The 250 kW FiR 1 TRIGA Research Reactor - International Role in Boron Neutron Capture Therapy (BNCT) and Regional Role in Isotope Production, Education and Training

I. Auterinen, S.E.J. Salmenhaara

VTT Technical Research Centre of Finland, Espoo, Finland

Abstract. The Finnish TRIGA reactor, FiR 1, has been in operation since 1962. From its early days the reactor created versatile research to support both the national nuclear program as well as generally the industry and health care sector. The volume of neutron activation analysis was impressive in the 70's and 80's. In the 1990's a BNCT treatment facility was build at the FiR 1 reactor. The treatment environment is of world top quality after a major renovation of the whole reactor building in 1997. Over one hundred patient irradiations have been performed since May 1999. FiR 1 is one of the few facilities in the world providing this kind of treatments. Due to the BNCT project FiR 1 has become an important research and education unit for medical physics. Education and training play also a role at FiR 1 in the form of university courses and training of nuclear industry personnel. Isotopes for tracer studies are produced normally twice a week. The reactor is operated by four reactor operators and five shift supervisors; this in addition to their work as research scientists or research engineers.

1. INTRODUCTION

The Finnish TRIGA reactor, FiR 1, has been in operation since March 1962. The reactor has been delivered by General Atomics, USA. The reactor belonged first to the Department of Technical Physics at the Helsinki University of Technology. The activities of the reactor were defined as training in nuclear technology, research and production of radioactive isotopes. In 1972 the reactor was transferred under the administration of the Technical Research Centre of Finland (VTT).

From its early days the reactor created versatile research to support both the national nuclear program as well as generally the industry and health care sector. The volume of neutron activation analysis was impressive in the 70's and 80's when the reactor was operated close to daily only for activation analysis. Now other analysis methods have nearly totally replaced neutron activation analysis. In isotope production a small research reactor is competitive only in producing short lived isotopes for local markets. In figure 1. the effect of the nearly total extinction of neutron activation analysis and also production of radiopharmaceuticals by the mid 1990's can bee seen in the total operation hours of the reactor. In recent years the increase in operation hours has come from the industrial tracer isotope production and BNCT.

Boron neutron capture therapy (BNCT) treatments dominate the current utilization of the reactor: two days per week are for BNCT purposes and the rest for other purposes such as isotope production, neutron activation analysis and education/training [1].

FiR 1 reactor has made already now a major contribution in the research and development of BNCT. Internationally important breakthroughs have been achieved in the application of BNCT for cancer treatment[2, 3]. The BNCT facility has been the center of extensive academic research especially in medical physics. In addition to BNCT FiR 1 continues to support research in radiopharmaceutical applications. Education and training play also a role at FiR 1 in the form of university courses and training of nuclear industry personnel.

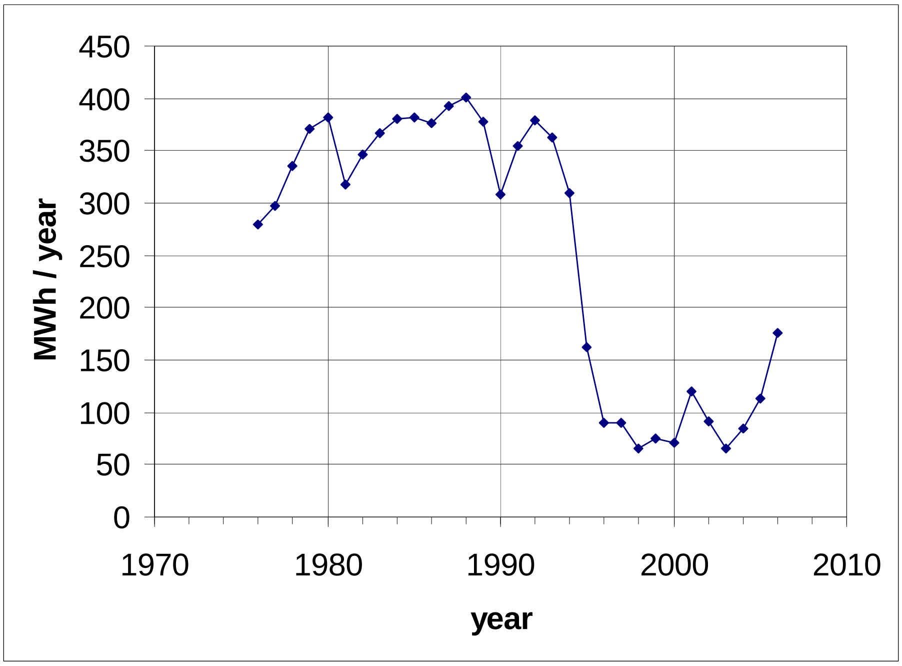

FIG. 1. Yearly production of heat by FiR 1.

