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# Annex 1
# NEUTRON BEAM PARAMETERS

## General considerations for neutron capture therapy at a reactor facility

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**Abstract.** In addition to neutron beam intensity and quality, there are also a number of other significant criteria related to a nuclear reactor that contribute to a successful neutron capture therapy (NCT) facility. These criteria are classified into four main categories: Nuclear design factors, facility management and operations factors, facility resources, and non-technical factors. Important factors to consider are given for each of these categories. In addition to an adequate neutron beam intensity and quality, key requirements for a successful neutron capture therapy facility include necessary finances to construct or convert a facility for NCT, a capable medical staff to perform the NCT, and the administrative support for the facility. The absence of any one of these four factors seriously jeopardizes the overall probability of success of the facility. Thus nuclear reactor facility management considering becoming involved in neutron capture therapy, should it be proven clinically successful, should take all these factors into consideration.

## 1. INTRODUCTION

Neutron capture therapy (NCT), and especially boron neutron capture therapy (BNCT), has had a varied history over the past half century. Early trials in the 1950s and 1960s were largely unsuccessful [1]. By contrast the treatments in Japan since the late 1960s have been relatively successful [2], although not widely accepted among the scientific community and certainly not among the medical community. Other than the Japanese work there was a general moratorium on NCT research from the early 1960s to the mid-1980s. Currently clinical trials are underway in four sites in the United States, Netherlands, and Finland.

If these clinical trials prove successful and the procedure receives formal approval, the question arises as to where NCT treatment would be available and at what type of facility. Currently and perhaps ultimately the answer to the second question is a nuclear reactor. Where such a reactor should be located is strongly dependent on accessibility of patients requiring NCT treatment. Ideally there would be a number of reactors adapted for NCT treatment at locations scattered throughout the populated regions of the world.

The concept of such a large number of reactors adapted for NCT treatment begs three more questions: (1) How can an existing research reactor be converted into a reactor with NCT capability? (2) Or what design features would be optimal if a new reactor facility were being built specifically for NCT? (3) What other considerations are necessary for a successful NCT facility? Discussed below are some of the nuclear design, operating, medical, and non-technical factors that must be considered in order to answer these three questions.

A preliminary question is why get involved with NCT at all? The answer to this question likely falls into one or both of two categories, humanitarian and financial. It is a charitable thing to be involved in extending people's life span and improving their quality of life by an activity such as NCT treatment. The second reason may be more self-serving. Many

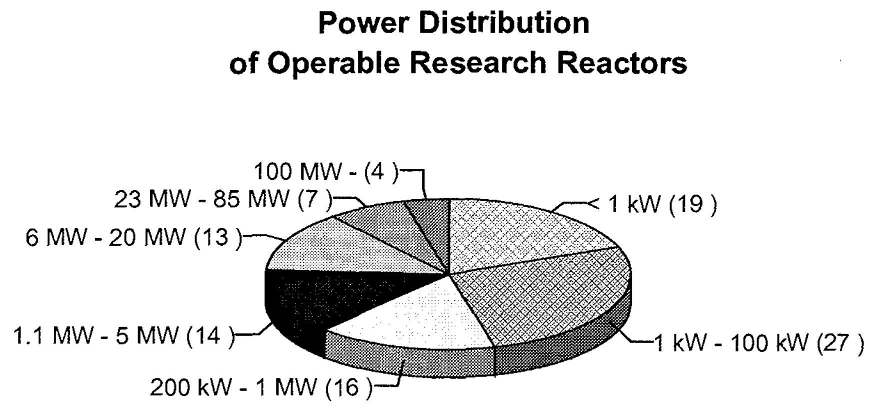

*Fig. 1. Power distribution of operable research reactors.*

research reactors have very limited budgets and are interested in becoming involved in revenue-producing activities. Some research reactors are in jeopardy of being shut down, often because of operations costs or level of use, and are looking for a “saviour” project to perpetuate their existence. As will be seen, this reason alone is insufficient for becoming involved in NCT.

## 2. NUCLEAR DESIGN FACTORS FOR NCT

Although NCT has been proposed using $^{252}$Cf sources, accelerators, and nuclear reactors, nuclear reactors have by far the majority of NCT experience and proven research results. Basically $^{252}$Cf sources, even with converter plates, do not produce an intense enough beam in a reasonable treatment time. Very large and expensive accelerators are required to produce a high, reliable neutron beam strength. Only nuclear reactors will be discussed further in this paper.

