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MULTIPLYING BOOSTER TARGETS ON THE SNS

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1. Introduction

The SNS at the Rutherford Appleton Laboratory is due to produce its first neutrons late in 1984 and to achieve full design intensity in 1986. The parameters of the SNS have been reported at a number of Conferences (1, 2) and in the literature (3).

No facility should be built without the potential for development and expansion. It is certainly a goal that the SNS should realise full utilisation of its beam lines, which are capable of supporting 20-25 instruments: to this end the SERC/RAL is actively seeking international collaboration and is in various stages of negotiation with a number of countries. This paper however is concerned with the development of the SNS as a source, in particular with the provision of an enhanced "booster" target. As pointed out in reference (3), the intrinsic brightness of the SNS is comparable to that of the ILL in the thermal energy region, somewhat inferior in the low energy region served by the ILL cold source but is markedly superior at higher energies (x 10 at 100 meV and x 1000 at 1 eV). Any improvement in the performance of the SNS in general, and of its target in particular, should therefore concentrate mainly on upgrading the facility in the cold neutron regime with any concommitant increase in the thermal and epithermal regions being an added bonus.

A collaborative project was set up early in 1983 between the RAL and Kernforschungsanlage, KfA Jülich, to study multiplying, sub-critical booster targets. The collaboration is also privileged to have the help of a number of individuals with special expertise contributing to this work. The project is divided into a number of broad headings, including the scientific case (future instrument demands, new science), high power booster concepts (targets with or without enrichment, with or without a fissile core or blanket), neutronic performance and moderator fluxes, technical problems (choice of fuel and coolant). At this early stage safety requirements are not included explicitly, but are of course always borne in mind. These topics will now be discussed in a little more detail.

2. Scientific Case and Requirements

Whether or not a booster target is built depends firstly on the strength of the scientific case. The SNS as being presently built will be a leading pulsed source into the 1990's and is expected to outperform all present sources, including high flux reactors, in the neutron energy regime > 100 meV. At lower energies the relative performance is less clear and in the cold neutron regime < 10 meV, may be inferior to reactors (due to lower intensity and, in some cases, lack of compatibility between cold neutron experiments and the time of flight technique).

The scientific case for a booster target thus falls into two parts: (a) to provide an uprate of performance of known instruments especially in the cold neutron regime and (b), which is more difficult, to envisage scope for new science in the 1990's. These in turn set the requirements on the system of pulse intensity, length and shape, resolution, repetition rate, background, etc.

As a first step to defining the source parameters, Table 1 lists some "typical" performance figures for reactor (ILL) and pulsed (SNS) instruments over four main activities of cold neutron science. Column 4 envisages new instruments which give a, say, factor 10 better performance. Care is required in defining "better" since, depending on the case, it may mean more intensity, or wavelength window or repetition rate, etc. Column 5 indicates the pulsed source parameters required to serve this "x 10 instrument". It can be seen that the broad requirement is for an increased (x 10) intensity per pulse at 20 (25) or 50 Hz, with pulse lengths (and shapes) similar to the present SNS. The high repetition rate is required to achieve the highest time-averaged intensity, within the frame overlap limitation, and most instruments can operate at high ($\sim$ 50 Hz) frequency.

3. High Power Booster Concepts for the SNS

Monte Carlo, point kinetics and neutron transport calculations are being performed by the member institutions on two basic concepts for a booster target, these are :

(a) An enriched uranium target, not dissimilar to the present SNS parallel plate target, with closely coupled moderators within a reflector assembly (e.g. beryllium).

(b) A spallation target (perhaps enriched) mounted within a core, or blanket of fissile material, surrounded by a reflector (e.g. nickel), with the moderators located at optimal positions to be determined.

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The concept of an enriched SNS-type target is being studied mainly at RAL with the codes (HETC/05R) used in the design of the original ^{238}U target (4). Similar calculations have been performed for the IPNS target by Carpenter et al (5) and similar results are expected. Emphasis is being placed on varying the ^{235}U enrichment along the target to increase the neutron production at the downstream and where the cold moderators are located (including the para-H_2 one). First preliminary indications are that by increasing the enrichment to produce a flat fast neutron output increases the power (from the original 230 kW) by a factor $\sim$ 4 with a similar increase in neutron flux coupled to the downstream moderator. Such gains are within the reach of the present services and so this concept is of interest also to the existing target station. It also serves as a baseline for a booster based more on reactor concepts.