2. TECHNICAL CHARACTERISTICS OF FiR 1

FiR 1 is a TRIGA Mark II open tank reactor with graphite reflector.

maximum steady state thermal power	250 kW
maximum pulse power (duration about 30 ms)	250 MW
maximum excess reactivity	4 $
maximum thermal neutron flux	$1.0 \cdot 10^{13}$ n/cm^{2}s

The core consist of about 80 TRIGA fuel elements, four control rods, some graphite elements and irradiation positions:

uranium-zirconium hydride:	8 or 12 weight-% U, rest Zr with 1 weight % H
uranium enrichment:	20 weight-% 235U of the U
core loading:	2.7 kg 235U (13.5 kg U)
fuel element cladding:	0.76 mm aluminium or 0.5 mm stainless steel
dimensions of the active configuration:	355 mm × 435 mm
control rods:	four boron carbide control rods

In order to achieve greater neutron flux the power of the reactor was raised from 100 kW to 250 kW in 1967.

3. BORON NEUTRON CAPTURE THERAPY AND MEDICAL PHYSICS

The main purpose to run the reactor has been lately the Boron Neutron Capture Therapy (BNCT). Boron neutron capture therapy is an experimental radiotherapy used in clinical trials in Europe, Japan and the Americas. In BNCT the highly lethal radiation (α, $^{7}Li^{*}$) released in thermal neutron capture of boron-10 atoms is used. The dose is targeted to the tumour using a boron carrier substance that is selectively taken up by the cancerous tissue.

The principle of epithermal BNCT is that epithermal neutrons have the capability to penetrate deep into the tissue thermalizing at the same time. The thermal neutrons are captured by boron-10 nuclei situated ideally in the tumor cells only and thus the reaction products destroy selectively only the tumor cells. The epithermal neutrons (0.5 eV – 10 keV) needed for the irradiation are produced from the fast fission neutrons by a moderator block consisting of $Al+AlF_3$ (Fluental™) developed and produced by VTT. The material gives excellent beam values both in intensity and quality and enables the use of a small research reactor as a neutron source for BNCT purposes[4].

3.1.The BNCT facility

In the 1990's a BNCT treatment facility was build at the FiR 1 reactor (Fig. 2.). The Fluental™ neutron moderator was installed for the first time in 1996 into the space of the former thermal column. In 1997 part of the biological shield was removed to make space for patient positioning and a collimator was installed for directing the neutrons into the tumor area. A heavy concrete shielded therapy room was built around the irradiation position. The reactor building was renovated to create a treatment environment is of world top quality.

The FiR 1 neutron beam is particularly well suited for BNCT because of its low hydrogen-recoil and incident gamma doses, and its high intensity and penetrating neutron spectrum characteristics[5].

3.2. Clinical trials

Three clinical trials sponsored by the Boneca Corporation are currently running at the FiR 1 BNCT-facility, see [6]. Since May 1999 well over hundred patient irradiations have been performed. The patient have been with glioblastoma, an until now uncurable brain tumour, (protocol P-01), with recurring or progressing glioblastoma following surgery and conventional cranial radiotherapy (protocol P-03) or with histologically confirmed recurrent inoperable head and neck carcinoma after standard external beam radiotherapy (HN-BPA-01-2003 trial). The irradiation procedure typically lasts for about one hour.

The conclusion has been that BPA-based BNCT has been relatively well tolerated both in previously irradiated and unirradiated glioblastoma patients. Efficacy comparisons with conventional photon radiation are difficult to perform due to patient selection and confounding factors such as other treatments given, but the general results support continuation of clinical research on BPA-based BNCT[2].

Recently the Finnish group working at FiR 1 was able to report that most head-and-neck cancers that recur locally after prior full-dose conventional radiation therapy respond to Boron Neutron Capture Therapy (BNCT) [3]. The scientific director of the research program Heikki Joensuu, professor of radiotherapy and oncology at the University of Helsinki, considers the results clinically significant and very interesting [6].

