ICANS IX

INTERNATIONAL COLLABORATION ON ADVANCED NEUTRON SOURCES

22-26 September, 1986

Neutron Sources
– Their Prospects and Their Problems –

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1. How Advanced is Advanced?

When this "International Collaboration on Advanced Neutron Sources" was first agreed upon, today's most powerful research reactors were already in operation and were obviously considered as conventional installations. Today, almost ten years later, our advanced sources are still thriving (although with notable progress) to match in performance those conventional "oldies" and it might well be that the organizers of this meeting had something like this in mind, when they asked me to give some thoughts to the problems and prospects of neutron sources in general.

Neutron scattering is a scientific tool and obviously, the better our tools, the more sophisticated questions will one be able to solve. It is therefore natural that continuing thought is given to the question, how the neutron sources and the instruments that go with them can be improved. This will also remain so with the very powerful sources of light and X-rays which can now be built on electron storage rings although there may be a shift of the border line between the domains of X-ray and neutron scattering. This question will not be given further consideration here. Instead, we will focuss on the more technical questions of the topic. Also, the two types of neutron sources - steady state and pulsed - with their characteristics being different, have their respective scientific justifications and don't need to be weighed against each other. It is therefore the aim of this paper to point out, where we stand today, and what potential for future growth one can see.

2. Continous Sources - A Never Ending Stream?

The impressive development in nuclear research reactors, leading within a span of less then 25 years from the first controlled chain reaction ever to the elaborately designed HFIR in Oak Ridge, did not only happen in a period of general enthusiasme for new technologies, it was also strongly motivated by the military and commercial interest in this new field. If at all, neutron scattering was only a side aspect in the design and use of most research reactors and there are but a few reactors which have been built with neutron scattering as the main motivation.

Although the quality of the beams in therms of fast neutron and gamma ray background is important, the prevailing quality criterion for a continous reactor is its time average thermal flux outside the core where the beam tubes end. It has been sitting at a value of 10^{15} $cm^{-2}s^{-1}$ for more than twenty years now with no ongoing new project in sight that would promise any significant progress.

2.1 Hopes and Horizons

A recent conference at the US National Bureau of Standards, organized to review the issue of an advanced steady-state neutron facility has produced some evidence, that an increase in flux by one order of magnitude might be feasible with present technology, although not without an extensive R+D programme to pre-ceede such an attempt.

Under some simplifying assumptions, it is not difficult to see (Difilippo et. al. 1986), that the flux outside the reactor core is approximately proportional to $P^{1/3} \cdot \rho^{2/3}$, where P is the thermal power and ρ is the power density in the core. This means that, although some geometric optimization is possible (see e. g. Böning et. al. 1985), the essential quantity that determines the useful flux in the moderator is the average power density in the core. This has several consequences

(1) It means that the volume fraction of coolant should be low, requiring high coolant mass flow and/or high outlet temperatures and pressure.

(2) The result is a strongly undermoderated core relying on thermal neutrons from the moderator/reflector to diffuse back into the core region. The resulting thermal flux gradiend across the fuel zone would lead to strong power peaking at the edges, unless variable U-235 content is applied.

(3) At the same time, since the neutrons have to cross a thick uranium layer before being moderated, resonance absorption becomes more likely and k_{eff} is reduced. This can only be compensated by a high uranium enrichment. At least outside the US this conflicts with the general US policy to push for the use of less than 20 % enriched uranium in research reactors.

(4) In cores using the standard fuel plate technology, the heat load on the plate surface increases. This leads to an enhancement of the formation of a thermally insulting oxide layer on the aluminium cladding and, as a consequence, to unacceptably high fuel temperatures.

Especially the last point is a concern for the reactor designers, because the conditions affecting the growth of the oxide layer are not well understood, it seems, however, that the growth rate depends on the heat flux as well as on the exposure time, the surface temperature and the quality of the cooling water (Gambill, 1986).

The various constraints are illustrated in Fig. 1 which shows the relation between power and power density for two flux levels, namely $5 \cdot 10^{15}$ $cm^{-2}s^{-1}$ and 10^{16} $cm^{-2}s^{-1}$. Also indicated is the maximum power density at which a reactor of a certain power can be operated to allow a 15 day core life, if a U_3Si_2-content of 30 % in the fuel matrix is assumed. The hatched area is where the design parameters must lie, if a flux between $5 \cdot 10^{15}$ and 10^{16} $cm^{-2}s^{-1}$ and a minimum of 15 day core life is to be achieved. If the oxide formation cannot be suppressed, $\approx$ 4 MW/l is an upper limit and no flux level higher than $5 \cdot 10^{15}$ $cm^{-2}s^{-1}$ is possible with this technology.

It should be noted, that the high power density during operation results in a substantial decay heat density also after shut down. It can not be expected that such a core could be cooled by convection soon after the reactor was switched off. Since D_2O is used as coolant, this makes core replacement not easy, because the transfer from D_2O to H_2O for core storage requires a certain minimum time for the core to be gas-cooled, unless substantial losses of D_2O at each transfer are accepted.

The core design proposed for a new CNR (Centre of Neutron Research) by the Oak Ridge Group, which is based on these considerations is shown in Fig. 2. Depending on whether or not a method can be found to suppress the oxide formation, it should operate at a power level of 135 or 270 MW, giving a thermal flux of $5 \cdot 10^{15}$ or 10^{16} $cm^{-2}s^{-1}$ respectively.

Some of the design parameters of the CNR-core are listed in Table 1, together with those for another design (UHFR) developed at the Idaho National Engineering Laboratory and shown in Fig. 3.

This concept uses much thinner fuel plates, only 0.89 mm thick with 0.39 mm meat thickness. This results in a heat flux of 13.5 MW/m^2. The plenum between the two halfs of the core allows mixing of the coolant to suppress hot stream lines. The U-235 concentration varies across each fuel plate to avoid excessive heat peaking (see Fig. 4). The thermal flux in the moderator around the central region has been calculated as $1.1 \cdot 10^{16}$ $cm^{-2}s^{-1}$ at a reactor power of 355 MW.

A completely different design (HFPBR),also included in Table 1 and shown in Fig. 5, which was proposed by the Brookhaven Group is quite interesting, although perhaps even more remote: Directly water cooled coated particles arranged in a thin annulus. Although the coated particles are well developed and commercially available, they do not seem to have been used with direct water cooling so far.

Nevertheless, the concept would present some attractive features. Among them are:

(1) No aluminium oxide formation because the coating of the particles is of pyrolytic graphite and the residence time is small.

(2) Large surface to volume ratio due to spheric shape (≈ 750 μm diameter) and small U-content.

(3) Use of uranium oxide or carbide allows high fuel temperature.

(4) High power density of 10 MW/l or more can be achieved.

(5) Fuel loading in the core is small (≈ 2 kg U-235).

(6) Low enriched uranium can be used.

Although this concept has not yet been developed very far, it has a basic potential to break through the limits that hamper present plate fuel technology. However, a large number of problems would have to be solved, among them on line fuel replacement, fission product retention in the particles, particle surface erosion etc.

2.2 Reactor Realities

Considering the amount of research required before such a very high flux reactor can be built, the tedious licensing procedure it would have to undergo and the amount of money required for its construction, there seems to be little hope that the present decade, and probably even the present century (or millenium) will see a steady state neutron source become operational which would constitute such a decisive step forward from what is presently available at the HFR Grenoble.

