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Optimization of a multiple source system for ADS

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The original design of an Accelerator Driven System - ADS [1] with one central source has several problems that are not easily resolved. One of the problems is the power peaking factor of such a system, which is high compared to conventional core designs. It seems that techniques for coping with high power peaking factor, by means of flow constraints, cannot ensure safe operation of such a system, and considerable overheating of the near centered fuel pins cannot be excluded. Other difficulties are concerned with the accelerator performance and the target. A lot of effort is invested today in upgrading the existing accelerator beam energy and intensity which at the moment is 600 MeV and 1.5 mA at the advanced PSI facility. At the same time efforts are made to reduce the number of "trips" of the accelerator system to a significantly lower level. Furthermore, the objective of a compact cyclotron imposes some technical constraints which in the end effect limit the achievable beam intensity and energy. An additional aspect of concern is the local heat generation produced by the spallation source. It seems that the heat removal capability by the lead coolant is lower than needed by the benchmark ADS designs, even if forced cooling is considered.

The above mentioned issues concerning the feasibility of a one central source configuration for an ADS led to a new concept [2] in which multiple sources are employed. Such a design should in principle overcome most of the limitations related to the central source configuration. The total beam intensity needed is to comply with the accelerator best current output performance. Since the accelerator beam is split into several subbeams, the heat produced by each target is correspondingly lower and thus can be removed by the coolant, in a safer manner. The thermal peak factor for the new multibeam concept is also expected to decrease significantly, in comparison with the central source design.

The adaptation of CITATION [3] code to ADS simulation enabled a basic study of the new concept of multiple sources systems. At first three main characterizing options were analyzed [2,4]. A central source configuration , a three and a six multiple sources configuration. Results reconfirmed the very high peak factor of the central source option and ruled out the six beams options due to the enhanced neutron leakage (in addition to the mechanical complexity of having six beam tubes entering the core region). The study emphasizes the importance of spatial effects when sources are introduced within the core. The spatial flux distribution of each configuration tested was shown to have crucial impact on the main design parameters of an ADS. Therefore a more detailed optimization is essential.

This work deals with an optimization of the most feasible multiple sources systems for ADS which appear to be the three or two sources configuration. The reliability of CITATION code enabled a detailed analysis in accordance with the updated status of the accelerator performances. A total of five configuration were analyzed. The difference between them is the placement of the beam targets within the core. The locations of the sources for each option are listed below and are connected to the core design of Figure 1. This plot shows one example (option 4 below) of the five possibilities examined in this study. It should be noticed that any location of a source is always surrounded by a lead coolant ring (six subassemblies). All the simulations are done with a fresh fuel core load (thorium enriched with U233). The five options are:

1. two sources located at subassemblies No. 38 and 50.
2. two sources located at subassemblies No. 20 and 29.
3. two sources located at subassemblies No. 44 and 56.
4. three sources located at subassemblies No. 42 and 50 and 58.
5. three sources located at subassemblies No. 20 and 26 and 32.

The performed analysis was aimed to deal with the high priority topics which include: 1. Total and single source strength 2. Heat removal from the target 3. Thermal peak factor 4. Criticality losses (gains) 5. Technological considerations

The criticalities of the different configurations are obtained directly as eigenvalues of the source free solution. When a source is activated the former method is not applicable, so the criticality is defined as the ratio between neutron production over neutron losses in the entire core. In addition, changes in criticalities are introduced by altering the enrichment of U233 within the thorium fuel matrix. Figure 2 points out the differences between the evaluated configurations related to the source strength and subsequently the heat removal capability. All the curves are compared to a reference single centered source and assume implicitly the same output power level from the core. The range of K_{eff} axis span the $0.9 - 1$ interval. Figure 2 shows the total source strength of each of the multiple sources systems considered. The best configuration is the three sources system requiring the lowest individual beam intensity (as it needs only about 15% more total beam power than the reference central source case). The best two sources configuration lies only about 5% above the best three sources configuration, which is not a significant difference. The major disadvantage of the 2 sources system is that each of the sources must have the strength of at least 60% of the compared single central source system whereas for the three beams option the single source strength is only around 38%. This of course affects also the heat generated and consequently reduces significantly the amount of heat to be removed from the target window. Yet the smaller mechanical complexity is in favor of the two beams systems.