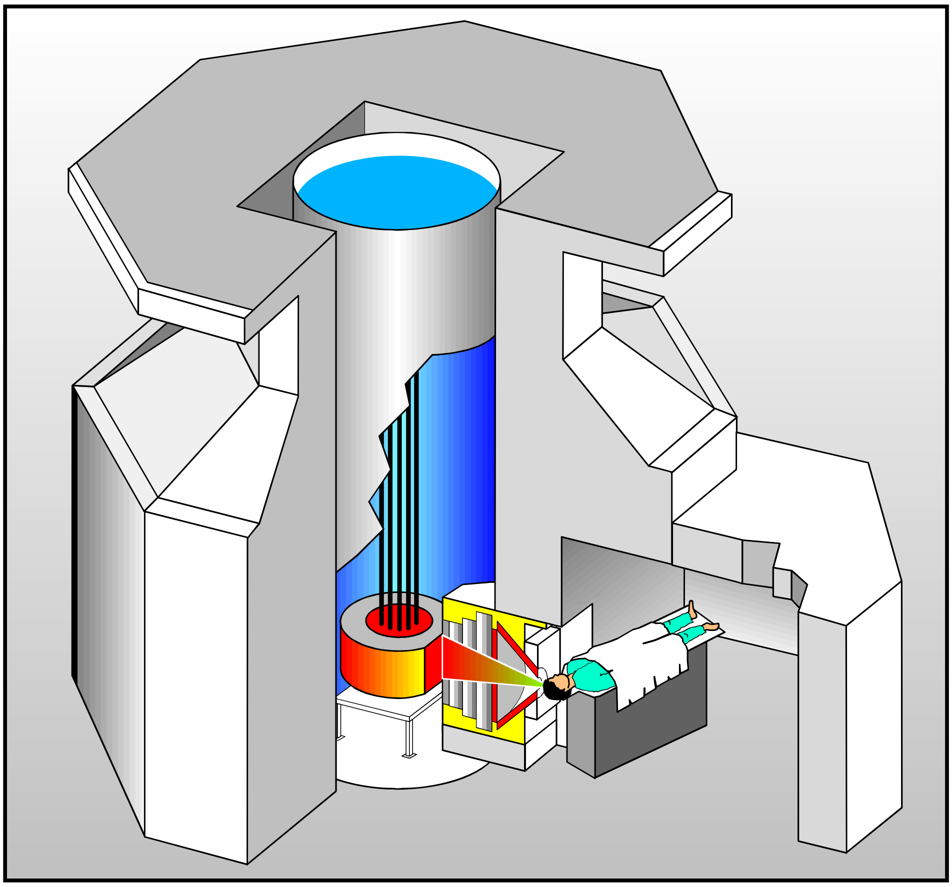

FIG. 2. The BNCT facility at FiR 1 nuclear research reactor. The epithermal (0.5 eV-10 keV) neutron fluence rate is $1.1x10^9$ $n/cm^2/sec$ at the exit plane using a 14 cm diameter collimator at 250 kW power. The undesired fast neutron dose per epithermal fluence is 2 $Gy/10^{13}cm^{-2}$ and the corresponding gamma contamination 0.5 $Gy/10^{13}cm^{-2}$.

3.3.Medical physics research and education

Due to the BNCT project FiR 1 has become an important research and education unit for medical physics. Since the early 1990's several graduate and postgraduate students from the medical physics program of the University of Helsinki have been working at the FiR 1 BNCT facility. In research projects funded by the Finnish Academy, the Finnish Center for Technology Development (Tekes) and EU the dosimetry, radiation transport modelling, treatment planning, prompt-gamma imaging and other medical physics aspects of the BNCT have been studied and developed. Over ten academic theses and dissertations have been produced in these projects, along with over hundred scientific publications. The research has been performed in close international collaboration with European, American as well as Japanese researchers. Also at Helsinki University of technology masters theses works have been made in connection to the BNCT research at FiR 1. The students aiming at the hospital physicist exam credit up to one year of required hands-on experience when working at the FiR 1 BNCT facility.