On the other hand, as can be seen from the data compiled by R. Moon (1985), there are several less ambitious projects on their ways, like e. g. the replacement of the JRR-3 at JAERI (Japan), the MPR-30 in Indonesia, which is presently being commissioned and, most notably, the light water cooled PIK-reactor at Leningrad which is under construction. Although not particularly outstanding in its peak flux to power ratio ($1.3 \cdot 10^{15}$ $cm^{-2}s^{-1}$ at 100 MW) because, like the HFIR in Oak Ridge, PIK is designed to provide a flux trap in its centre, it is quite remarkable with its outer diameter of only five metres (see Fig. 6). This is based on the fact that the shielding around the instruments will add to the overall shielding and reinforcements can be provided where necessary. Some parameters of this reactor are listed in Table 2 in comparison to the HFR at ILL. Also included in this table for easier comparison are two of the advanced desigs of Table 1 and a new proposal for an FRM-II forwarded by the Technical University at Munich (Böning et al, 1985). The latter excells by its high flux-to-power ratio, made possible by the use of high density, highly enriched fuel (as in the advanced concepts described above) and a small core diameter. Development work for this core is funded by the German Ministry for Research and Technology under its nuclear development programme.

Medium flux research reactors, which have mostly been designed as multipurpose reactors and therefore often do not provide adequate conditions for frontier neutron scattering have nevertheless played an important role in the past as far as training of young scientists and development of methods and instruments was concerned. With materials testing on these reactors becoming less important, there is, however, growing concern about the relatively high operating costs of these facilities in relation to their scientific output. In West Germany two such reactors, at Karlsruhe and Jülich, have been shut down permanently for this reason. Plans for upgrading existing facilities are being developed in several places. One basic problem, which may become even more serious, as public concern over the nuclear issue in general increases, is the following: Shutting such a reactor down for a major change will mean that its operating license expires and a new one will have to be obtained under the rather more stringent regulations now in effect. This may prove expansive in some cases and almost impractical in others. At present, it is almost impossible to predict, what exactly would be required for the renewal of an operating license for a modified older reactor.

2.3 If not Reactors, what else?

It started out as a big deal 25 years ago: 10^{16} $cm^{-2}s^{-1}$ was the goal; spallation was the clue! Chalk River's ING project, when proposed in the early 1960's (Bartholomew and Tunnicliffe, 1966, was sufficiently ambitious that it doesn't fail to amaze people even today: a 1 GeV - 65 mA cw-proton linac would produce enough neutrons in a flowing liquid lead-bismuth target that the flux goal could be achieved in a D_2O moderator around the target. The numbers were correct but - pitiful enough - there was no suitable accelerator which could be tapped, nore was there the money available to develop one. The project died after 5 years.

Today, twenty years later, this is where we stand:
$1.5 \cdot 10^{14}$ $cm^{-2}s^{-1}$ is the goal. the method is still spallation, the accelerator is (almost) there and the prospect for getting the money for the target station is good: the SINQ-project. The target station of this spallation neutron source

(Fig. 7) resembles closely a reactor, since it will operate in a continuous fashion and relies on a high time average flux.

The fact, that SINQ will be built is more than just the birth of another medium flux neutron source, it is a major step forward in a new technology and it is the test case for the question, how well spallation sources can be utilized. It is well known that, while being attractive for its low heat release, γ-radiation level and inventory of hazardous fission products, a spallation neutron source tends to produce a high energy component in its neutron spectrum, which is quite difficult to shield. At the very least, a more massive shield than for a reactor is required. In fact, the shield designed for the SINQ has about twice the diameter of that of the PIK-reactor which has a ten times higher thermal flux. Obviously, at the first glance this is a drawback as far as beamhole experiments are concerned. It is not quite so serious on the long run, however: Firstly, the shield thickness would not have to increase in proportion to the flux if more proton current was available, secondly, at a heavily used source a larger circumference allows more instruments to be accommodated and, last but not least, the cold neutrons, which are much in demand at present, can be easily guided away from the source over quite long distances. The effect of high energy contamination in the extracted beam on the quality of the experiments is extremely difficult to predict (Atchison, 1985). It should not be overemphazised, however, since also the scattering power of the monochromator (or sample) for these neutrons will be quite low. Of course, a carefully designed beam path and beam stopper at its end as well as adequate detector shielding will be essential. The question what the future potential of sources of this type really is can only be answered by trying it. SINQ offers the opportunity!

Another medium flux spallation source is under construction at the Moscow Meson Factory in Troitsk (USSR) (see Table 3) which is designed for operation in a quasi continuous mode or as a pulsed source. For this purpose two target locations are incorporated in the shielding (Fig. 8), which can be fed with protons either from the linac directly or via a pulse regrouping ring. There is also a proposal to build a rather more powerful one for fusion materials test purposes (Kley and Bishop, 1985).

3. Pulsed Beams - Salvation by Concentration?

The idea is quite simple and can be told in many different ways. Here is one: From the early days of neutron scattering on reactors, two methods of determining the neutron energy have been known: monochromatisation by Bragg scattering and time-of-flight measurements. Since each neutron can only be detected once (thus terminating its existence as a free neutron), time-of-flight measurements are only possible, if the starting time of the neutron can be defined by other means, e. g. if all neutrons start in a bunch from a known location. Although the choppers, which have to be used to impose this condition on a continuous beam reduce the average beam intensity often by more than 99 %, the technique managed to remain competitive on reactor sources for certain types of investigations, where large spectral width and large data collection angles around the sample could be used simultaneously to make up for the chopper losses. What a thought to have all the neutrons produced in the source concentrated in those time bins which would be transmitted by the chopper (and thus perhaps do away with the chopper altogether)! A closer inspection shows that such a source has a number of other attractive features which can be exploited to collect scientific information, in particular a large fraction of epithermal neutrons, which are generated in pulses suitable for time-of-flight measurements.

3.1 Tricks and Tradeoffs

Unfortunately it turns out that it is not easy to devise a neutron source which delivers a time average flux even of a medium flux reactor in pulses of one or a few microseconds duration and with a suitable repetition rate. The fundamental problem is, that neutrons are not born at the energies the scientists desire but have to be slowed down by about eight orders of magnitude in energy by collisions with the atoms of a moderator. It is not so much that this takes time to happen (of the order of a few to a few tens of microseconds) as it is the fact that, once thermalized, the neutrons take their time to diffuse out of the moderator, which causes trouble. Obviously, this makes the main trick, which is used on cw-sources to obtain a high flux of thermal neutrons, namely a large moderator in which neutrons have a long lifetime, impossible. On the contrary, even small moderators have to be decoupled from the reflector and internally poisoned to obtain pulses of the desired shortness. With respect to an assembly designed for optimum time average thermal neutron output this may result in a loss in time average flux up to a factor of 20 (see Fig. 9). Also the peak flux is reduced, although only of the order of some 20 to 30 percent (Bauer et al, 1981). This is the main tradeoff one has to pay. Others result from the cyclic thermal load on the neutron producing zone and from the extra effort and cost to produce short bursts of fast neutrons in the first place. Pulsed reactors and proton beam driven spallation sources are the main options and we will limit our discussion to these. A nice feature common to all pulsed sources (at least to a certain extent) is the fact, that the fast neutrons and γ-radiation flash have disappeared from the beam when the signal neutrons arrive at the detectors. Although this doesn't affect the need for appropriate bulk shielding, it helps to keep the experimental conditions clean.

3.2 The Reactivity Roulette

Pulsing a reactor means to change its reactivity periodically from a value of k_{eff} well below one to slightly above one, to build up a high neutron population for short times. This can be done by moving part of the core or part of the reflector. While the first method may be more efficient, only the second one is possible at higher power levels because of cooling problems. The Mekka of pulsed reactor technology undoubtedly is the Joint Institute of Nuclear Research in Dubna, where the first pulsed reactor for beamhole research became critical in 1960 and the world's most powerful one, the IBR II, is presently being commissioned, operating at 2 MW, which is 50 % of its design power.