The peak factor aspect is plotted in Figure 3. The values presented are based on the maximum power density over the average power density. The calculated maximum power density depends on the number of subregions (defined by the user) for each subassembly. In this work the subassemblies were divided into 4 regions.

The results shown in Figure 3 can be divided into two zones: above and below $K_{eff} \approx 0.97$. Below $K_{eff} \approx 0.97$, the three beams option exhibits an expected increasing peak factor, but for higher criticalities this effect is reduced due to the enhanced influence of the core fission material. Furthermore, in this higher K_{eff} range the peak factors of all the two and three beam options are all close together within an interval of 10% at the most. This value is sufficiently small from a thermohydraulic point of view. In the lower criticality range it is seen that the two sources options curves exhibit a sharp slope of the peak factor. It thus appears, only the three beams systems could be practical for transmutational ADS. The peak factor of the central source configuration is also presented. It is seen that in this case the flux shape is strongly dependent on the source up to very high criticalities levels, and as a result the peak factor is much more higher in comparison with the other configurations.

A very important parameter which influences the safety of the system, as well as its operational mode, is the criticality of the core, and in particular its dependency on the location of each source. The spatial effects of the sources are demonstrated in Figure 4. All the curves in Figure 4 are in comparison with the criticality of a reference source free core (the values of the X axis). The center source has the largest positive multiplicity factor (neutron production over neutron losses). For the core configurations considered it is seen that for those options, where the sources are closer to the center, there is an additional gain in the multiplicity factor, and therefore possess preferable safety features. In those systems the effect of positive reactivity feedback leads to a reduced multiplicity increase, in comparison to the same source free configuration, so that the system is more stable. The same effect occurs when negative reactivities are introduced. In those cases the multiplicity decreases by a lesser amount, and again the core transient mode is smoothed due to less pronounced feedback effects. In case of a severe accident, shutting down the source will introduce an additional negative reactivity (namely the positive multiplicity difference) ramp, increasing the inherent safety features of such configurations (see also [4]).
Regarding operational aspects, the configurations in Figure 4, which exhibits an increase in the multiplicity (M), are preferable. In ADS the power is linearly proportional to the intensity of the source and is inversely dependent on $(1 - M)$. So the fact, that the actual multiplicity is higher for certain options means that the same reactor power can be achieved with a less intense source. On the other hand, if the accelerator beam is unchanged, there will be an additional gain in the output core power.

From the current study it is concluded that the peak factor is not a crucial issue for optimizing a three or two sources core. The peak factor is the same within a range of 10% whereas for the central source option, the peak factor is almost doubled and therefore not recommended. The preferable option between those tested seems to be mainly dependent on the accelerator and target performances. New developments in the removal of the heat from the target, in parallel to the establishment of high intensity sustainable beams will allow the use of a two beams system which may reduce the technological effort considerably. Yet the three sources options exhibit the most realistic characteristic for transmutation at relatively low criticalities. In addition, as only fresh fuel was simulated in this work, it is necessary to analyze the core behavior during its life time and reevaluate the impact of the source location on the multiplicity of the system and its spatial power distribution during the burn-up phase.