A logical question then is what type of nuclear reactor is the best for NCT? The answer to this question lies primarily in determining what types of reactors can produce an adequate strength and quality of radiation beam for NCT. Whether converting an existing reactor or designing a new reactor for NCT, there are some specific principles to consider. The two primary radiation-related requirements for NCT are a sufficiently high intensity epithermal neutron source and an excellent beam quality. In particular, an optimal NCT beam has an adequate epithermal neutron flux with relatively low contributions from fast neutrons, gamma rays, and other in-patient doses.

General consensus [3] is that an epithermal neutron fluence of about $1\text{x}10^{13}$ n*cm$^{-2}$ is required for successful NCT. For an epithermal neutron flux of $1\text{x}10^{10}$ n*cm$^{-2}$*s$^{-1}$, a very reasonable treatment time of only about 17 minutes is necessary. An epithermal neutron flux of $1\text{x}10^{9}$ n*cm$^{-2}$*s$^{-1}$ requires a treatment time of about 3 hours. To some extent these parameters rely on reactor power. Reactors with power levels as low as 100 kW have produced beams which meet some or all of the above parameters. About half of the research reactors in the world have power levels greater than a few hundred kW (see Figure 1), although power level alone is not a sufficient condition for a successful NCT beam.

There are several undesirable components of the NCT beam due to fast neutrons, thermal neutrons, gamma rays from the reactor core, capture gamma rays produced along the beam, and three in-patient radiation sources: gamma rays from neutron capture in hydrogen, protons from the (n,p) reaction in nitrogen, and proton recoil by neutron scattering from hydrogen. It is generally considered to be desirable to have a fast neutron dose to epithermal fluence ratio of less than about $1 \times 10^{-10}$ Gy*cm$^2$ [4] and a gamma ray dose to epithermal fluence ratio of less than about $2 \times 10^{-11}$ Gy*cm$^2$ [5].

Another important factor is the neutron current-to-flux ratio, which affects the penetrability of the neutrons into the patient. A high ratio is indicative of a more forwardly directed beam, with a ratio of 1.0 being monodirectional and 0.5 being isotropic.

Converter plates have been designed and tested and have shown that they can improve the intensity of the beam. This is not without its cost since converter plates must be shielded, sufficiently subcritical, and often generate enough heat that they must be cooled. They also take up space that may not be available in reactor conversion.

Although the focus of NCT beams is primarily on epithermal neutrons, it should be noted that highly thermal neutron beams are desirable for NCT research with cells or small animals (few cm in size) or for surface or near-surface tumours.

Two other important properties of an NCT beam, the core-to-patient distance and the cross-sectional area that the beam intersects the core, are somewhat related. Both a small beam diameter and a long core-to-patient distance decrease the epithermal neutron flux at the patient and increase the neutron current-to-flux ratio. A compact reactor design is optimal to produce a sufficient NCT beam. A better NCT beam may also be able to be attained by a change in the reactor moderator or reflector, particularly if this decreases the core-to-patient distance, but these factors also affect core criticality and so may have an offsetting effect.

What type of irradiation facility has these features? Small diameter beam tubes are not adequate. Calculations [6] at Oregon State University have shown that both a radial and a tangential beam port (20 cm stepped down to 15 cm, 3 m long) at a 1 MW reactor produce a beam that is about an order of magnitude too low for a reasonable NCT beam. This is primarily because the neutron flux decreases about four orders of magnitude over the 3 m distance.

Thus primarily thermal columns have been modified to achieve optimal beam characteristics. An existing thermal column is easiest to modify, as was done at FiR-1 [7]. It is possible, although expensive, to cut a large hole in the concrete shield to add an NCT facility as was done at the McClellan TRIGA reactor in California.

In NCT design there is also a need to consider other general reactor design features, such as negative temperature coefficient, cooling, shielding/beam stop, and overall reactor safety, as is the case for any reactor.

Without extensive analysis the effect of the particular type of fuel, moderator, and reflector combination on the NCT beam is difficult to assess. In general, though, the harder the reactor spectrum, the easier it should be to produce the required epithermal beam at the patient location.

There are a number of different types of research reactors that might be considered for NCT, although the author's experience is mainly with TRIGA reactors. [8,9]. TRIGA reactors of several hundred kW or more are generally well suited for NCT. Several TRIGA reactors are currently being (McClellan, Washington State University) or have been previously been (FiR-1) modified for NCT. Several other reactor designs have been proposed, including such diverse features as a dual epithermal and thermal beam [10,11], an eccentric core [12], and a square slab design [13].