Figs. 10 and 11 show a cutaway view and a horizontal section of the core and reflector arrangement. While the reflector is stationary on five sides of the hexagonal core, two moving reflector arms are arranged on the sixth side. The three-forked auxiliary reflector rotates at 5 Hz while the solid main reflector rotates in opposite direction at 25 Hz. Each time both reflectors meet in front of the core, the main pulse is produced, while satellite pulses which are about 0.03 % in height of the main pulse are produced when the auxiliary reflector alone passes in front of the core (Fig. 12). The background level from delayed neutrons between the pulses is quite low, 0.006 % of the peak height, which is due to the low reactivity with the reflectors removed.

Obviously, in order to obtain short pulses, the core has to be prompt supercritical during the pulse. The core is made up of PuO_2 fuel, arranged in hexagonal packs of fuel rods. The cooling medium is Na to avoid thermalization inside the core and to allow high fuel temperatures. Table 3 gives some data of the IBR II in comparison with other high performance neutron sources (see also below). The pulse duration is about 150 μs for the primary pulse as well as for the thermal neutrons emerging from the moderators. This makes it necessary to use choppers for many experiments. These choppers can be accommodated in an annular space within the main reactor shield. As a rule, their rotation axes have to be parallel to the beam lines.

IBR II had been under construction for about 15 years with many problems to be solved before it started operating in 1982.

With its complicated technology and its restrictions with respect to pulse length and spectral tailoring it is likely that it also marks the end of a development line although the engineering that went into it deserves utmost admiration.

3.3 The Pulsed Proton Poker

While older than reactors, in principle, accelerator based pulsed neutron sources are only gradually making their way into routine application to thermal and cold neutron scattering. The one type which really has a prospect for growth and development are neutron sources using the proton-induced spallation reaction. These sources depend on the availability of proton accelerators in an energy regime of about 1 GeV to make the targets radiate with neutrons. Such machines have been built in the past as boosters for high energy accelerators and as drivers for meson factories. Parasitic use for neutron sources was gracefully granted. KENS, WNR and IPNS were all born in this craddle, although, with IPNS leading the way, they are gradually maturing into neutron scattering facilities of their own right: The old AGS Booster synchrotron has been upgraded and is operating for the sole purpose of keeping IPNS ablaze, WNR has been supplied with a proton storage ring recently and KENS was an important factor in the planning of future medium energy accelerators at KEK right from the beginning.

The only member in this family of accelerators which, although thriving on existing buildings and equipment, was designed as a neutron source driver from the very beginning is the 50 Hz ISIS Synchrotron at the Rutherford Appleton Laboratory, which is presently working its way up to its design specifications. These specifications reached, the facility will be competitive and, due to a suitably designed set of instruments in some cases even significantly superior to the HFR at the ILL Grenoble. This is true in all cases, where the pulse structure can be exploited beneficially to collect the desired information and it is especially true for energies in the slowing down regime where the spectral fraction at the ILL is low and where the pulses on ISIS are short and time-of-flight is the only viable technique for energy determination.

On the other hand, the need for keeping the pulses short for good time resolution results in a disapointingly low time average flux and makes some well established and important techniques such as triple axis spectroscopy impossible. This is one of the tradeoffs that have to be accepted on pulsed sources.

Another problem with accelerators is their technical complexity, which unfortunately leads to more or less frequent failures. This is not only a nuisance to the neutron users, it also has the effect of thermally quenching the target, thus reducing its life time. This is the more serious, the higher the power on the target and hence its operating temperature is. The temperature in a spallation source target will always be a problem because, in order to produce a "bright" source of fast neutrons, the metal density in the target should be high and hence cooling channels are undesirable (but can, of course, hardly be avoided). Also, the very inhomogeneous heat distribution inside the target resulting from the intensity profile of the beam and its exponential decrease along the target axis poses problems: The coolant flow has to be able to handle the power density at the hot spot and thermal stresses within the individual target plates may become considerable.

Part of these stresses are cyclic and follow the pulse repetition rate of the protons. Here comes one of the main problems with these targets: The temperature rise in each pulse is determined by the power density in the target plate and because of the shortness of the pulse and the need to keep the beam size within the order of a few centimeters, the heat load becomes considerable as one tries to go up in beam power. Also, there is no way to reduce the power density within the materials.

While it is just to say that today's spallation sources are not yet probing the limits of target technology, not even at ISIS when its full design current will be reached, the rapid cycling ISIS synchrotron will be more or less at the limits of what one can do with this technique.

Trying, as we did with the reactors, to take a look at the future development protential of spallation sources in general, there doesn't seem to be such a clear cut limit, but, of course, much less experience is available, too. In the accelerator field, two routes seem to be feasible to achieve more intense but still short pulses: The FFAG's on the one hand and linacs with pulse compressors on the other. The first route has been proposed for Argonn's next generation neutron source, the ASPUN, aiming at a time average current of 3 800 µA at 1 500 MeV (as compared to 200 µA at 800 MeV for ISIS). At this level, a number of problems have to be dealt with also on the target side and certainly engineering constraints will prevent the flux from the moderators to increase in proportion to the target source strength.

The combination of a linac with a compressor ring is being pioneered at LAMPF/LANCE and the Moscow Meson Factory has similar plans. The idea here is, to inject into the ring at full energy and at a phase space density which is much higher than at the low injection energy into a synchrotron. The long pulses of a linac can be injected over many turns and extracted during one single revolution of the protons. The current amplification is then approximately given by the ratio of the linac pulse length to the revolution time in the ring. In the German IKOR study (Schaffer ed., 1981) this factor was to be about 650, starting with a 100 mA in the linac and delivering a time average current of 4.5 mA at 1 100 MeV.

Pulsed sources at this sort of intensity level would certainly not only be a tremendous engineering challenge in accelerator as well as target technology, they

3.4 The Enchantment of Enrichment

In the absence of the high current accelerating systems mentioned above, one is of course tempted to enhance the neutron production in the target by going back to good old fission as long as the heat removal system can cope with the power deposition. This route is being taken by IPNS (see e. g. Schulke, 1985) and similar considerations are under ways at ISIS . The basic concept is, to produce a more or less flat heat distribution over the whole target volume by increasing the content in fissile material in those regions, where the power density would otherwise be low. The options considered for ISIS are reported in a different paper in this meeting (Bauer, 1986). Although the work is still in an early stage, it is clear, that a decoupler has to be used around the target to avoid thermal fission and the resulting pulse degradation. This means, that a relatively large quantity of material is required to reach the desired enhancement factor of 10 or more in the leakage from the moderator. With a beam current of 40 μA time average, and at an overall thermal power of 1.75 to 2 MW in the booster, the amplification of source neutrons relative to a target of depleted uranium would be about a factor of 20, while the power is increased by a factor of 30. Not allowing for any engineering constraints, the thermal flux from a slab moderator would be increased by about a factor of 12 to 15, but since a wider target had to be assumed to achieve the necessary k_{eff}, the coupling into a wing moderator will be poorer than in the present ISIS arrangement and the goal of a factor 10 in enhancement will rather be an optimistic estimate.

It is worth noting, that at this power level the ISIS-target will be in the same regime as the IBR II pulsed reactor although, of course with less sophisticated technology. However, in contrast to a pulsed reactor, a booster target will in general not be reactivity modulated. As a consequence, delayed neutron background will constitute much more of a problem; the worse, the higher the multiplication (k_{eff}) is. It may well become necessary to devise quite sophisticated equipment (such as choppers close to the target) to control this problem.

In general it is probably fair to say, that a booster is a viable solution if the time average proton current is of the order of a few tens of microamperes but will probably not be an option if a current in the milliampere regime is available.