4. RADIOISOTOPE PRODUCTION

Although the main part of the operating time of the reactor has been reserved for the work at the BNCT irradiation facility there still remains 20% - 40% of the time the possibility to irradiate samples either to produce some short-lived isotopes or to do neutron activation analysis. Typical isotopes for tracer studies in industry produced in the reactor are Na-24, Br-82 and La-140. The tracer studies in industry may be calibrations of liquid or gas flow meters [7]. Tracer studies can be used in many cases also to solve the reason for some disturbance in chemical or other processes. The most popular carriers for Br-82 are either KBr or ethylene bromide. Typical activity of one irradiated Br-sample is 20 - 80 GBq. Total activity produced in one year is 3 TBq (see table 1.).

In the 1980´s FiR 1 had a major role in the Finnish radiopharmaceutical research and development. The spin-off company established at the reactor at that time, MAP Medical Technologies, has been successful but relies now on other sources for its radioisotopes, the accelerator at the Jyväskylä University in central Finland and traditional international isotope producers. Now FiR 1 is utilized by researchers at the University of Helsinki for studying the use of samarium as a tracer in pharmaceutical formulation development.

5. NUCLEAR ENGINEERING EDUCATION AND TRAINING

Education and training play also a role at FiR 1 in the form of university courses and training of nuclear industry personnel. Helsinki University of Technology has a right to use the reactor for its purposes. Yearly there are at least two courses for technical physics and energy technology students in reactor and neutron physics that utilize the reactor and the BNCT facility. Reactor physics demonstrations are also organized for the students of the Lappeenranta Technical University.

FiR 1 is utilized also in the continuing education and training of the personnel at nuclear power companies, both in Finland and in Sweden, and other organisations connected to nuclear power. These are typically one day intensive courses with hands on exercises, or demonstrations and excursions in connection to longer lecture courses.

6. COST OF OPERATION

The reactor is operated by four reactor operators and five shift supervisors. All of them are part time operators or supervisors in addition to their work as research scientists or research engineers. This amount of operators and supervisors ensures that the reactor is easy to keep in operation during normal working hours and also during exceptional hours.

The basic cost for maintenance and operation of the reactor is about 400 000 euros per year, including licensing administration. The operational costs of the reactor are moderate as one operation shift includes only the reactor operator and the shift supervisor. As they are not fully occupied by the reactor operation they are allowed to perform other duties during the reactor shift. With an increasing number of patients more reactor operators have to be involved causing a stepwise increases of the operation costs. The radiation protection has one duty officer. If the demand requires the reactor can be made available for BNCT-treatments from early morning till late evening allowing irradiation of several patients a day. For the moment Mondays and Fridays are reserved for activation analysis and isotope production, on Tuesdays and Thursdays the reactor is reserved for BNCT.

The aim is to cover a substantial part of the reactor costs with the income from the services. For example the income from the production of isotopes is about 20 % of the turnover. Still financial support from VTT-basic funding or other government sources is required.

7. DISCUSSION

FiR 1 reactor has made already now a major contribution in the research and development of BNCT. Significant breakthroughs have been achieved in the application of BNCT for cancer treatment. FiR 1 has an important international role in the development of boron neutron capture therapy for cancer as it is one of the few facilities in the world providing this kind of treatments. The successes in the BNCT development have now created a demand for these treatments, although they are given on an experimental basis. The BNCT facility has been also a center of extensive academic research in medical physics.

The advantages of the TRIGA design for BNCT include large flux-per-Watt feature and inherent safety of the TRIGA fuel. Due to the strong and fast negative temperature coefficient of the reactivity of the TRIGA fuel and easy operation of this type of a relatively low power reactor FiR 1 is a safe neutron source for a clinical BNCT facility. The reactor has a good safety and availability record from 45 operating years.

The FiR 1 reactor has proven to be a reliable neutron source for the BNCT treatments; no patient irradiations have been cancelled because of a malfunction of the reactor. Over one hundred patient irradiations have been performed at FiR 1 since May 1999, when the license for patient treatment was granted to the responsible BNCT treatment organization, Boneca Corporation.

FiR 1 has an important regional role in producing short lived isotopes as well as in education and training as there are only a few research reactors in Scandinavia and the Northern Europe (EU) suitable for these tasks (see figure 3.). The production of isotopes for insdustrial measurements has been growing steadyly in the recent years.