## 3. FACILITY MANAGEMENT AND OPERATIONS FACTORS FOR NCT

There are also important operating characteristics that must be considered for an NCT facility. An obvious one is operating hours and scheduling. Availability for NCT may be considerably different than for research. Furthermore, unless it is a dedicated NCT facility, the reactor will need to be available for other research uses beside NCT, such as education, isotope production, and instrumental neutron activation analysis. In this case the NCT facility design cannot displace facilities for other applications. Also worthy of consideration is continuous versus intermittent use. In this regard, can the reactor facility be kept at power while personnel are in the patient treatment room?

A key issue regarding an NCT facility is the definition of responsibility and authority. In the event of an unusual situation, who has the authority to abort the treatment procedure? The best arrangement would be for *both* the principal reactor administrator *and* the physician in charge to each individually have this authority.

Staffing considerations are important, because in addition to the regular reactor staff, there must be a large contingent of medical staff, medical physicists, and other personnel for the NCT set-up and treatment.

Technical co-operation between reactor and medical staff, between technical and non-technical staff, among different technical disciplines, and among international investigators and treatment centers is important for the overall success of NCT.

It is imperative that procedures for normal and abnormal operation conditions, radiological protection, reactor safety, and their associated training be in place. The procedures should be clear and complete step-by-step instructions.

An NCT facility should be located such that patient and medical staff accessibility is not an issue. Often that means a location near a major hospital or medical center with an airport in the vicinity.

## 4. FACILITY RESOURCES FOR NCT

There are facility-related factors to consider for an NCT facility at a reactor. Several of these relate to the physical space required for the NCT facility. Chief among these is a radiotherapy infrastructure, which includes a patient treatment facility with proper accessibility to the beam, accurate patient positioning, calibration and on-line beam monitoring, and patient comfort features. Other considerations are a patient preparation facility, ideally a patient simulation room identical to the patient treatment room, medical laboratories, and patient safety and shielding.

Personnel-related features of the NCT facility include an adequate and qualified medical staff, personnel dose minimization, patient treatment planning, sanitation, emergency response evacuation of patients and medical staff, and communications between reactor operations and medical staff.

An on-line boron (for BNCT) assay system is critical to the operation of an NCT facility, since boron levels in the blood limit the dose that can be given to the patient.

## 5. NON-TECHNICAL FACTORS FOR NCT

There are also non-technical factors to consider, not the least of which is cost (renovation or new construction and also operating costs). Conversion costs for an NCT facility could vary from a few hundred thousand to several million US$. A new reactor specifically designed for NCT could cost from a few million to tens of millions of US$.

The facility must be well maintained and reliably operated. Medical liability issues are a major factor with which most research reactors don't normally have to deal. Public acceptance issues must be considered, as for any nuclear facility being built or undergoing major renovation. An NCT facility will generally require licensing by the appropriate reactor regulatory agency and by the appropriate health regulatory agency. There are also ethical issues associated with NCT, namely in the treatment of human subjects and in the use of laboratory animals for NCT research.

An NCT facility incurs liability factors that are not present for most reactors which are not involved in medical treatment. These factors must be carefully addressed before beginning NCT treatment.

Another strongly required consideration for an NCT facility is the approval and support of the administration under which the reactor facility functions. Consideration for starting a new NCT facility without this support is strongly discouraged.

## 6. CONCLUSIONS

To date NCT therapy has been conducted only in Japan. Clinical trials are currently underway at Brookhaven National Laboratory and Massachusetts Institute of Technology in the United States, at Petten in the Netherlands, and at the Technical Research Centre of Finland. The success of these trials will strongly determine the future of NCT and the need for other NCT treatment facilities.

An NCT facility could be built as part of a comprehensive nuclear medicine center that provides, in addition to NCT, nuclear medicine diagnostic and therapeutic services and palliation treatment, all on an outpatient basis.

Reactor designs have been shown to be adequate to produce the NCT beam characteristics considered essential. There are existing reactors throughout the world that potentially could be converted for NCT. Other factors mentioned in this paper should be considered as factors to be seriously addressed, but not as insurmountable obstacles. The bottom line, if NCT clinical trials prove to be successful, is that for a price reactors can be made available for NCT treatment.

There are four keys to the success of an NCT treatment facility, assuming clinical feasibility is demonstrated. These factors are an adequate neutron beam intensity and quality, necessary finances to construct or convert a facility for NCT, a capable medical staff to perform the NCT, and the administrative support for the facility. The absence of any one of these factors seriously jeopardises the overall success of the facility.

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