3.5 Abandoning Abortion

It is a pity to see that, in a pulsed source, 80 % of all neutrons which could leak from a suitably optimized moderator are killed in order to keep the pulses short (Fig. 9). This is even more a problem with a booster assembly, which has to suppress thermal fission to keep the pulses reasonably short. For a well coupled moderator designed for maximum neutron leakage the pulse duration is of the order of 100 μs even for very short proton pulses and increases as the duration of the source pulse reaches the same order of magnitude. If a proton current of the order of 1 mA time average can be devised, such a moderator could yield a time average flux of the order of $2 \div 3 \cdot 10^{14}$ $cm^{-2}s^{-1}$, thus lying well inside the regime of medium flux reactors, but with the added advantage of having the neutrons concentrated in bursts. Such a source has been termed "intensity modulated" in contrast to the pulsed sources discussed above. During the study work for the German SNQ project, substantial effort has been devoted to the question, how such a time structure could be optimally exploited (see e. g. Scherm and Alefeld, 1985). The net result of a very careful evaluation is that, relative to a cw-source of equal time average flux, there is not a single technique which could not benefit in one way or the other from such a time structure. While in some cases only nominal gains (as defined as the time required to obtain a certain information) of the order of 2 would be expected, the average was found to be at least an order of magnitude, with some special cases being able to profit from the full peak-to-average flux ratio, which was 35 in this case, but could be higher for shorter proton pulses.

No such source exists or is planned at present, but with the limitations that can be seen for cw-reactors on the one hand and for pulsed sources on the other, this intermediate route might constitute another way to improve conditions for neutron scattering in the more distant future. It would help, if an interest in high intensity accelerators builds up also for other reasons.

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	CNR		UHFR	HEPBR
Reactor concept	Baseline	Enhanced	("double donut")	("particle bed")
Peak thermal flux (cm^{-2}s^{-1})	$5\cdot10^{15}$	$1\cdot10^{16}$	$1.1\cdot10^{16}$	$6\cdot10^{15}$ ($1.2\cdot10^{16}$)
Thermal power (MW)	135	270	355 → 300	163 (350)
Fuel enrichment (% U-235)	93	93	93	20
Type of fuel	U_3Si_2	U_3Si_2	U_3Si_2	UO_2
Core volume (l)	35	35	50	27.6 (35.3)
Core fissile loading (kg)	18	18	26.5	≈ 2
Plate thickness (mm)	1.27[*1]	1.27[*1]	0.89[*1]	≈ 0.75[*4]
Coolant channels (mm)	1.27	1.27	0.76	---
Peak heat flux (MW/m^2)	9.77	19.55	13.5	
Coolant velocity (m/s)	27.4	27.4	16	
Coolant flow (l/s)				400 (580)
Coolant pressure[*2] (bar)	55.7	55.7	41	80 (100)
Pressure drop[*3] (bar)	13.7	13.7	7	6 (15)
Coolant exit temp. (° C)	70.6	91.7	123	130 (180)
Reactor cycle length (d)	23	14	14	2 (1)[*5]

[*1] including 2·0.25 mm cladding; [*2] at core inlet; [*3] across core only; [*4] particle diameter;
[*5] continuous refuelling desirable.

Table 1 Some characteristic data of proposed advanced US beamhole reactor concepts. The coolant is D_2O in all cases.

Reactor	HFR, ILL	PIK	FRM-II	CNR (Design 25)	(UHFDD) UHFR	Dim.
Max. thermal flux Φ_{th}^{max}	1.5	1.3	0.8	10	10	$x10^{15}$ $cm^{-2} s^{-1}$
Thermal power	57	100	20	270	355	MW
Av. power density	1.15	2	1.18	7.7	8.9	MW/l
Power peaking factor	2.9	2.1	< 3	1.6	1.5	---
Core dimensions $R_a/R_i/H$	19.5/14/80	19/6/50	10.8/6.7/70	22/7/35	21/5/2x15	cm/cm/cm
U-235 loading	8.6	27.5	6.64	18	26.5	kg
Fuel	UAL_x	UAL_x (?)	U_3Si_2	U_3Si_2	U_3Si_2	---
Enrichment	93	90	93	93	93	%
Coolant	D_2O	H_2O	H_2O	D_2O	D_2O	---
Pressure (outlet)	---	4	---	4.1	3.4	MPa

Table 2: Selected Reactor Parameters

Accelerator:

Maximum energy 600 MeV
Proton macropulse duration 100 μs
Injection: dc-preacceleration to 750 keV
100-600 MeV: disk-and-washer, 1000 MHz
Total power consumption 25 MW
Repetition rate 100 Hz
Peak proton current 50 mA
750 keV-100 MeV: Alvarez structure 200 MHz
Active time of rf-structure: 200 μs/pulse

The proton pulse regrouper: Ring equipped with a 200 MHz rf-cavity

Mode of operation	pulse duration	rep. rate	Protons per pulse
40 buckets filled	200 ns	100 Hz	3x10^{13}
1 bucket filled	5 ns	100 Hz	7.5x10^{11}
4 buckets filled	5 ns	400 Hz*	7.5x10^{11}
4 x 5 buckets filled	25 ns	400 Hz*	3.75x10^{12}
5 linac pulses stored	200 ns	1 Hz**	1.5x10^{14}

* storage and pulse-by-pulse extraction
** limited by activation of ring, because losses are more serious in storage mode than in compression mode

Table3: THE MOSCOW MESON FACTORY AT TROITSK

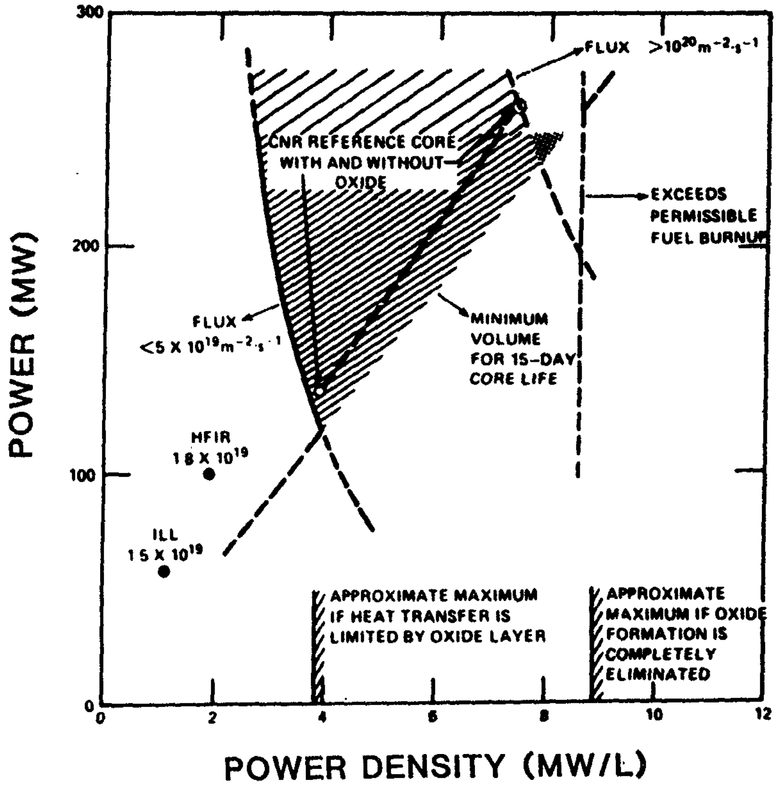


Fig. 1 Constraints for the power density for 30 vol % of U_3Si_2 fuel in an aluminium matrix with aluminium cladding. The request to have a minimum of 15 days core life leads to a minimum volume required to accommodate the necessary fissile material at a given volume fraction. Together with the operating power this determines a maximum allowable power density. Other constraints see text (from Difilippo et al, 1986).