References

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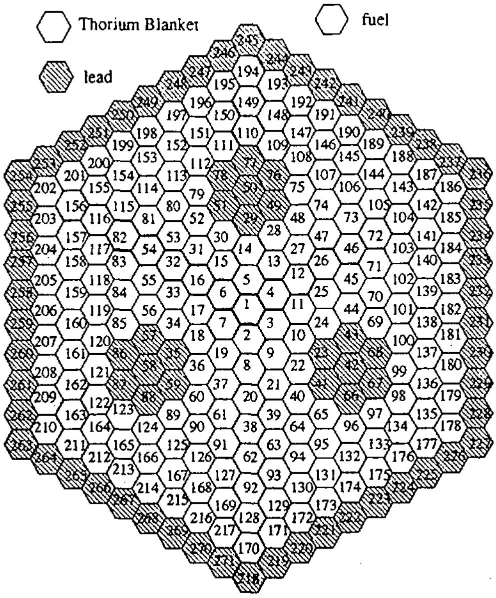

Fig. 1: Hexagonal mid plane, 3 source core configuration (option 4).

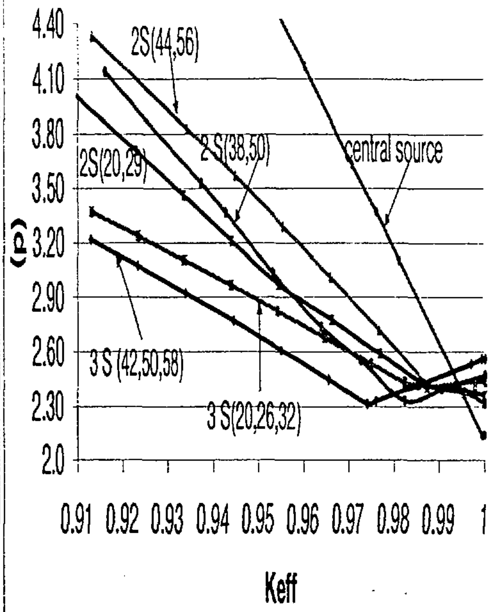

Fig. 3· Peak factor (P)

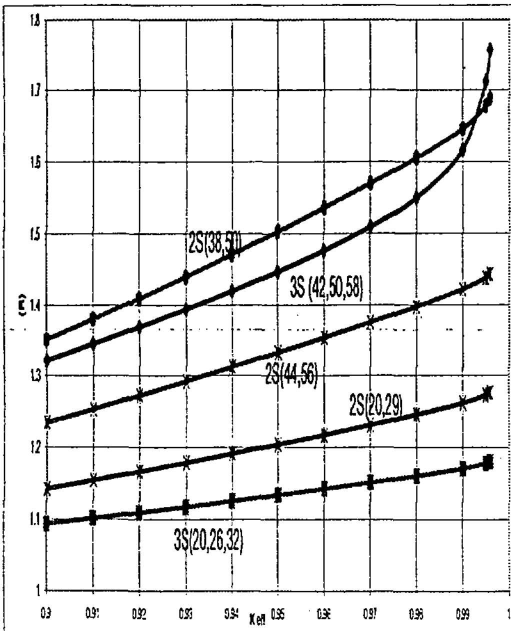

Fig.2: Total strengths of Multiple Sources system Relative to a Central Source (R)

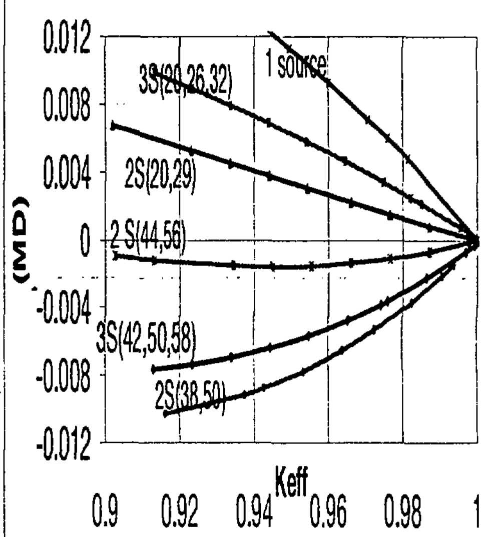

Fig.4: Multiplicity Difference (MD) between source(s) *on* and source(s) *off*