The concept of a fast neutron target surrounded by a small sub-critical fast assembly is also being studied, mainly at KfA. Initial work was done by Constantine and Taylor (6), based on the "Superbooster" studies for the Harwell electron linac (7). The one dimensional neutron transport code ANISN was used to consider the affects of (oxide) fuel volume fraction in the core, nickel reflector thickness, criticality k and the use of ^{239}Pu instead of ^{235}U. The target was the ^{238}U SNS and sodium was the assumed coolant throughout. The results indicated that a subcritical assembly (k = 0.95, corresponding m = 20) of 50% volume fuel and a 200 mm reflector would achieve a compact core of about 15ℓ (30% PuO_2) or about 20ℓ (UO_2) only. Table 2 shows the performance of such a 15ℓ core (30/70 Pu/U fuel) for a 5 and 10 MW mean power booster, taking into account the delayed neutron background (delayed neutron fraction $\beta \sim 0.48\%$). Significant numbers are the prompt multiplication m and the mean fuel temperature rise per pulse (q.v.). The values of m are greater than the actual gains achievable in the neutron flux feeding a moderator for such a system because of the increased surface area compared with the SNS target: the neutron flux is 2.7 x SNS value at 50 Hz, 13.5 x at 10 Hz.

The preliminary estimates have been followed by more sophisticated computations at KfA. Calculations have been performed using the time dependent homogeneous diffusion equation, point kinetics (with time) and MORSE on cylindrical and spherical models of a booster. Comparisons have been made between the codes in determining criticality k, neutron lifetime and pulse lengths, with the result that the simple equations appear adequate to make a survey of booster geometry and parameters before needing the full Monte Carlo codes. As an example, figure 1 shows a "typical" spherical configuration with a $k_{eff} \sim 0.97$. Outgoing fluxes were compared with and without booster (i.e. with the Ni reflector in contact with the spallation target). With the booster a neutron lifetime of 0.5 μs was obtained and neutron flux enhanced by x 3 compared with a conventional target. Pulse length from the moderator was again calculated using the 3 methods above, showing the simple calculations to be adequate for first optimisations. Pulse lengths ($\sim$ 50 μs) were dominated by moderation times.

An interesting model has been proposed by Kuchle using a pancake core of 4 MW (Th) with horizontally arranged plutonium fuel rods in a 0.3 x 0.3 x 0.2 m^3 assembly with Na cooling. A prompt multiplication of m = 50 at 10 Hz within a 5 MW power ceiling gives a x 10 gain in cold neutron yield. Using a 150 or 200 mm diameter parahydrogen moderator yields a x 100 flux at 4 Å compared with the ILL cold source.

4. Neutronic Performance and Moderators

Evaluation of neutronic performance using different calculational methods has already been referred to. Further codes in common usage by the collaboration are ENDF 8/2, 8/3 and 8/4, derived data libraries for neutron and γ-photon data and ORIGEN II, for fission products, burn-up and induced activity studies.

The design of a cold moderator and its optimisation in the wavelength range $0.5 \text{ Å} < \lambda < 20 \text{ Å}$ required pulse length $\lesssim$ 100 μsec are being studied at Birmingham. Clearly moderator performance is intimately linked with the booster due to its relative size and location within the assembly. The optimum booster-moderator assembly is one which satisfies the experimental requirements, within its own physics, engineering and (ultimately) safety constraints. Of the basic orientations for a moderator, wing geometry is strongly preferred to suppress the γ-flash and fast neutron backgrounds. A likely material for the cold moderator is para-hydrogen, if the purity can be maintained. Whilst the thickness of a moderator determines, to first order, its pulse length (e.g. it is $\sim$ 50 mm on the SNS), increasing the transverse dimensions can increase the neutron flux with small or no increase in pulse length if suitable heterogeneous poisoning is introduced. Delayed neutron background becomes an important problem in the paramaterisation and experimental utilisation of the moderator. The suggestion has been made of using close-in choppers to reduce this problem.

5. Technical Problems, Choice of Fuel and Coolant

The choice of fuel for the booster lies with uranium enriched with ^{239}Pu or ^{235}U, in the form of oxide, ceramic, or alloyed with molybdenum. The use of plutonium offers a number of advantages, including shorter pulse times available because of the smaller delayed neutron fraction and the smaller core sizes achievable. As indicated in the examples above the latter is particularly important since it permits a higher neutron brightness at the surface feeding the moderator. Some of the disadvantages of plutonium are obvious and need not be discussed.

Alternative candidates for the fuel material are oxide and metal, possibly as an alloy (8%-10%) with molybdenum as used in the PFR. In either case reactor experience indicates pin rather than plate-type fuel will be required to give the high volume fraction of fuel needed to achieve high k_{eff} in a small, hard-neutron spectrum core, at the same time giving good heat transfer performance and (by virtue of its shape) superior resistance to swelling and fission product build-up. The impossibility of attaining bonding for oxide fuels virtually makes pins imperative.