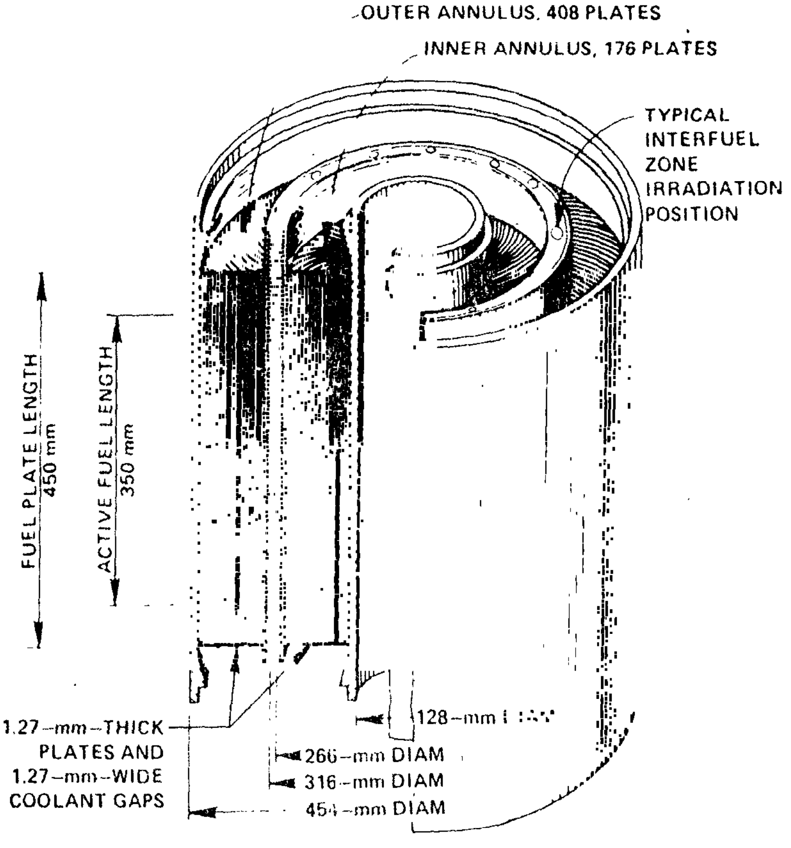


Fig. 2 Schematic of the CNR fuel element proposed by the Oak Ridge design team. The design is based on the present HFIR fuel element with irradiation positions located between the two annular fuel zones (from Difilippo et al, 1986)

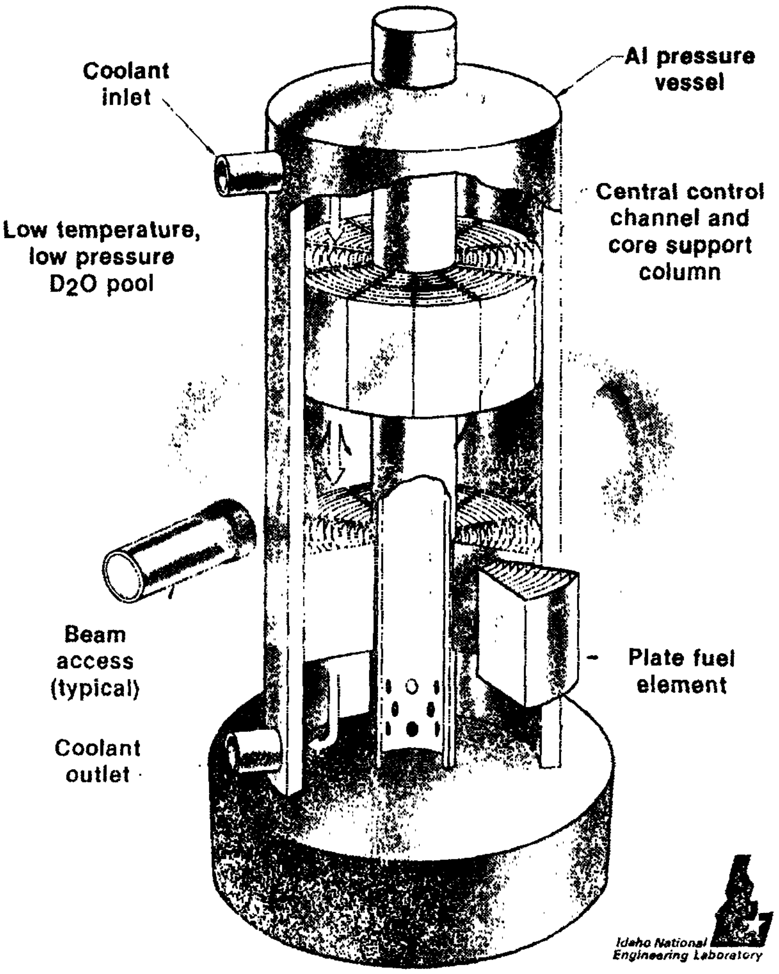
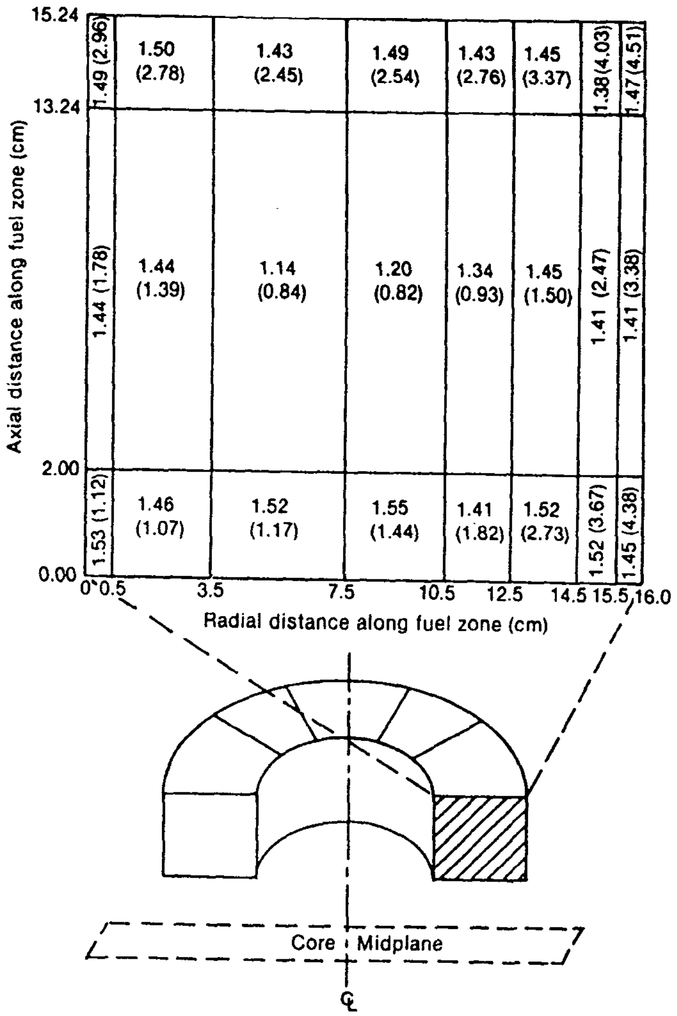


Fig. 3
The "double donut" core concept developed at the Idaho National Engineering Laboratory for an Ultrahigh Flux Reactor (from Lake et al, 1986).



1.49 (2.96)	1.50 (2.78)	1.43 (2.45)	1.49 (2.54)	1.43 (2.76)	1.45 (3.37)	1.38 (4.03)	1.47 (4.51)
1.44 (1.78)	1.44 (1.39)	1.14 (0.84)	1.20 (0.82)	1.34 (0.93)	1.45 (1.50)	1.41 (2.47)	1.41 (3.38)
1.53 (1.12)	1.46 (1.07)	1.52 (1.17)	1.55 (1.44)	1.41 (1.82)	1.52 (2.73)	1.52 (3.67)	1.45 (4.38)

Fig. 4
Power peaking factors for the core design of fig. 3 for the cases with variable and (in parentheses) with uniform fuel loading. Fuel loading is varied both, axially and radially (from Lake et al, 1986).