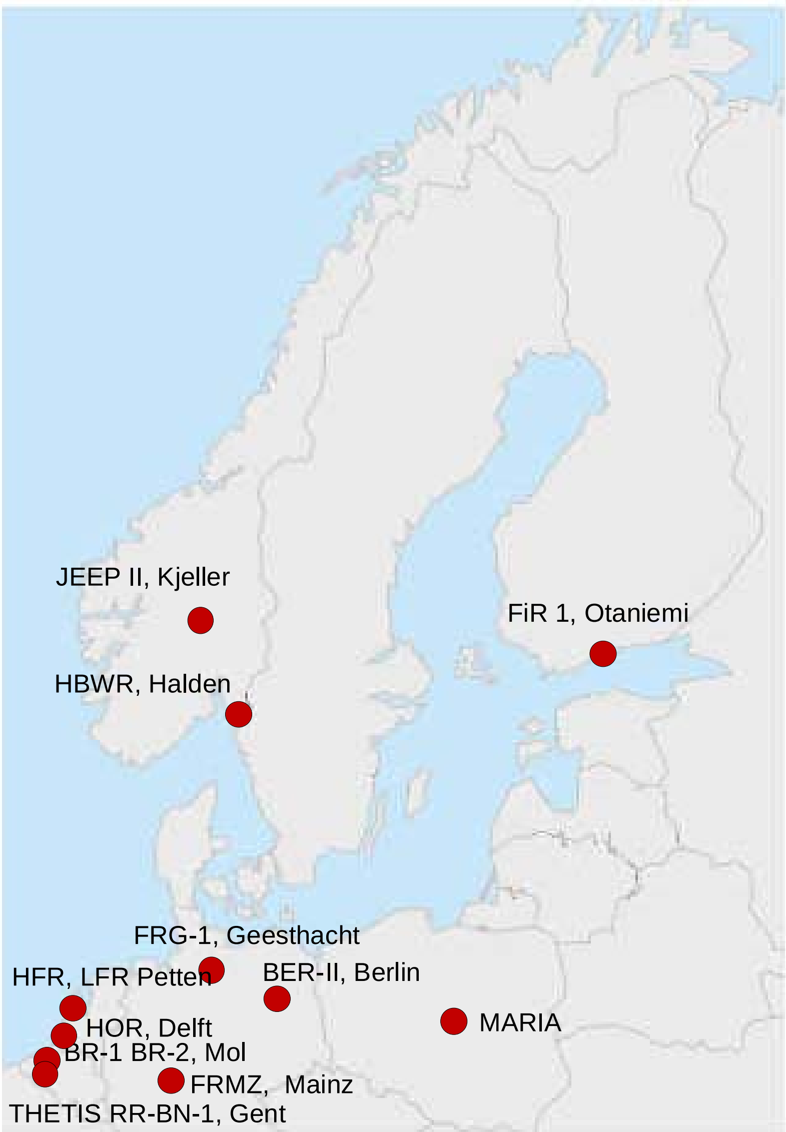

FIG. 3. Research reactors in Scandinavia and the northern European Union.

Table 1. Yearly production figures of FiR 1 with main isotopes produced, use category of the isotopes, number of activation analysis samples and number of BNCT patient irradiations per year.

	1999	2000	2001	2002	2003	2004	2005	2006
	MBq	MBq	MBq	MBq	MBq	MBq	MBq	MBq
Na-24	100 074	20 720	31 450	29 600	8 880	10 730	5 957	125 837
Ar-41	185	296		2 664	55 500			14 800
Cr-51					592		250	300
Cu-64	11		45 740	720	7	170	358	130
Br-82	668 960	732 915	878 565	1 831 500	1 531 800	1 554 000	2 738 000	2 863 800
Ru-103	37						15 540	49 136
La-140	23 680	7 400	16 650	74 000		55 500	6 290	15 207
Sm-153			1 221	1 184	307	28	2 130	
Au-198		3 182	1 110	1 110	8	9	4 451	12
own use	103 803	19 595	4 929	6 705	3 441	25 160	26 048	201 132
science	26	0	1 110	120	603	183	286	441
industry	692 640	748 566	978 576	1 942 944	1 596 491	1 619 888	2 756 447	2 900 134
hospitals	0	0	0	0	0	0	0	0
TOTAL	796 469	768 161	984 615	1 949 769	1 600 535	1 645 231	2 782 781	3 101 707
	pcs	pcs	pcs	pcs	pcs	pcs	pcs	pcs
activation analysis samples	481	738	750	367	240	336	123	312
BNCT-irradiations	7	5	9	0	8	17	38	26

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