The central problem in the use of any fuel is indicated in Table 2, i.e. the behaviour under pulsed conditions. Stress problems arise not only with the rapid rise of temperature during the pulse, but also of quenching due to accelerator beam trips. Further problems include fatigue and possibly ratchetting of the fuel within the clad. Whilst there is experience of oxide fuels to 8-10% burn-up in fast reactors, the more arduous operating conditions in a booster might suggest that much lower design levels (say 2%) be considered initially. The question of reprocessing has yet to be studied.

The choice of coolant is dictated by the projected high power densities and the requirement (via its moderating properties) for a short ($\sim 10^{-7}$ sec) neutron generation time. The power densities in the range of 300-500 kW/l suggest the use of liquid sodium on the coolant. However D_2O is also a candidate if the increased pulse lengths are acceptable. In either case it may be necessary to use 1/v and resonant absorbers in the core.

The combination of these power densities, the nature and magnitude of the fuel inventory and the pulsed-power operation of the system (let alone the problem of high power density pulsed cryogenic moderators) necessitate a detailed series of safety and criticality studies to ensure safe operation of the booster. The safety studies must produce a design which minimises the possibility of power excursions, coolant channel blockage and core melt-down incidents.

6. Conclusions

The development of the SNS by the provision of an enhanced "booster" target and optimised for cold neutrons offers a facility which will outperform all known sources into the 1990's. A goal of the order of 10 x improvement is aimed at: whether and how this will be achieved and what compromises have to be made will be the subject of study by this collaboration over the next few years. We look forward to this exciting prospect.

7. References

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TABLE I

Scientific activity	ILL Instrument	SNS Instrument	Ten times "better" instrument than currently available	Pulsed source parameters required to achieve "x 10" instrument
LOW-Q small angle scattering (metallurgy, magnetism, polymers, chemistry, biology)	D11 $Q = 0.001 - 0.3$ Å^{-1} Intensity $\sim 10^{6}$ n cm^{-2} s^{-1} at 10Å ($\Delta\lambda/\lambda \sim 10\%$)	LOW-Q $Q = 0.003 - 1.0$ Å^{-1} Intensity $\sim 3 \times 10^{5}$ n cm^{-1} s^{-1} for $1 < \lambda < 10$Å	$Q = 0.001 - 5$ Å^{-1} Intensity $\sim 3 \times 10^{6}$ n cm^{-1} s^{-1} for $1 \cdot \lambda < 20$Å	$0.5 < \lambda < 20$Å prf = 20 Hz Intensity/pulse = 25 x SNS
Broad resolution quasielastic scattering (rotational diffusion in liquids etc.)	IN5 Resolution = 90 μeV Wide $\hbar\omega$ Intensity $\sim 10^{5}$ n cm^{-2} s^{-1}	IRIS(PG) Resolution = 13 μeV $\hbar\omega$ = 1 meV Intensity ≡ IN5	Intensity/pulse = 10 x SNS	$\lambda = 6.7$Å, $\delta t_{mod} \sim 100$μs prf = 50 Hz Intensity/pulse = 10 x SNS
			Intensity/pulse = 10 x SNS $\Delta\lambda$ = 2.5 x SNS	$\lambda = 6.7$Å, $\delta t_{mod} \sim 100$μs prf = 20 Hz Intensity/pulse = 10 x SNS
High resolution quasi-elastic scattering (eg. jump diffusion processes in metals, etc.)	IN10 Resolution = 1μeV $\hbar\omega = \pm$ 15μeV Intensity $\sim 10^{4}$ n cm^{-2} s^{-1}	IRIS(Si) Resolution = 1.2μeV $\hbar\omega$ = 80μeV Intensity/μeV ≡ IN10	Intensity/pulse = 10 x SNS	$\delta t_{mod} \sim 100$μs prf = 50 Hz Intensity/pulse = 10 x SNS
			prf = 500Hz Intensity/pulse ≡ SNS	$\delta t_{mod} \sim 100$μs prf = 500 Hz Intensity/pulse ≡ SNS
Ultra-high resolution quasielastic scattering (eg. polymer segmental diffusion)	IN11 (1982) Resolution = 10 neV $Q = 0.02 - 1.5$ Å^{-1} Intensity $\sim 1.5 \times 10^{7}$ n cm^{-2} s^{-1}	SES (RL-81-019) Resolution = 70 neV $Q = 0.04 - 2.2$ Å^{-1} Intensity $\sim 1.5 \times 10^{6}$ n cm^{-2} s^{-1} $4.5 < \lambda < 7.5$Å	Resolution = 70 neV Intensity = 1.5×10^{8} n cm^{-1} s^{-1}	$2 < \lambda < 10$Å $\delta t_{mod} \sim 2$ x SNS prf = 20 Hz Intensity/pulse = 250 x SNS