Legend

1.38 = F_R^N with variable U^{235} loading

(4.03) = F_R^N with uniform U^{235} loading

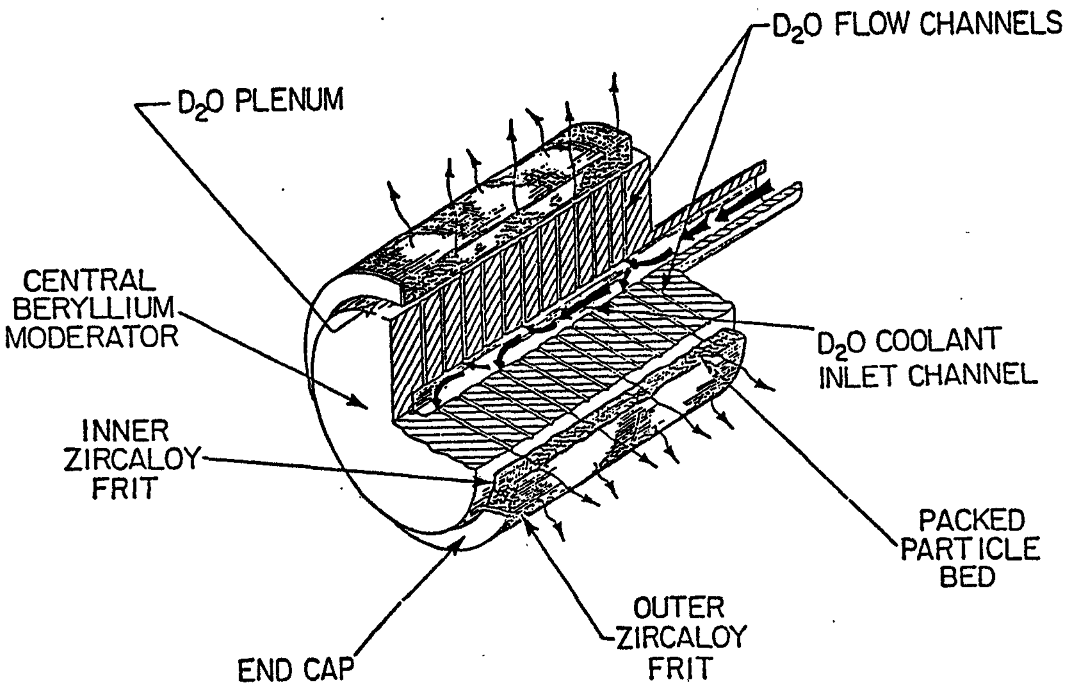
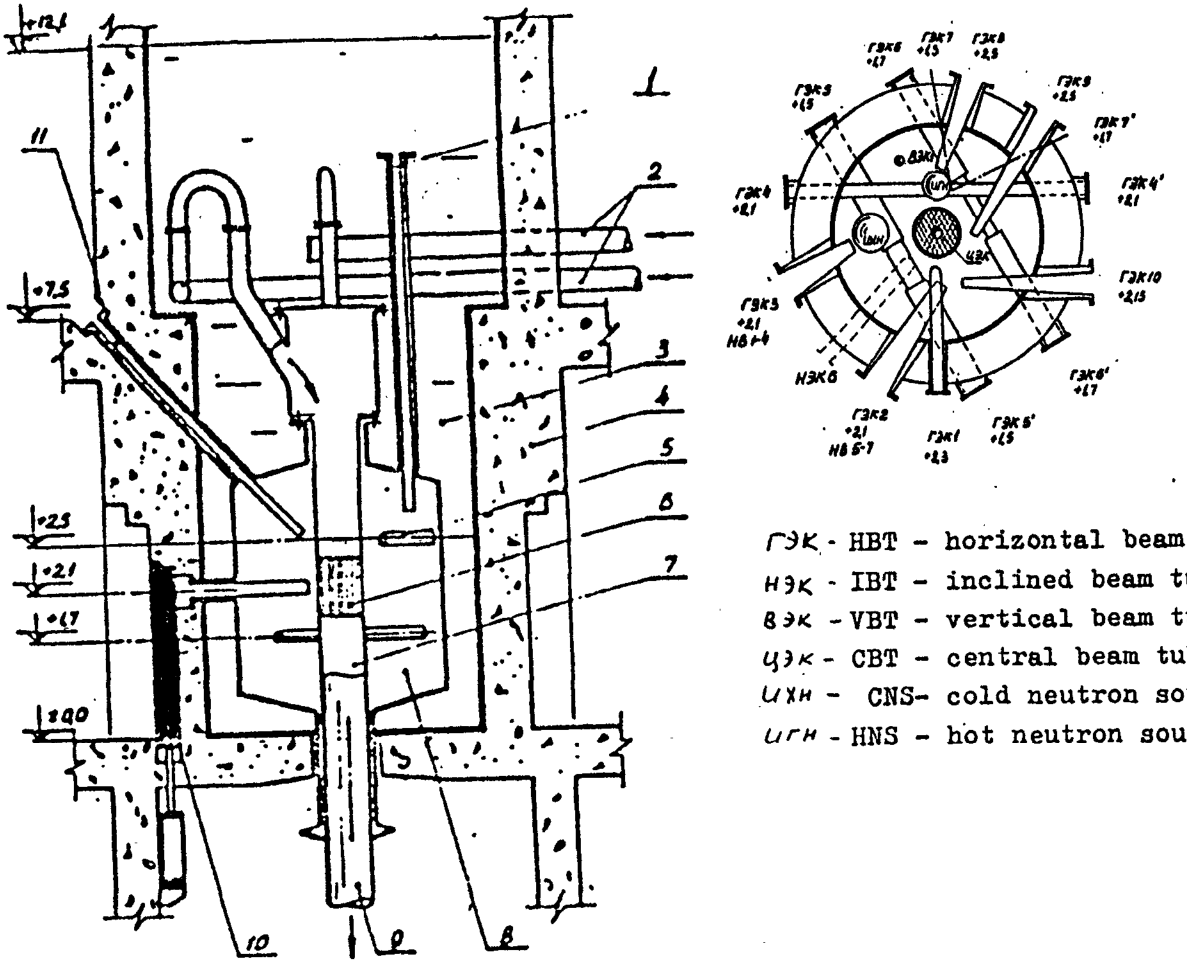


Fig. 5 A conceptual design for a High Flux Pebble Bed Reactor (HFPBR) proposed by Brookhaven (from Powell et al, 1986).



ГЭК - HBT - horizontal beam tube;
НЭК - IBT - inclined beam tube;
ВЭК - VBT - vertical beam tube;
ЦЭК - CBT - central beam tube;
ЦХН - CNS- cold neutron source;
ЦГН - HNS - hot neutron source;

Fig. 6 The PIK reactor (schematic) under costruction at Leningrad (from Konoplev, 1986).
1- vertical tube; 2- coolant inlet; 3- well with water; 4- biological shielding; 5- horizontal beam tube; 6- core; 7- replaceable vessel; 8- heavy water reflector; 9- coolant outlet; 10- gate; 11- inclined beam tube. Given on the left are distances from experiment floor in meters.

