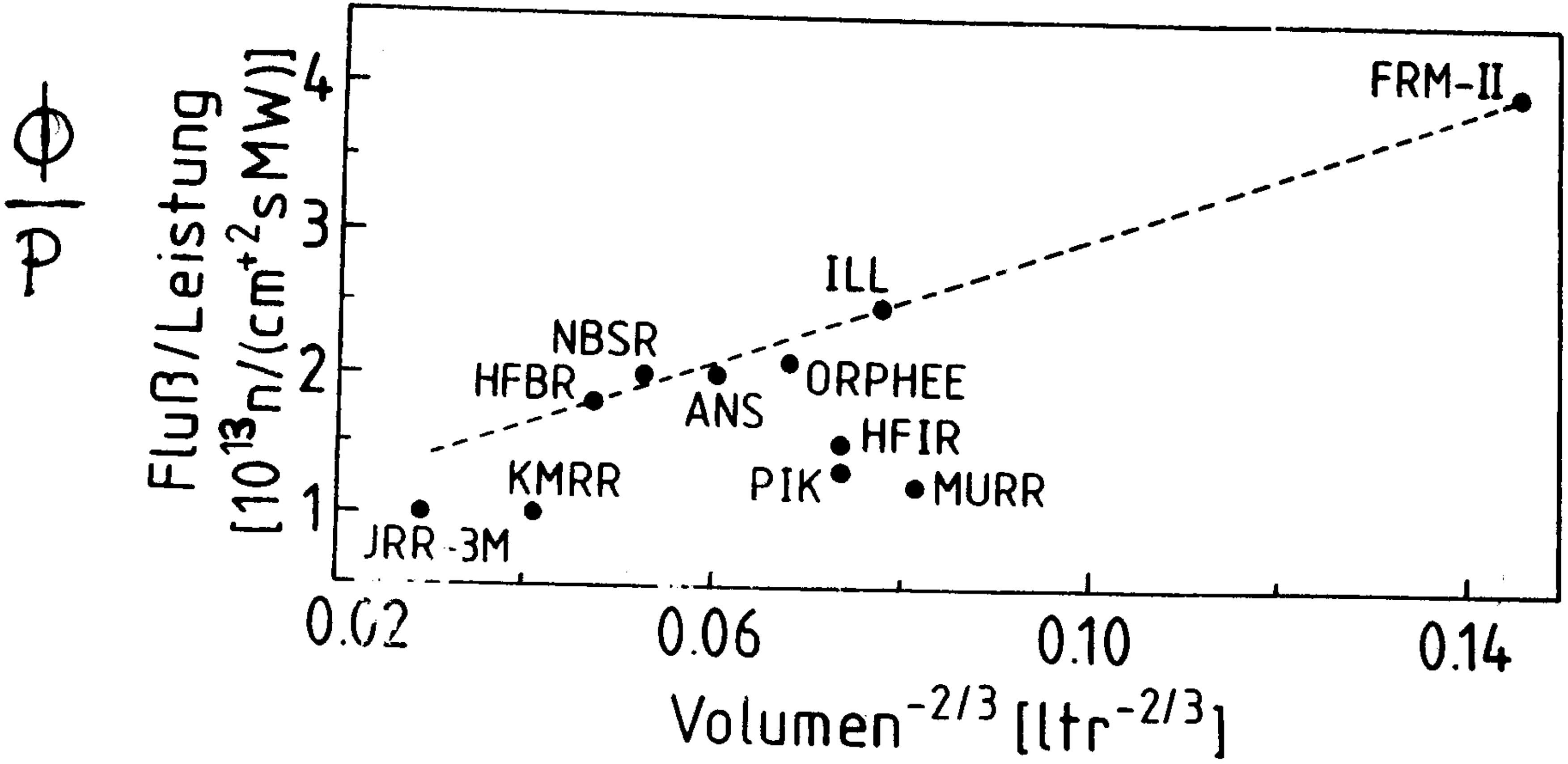
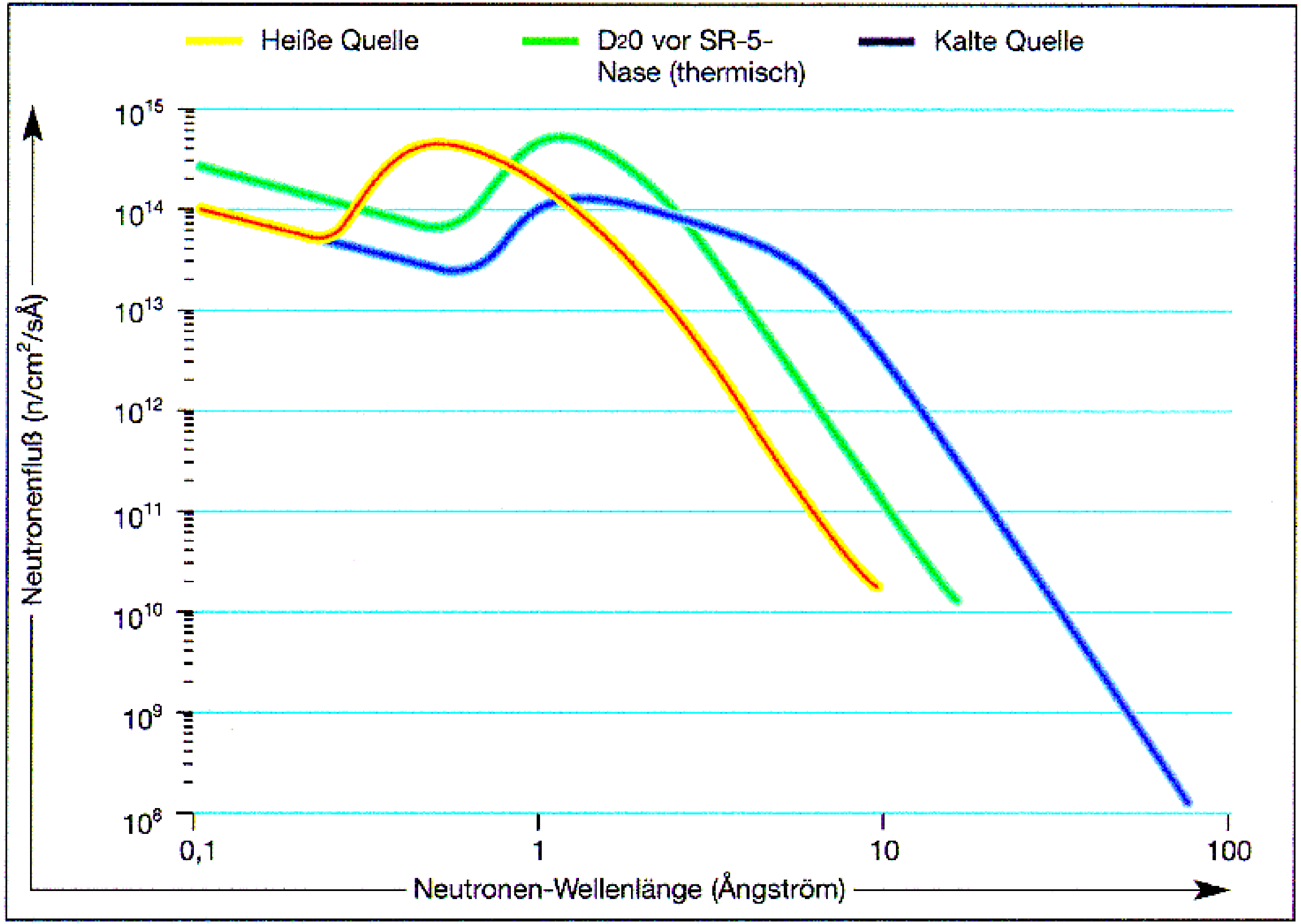


Abb.1: <u>Flußoptimierung verschiedener Neutronenquellen</u> (HFBR: Brookhaven; NBSR: National Institute of Standards and Technology; ANS: Oak Ridge; Orphée: Saclay; ILL: Grenoble).

Figure 5



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ZBE FRM-II-Bau

FRM-II: Nutzbare Neutronenspektren (heiß, thermisch, kalt)

Figure 6

Neutronenquelle FRM-II
Instrumentierung