TABLE 2

prf n (Hz)	Multi-plication m	Fraction of Useful Power	Pulse in MJ	Mean temp rise C in 80 kg as oxide
1	106.4 (140.8)	0.49 (0.32)	2.45 (3.24)	91 (120)
2	71.4 (106.4)	0.66 (0.49)	1.64 (2.45)	61 (91)
5	36.0 (61.3)	0.83 (0.71)	0.83 (1.41)	32 (52)
10	19.7 (36.0)	0.91 (0.83)	0.45 (0.83)	17 (32)
25	8.3 (16.9)	0.96 (0.92)	0.19 (0.37)	7 (14)
50	4.3 (8.3)	0.98 (0.96)	0.098 (0.19)	3.6 (7)

Operating Modes at 5 and (10) MW mean power, allowing for delayed neutron fraction; 30/70 Pu/U fuel as oxides, Na coolant

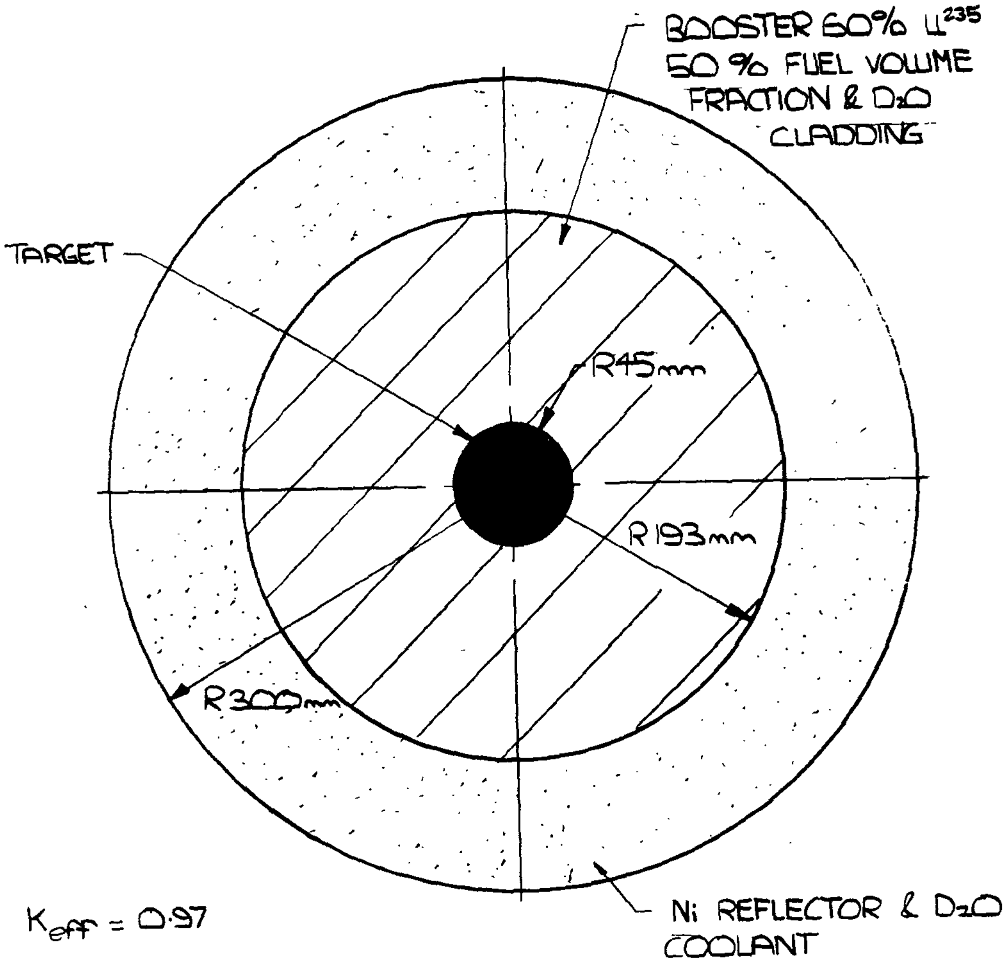

FIGURE : 1 BOOSTER GEOMETRY & MATERIALS STUDIED BY K.F.A. GROUP