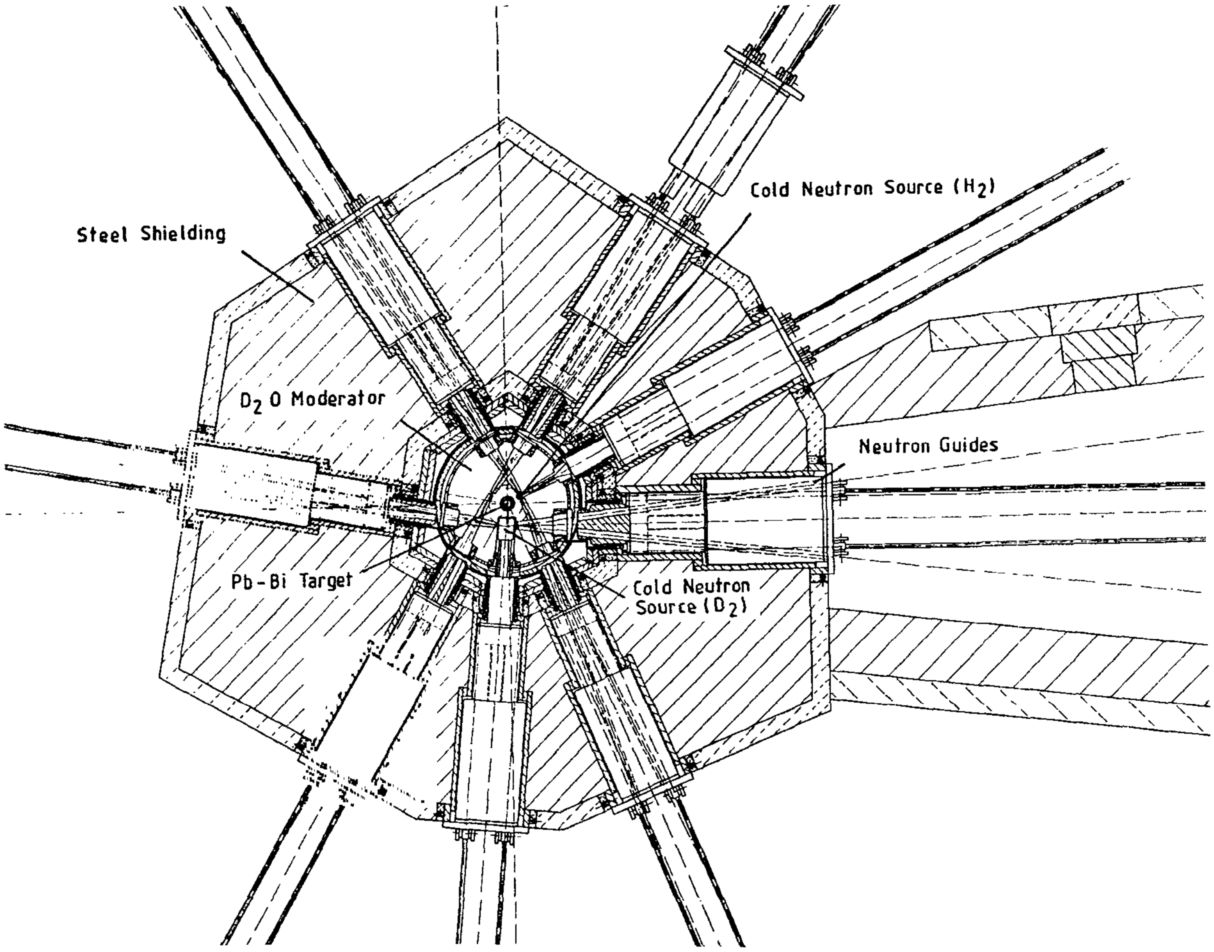
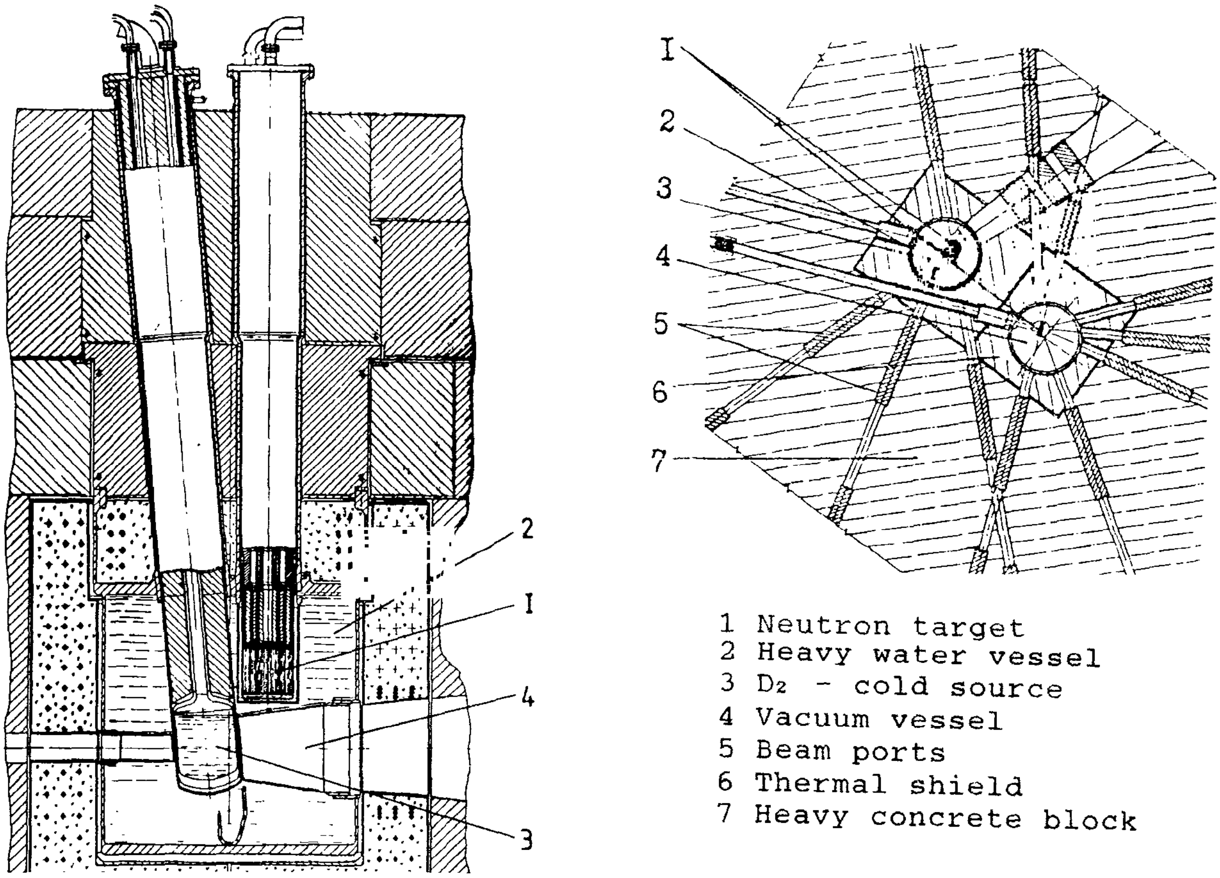


Fig. 7 Horizontal section through the target station of SINQ. A large D_2O tank surrounding the cylindrical target and in which the beam tubes end will accommodate two cold neutron sources



1 Neutron target
2 Heavy water vessel
3 D_2 - cold source
4 Vacuum vessel
5 Beam ports
6 Thermal shield
7 Heavy concrete block

Fig. 8 Target station of the Moscow Meson Factory spallation neutron source. (from Bulkin et al, 1985).

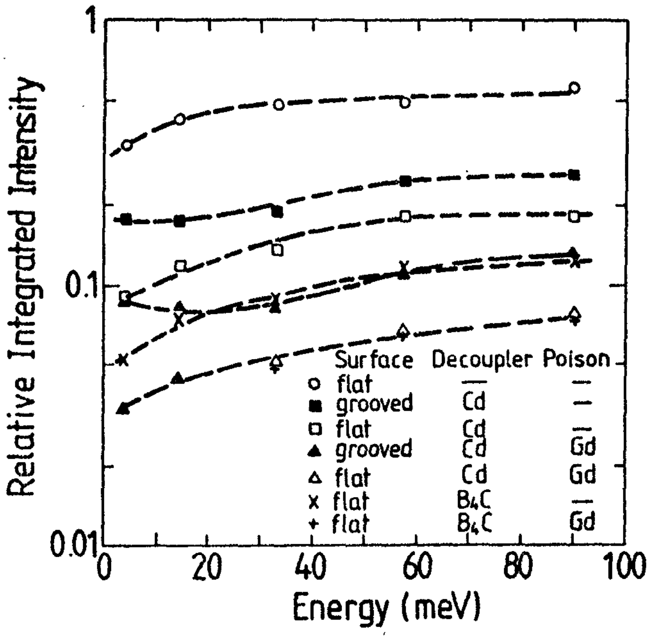


Fig. 9 Tradeoffs in integrated intensity resulting poisoning and decoupling the moderator for short thermal neutron pulses. The reference value (1) is the intensity obtainable from a well coupled moderator as proposed for the German SNQ-project (from Bauer et al, 1985).

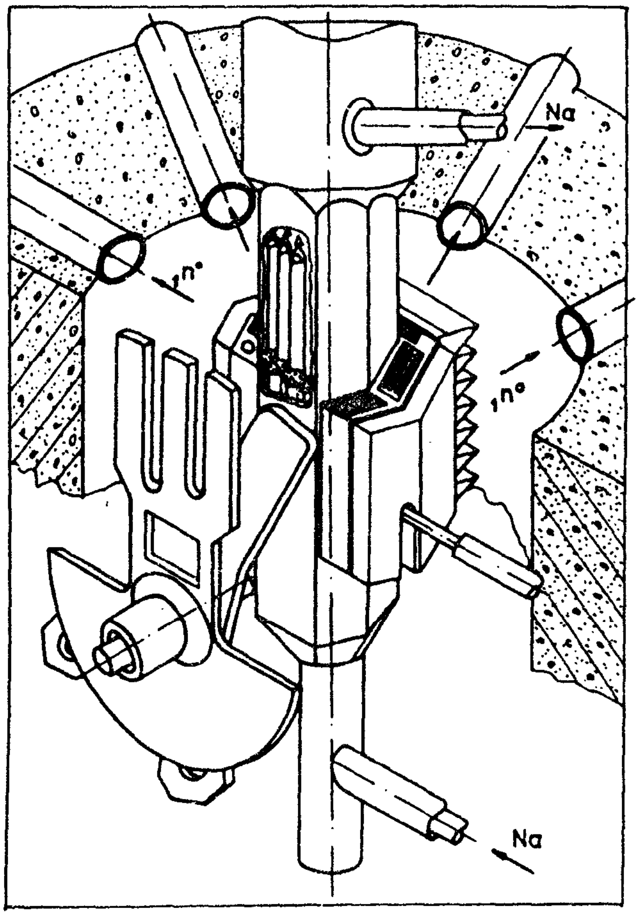
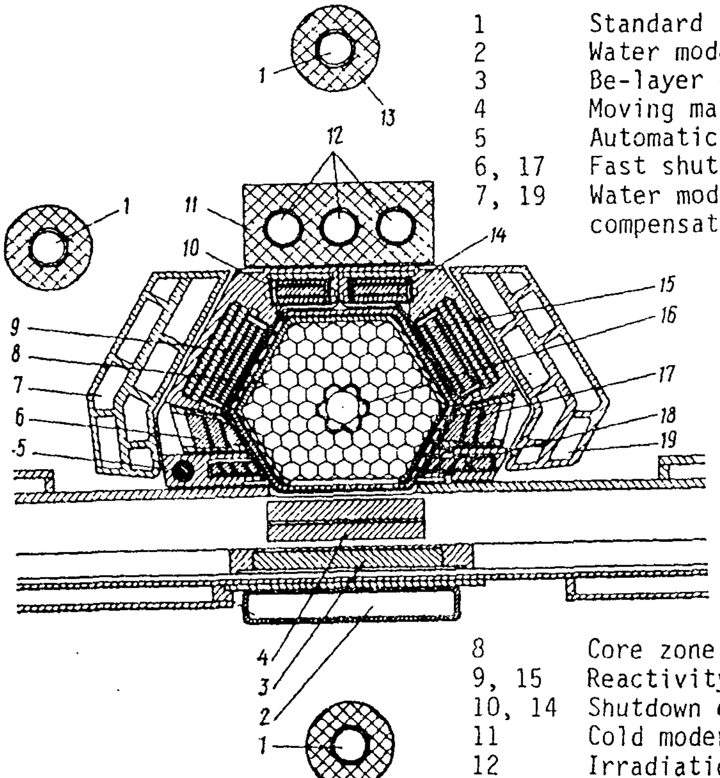


Fig. 10 Schematic of the IBR-II core region (from Ananiev et al, 1985).



1	Standard fission chamber
2	Water moderator for moving reflector
3	Be-layer of the auxilliary reflector
4	Moving main reflector
5	Automatic control rod
6, 17	Fast shutdown equipment
7, 19	Water moderator for reactivity compensator
8	Core zone (PuO_2-fuel elements)
9, 15	Reactivity compensator
10, 14	Shutdown equipment
11	Cold moderator mockup
12	Irradiation positions
13	Moderator for standard fission chambers
16	Central irradiation position
18	Intermediate control equipment

Fig. 11 Horizontal section through the IBR-II core region

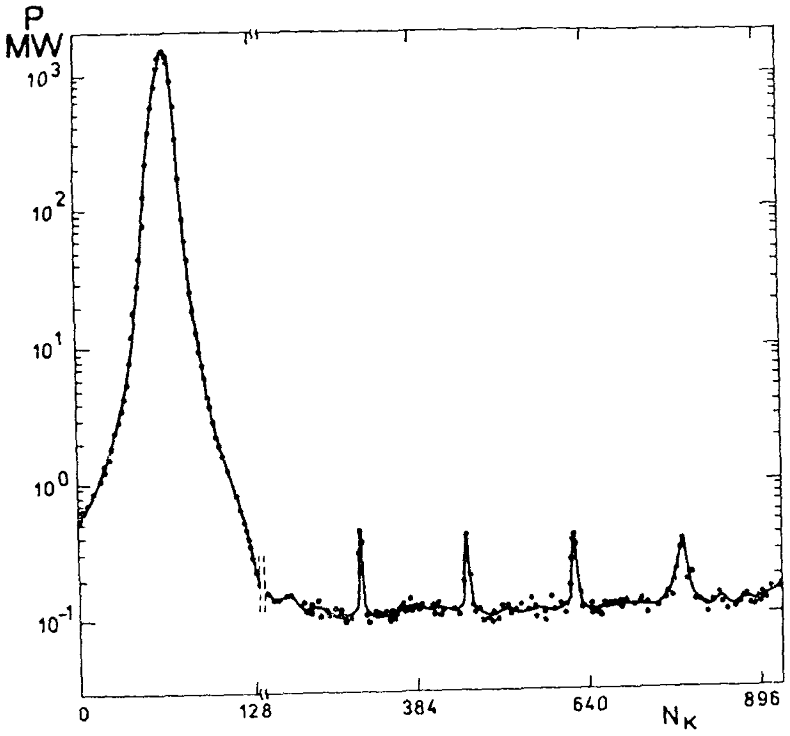


Fig. 12 Time structure of the IBR-II reactor power spectrum. In the Interval 0 - 128 the scaling is 32 μs/channel, in the later ones - 256 μs/channel. The narrow peaks on residual background result from the fast main reflector. (From Ananiw et al, 1985)