FOUR YEARS OF OPERATING EXPERIENCE WITH THE HARPER HOSPITAL SUPERCONDUCTING CYCLOTRON FOR NEUTRON RADIATION THERAPY

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Routine patient treatment commenced at the Harper Hospital superconducting cyclotron neutron therapy facility in March 1992. During the second year of operation the facility was available for 80.8% of the scheduled time, while in the third year availability was 91.6%, and so far in the fourth year (March-September) it has averaged 92.7%; strategies for further improving performance will be discussed. The paper also reviews problems peculiar to the operation of the superconducting cyclotron in a hospital environment together with plans to implement a continuous flow helium system to replace the daily batch fill system presently in use; such a system would increase the machine availability from 16 to 24 hours/day. Many patient treatments are planned using 3D techniques with non-coplanar beams. Such treatments are time intensive during patient set-up which results in radiotherapists (i.e. technologists, radiographers) receiving relatively high occupational exposures.

1. Introduction

The Harper Hospital superconducting cyclotron was built at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University under the direction of Henry Blosser. The original project was conceived in 1981 by William E. Powers, then Chair of Radiation Oncology at Harper Hospital and Wayne State University. The cyclotron was installed in Harper Hospital in July 1990 and the first patient was treated in September 1991.

The characteristics of the cyclotron have been described in detail elsewhere.[1,2] The clinical characteristic of the neutron beam have been described by Maughan and Yudelev[3] and a detailed description of the unique multirod collimator used in this facility has been given by Maughan *et al.*[4]

In the present paper, the first four years of clinical operating experience are discussed, with particular reference to the patient load and accelerator reliability. A detailed analysis of the causes of machine downtime is given and strategies for improving reliability and availability of the facility are discussed. The cryogenic system is of particular interest in this regard, since the present mode of operation which involves filling the magnet cryostat with liquid helium once a day only permits the cyclotron to be used between 08:00h and 24:00h(16 hours per day).

Another important aspect of neutron radiation therapy is the radiation exposure received by the therapy staff who set-up the patients for treatment. The exposures received by therapists at the Harper Hospital Neutron Therapy Facility are reported and compared to the levels of exposure reported by other institutions.

2. Patient Load and Downtime

After the initial treatment of several patients in September 1991, there was a break in treatments for collimator development until March 1992, when a full-time program of neutron therapy started in the facility. For this reason the data presented here are for periods of one year running from March thru February. Table 1 is a summary of the number of treatment sessions delivered and fields treated since March 1992. During this period, the accelerator has been available for treatment from 08:00h to 18:00h Monday thru Friday, with one hour scheduled for lunch.

Since January 1993 detailed records of machine failure have been kept. At the time of failure the therapist logs the machine as being down and does not re-enter the machine as being available until patient treatments recommence. Hence, the downtime during the scheduled working day is logged. The

Table 1 : Summary of operating statistics, March 1992 - September 1995.

YEAR	TREATMENT SESSIONS PER DAY	FIELDS TREATED PER DAY	% AVAILABILITY	% UTILITY
1992 - 1993	1.18	2.80	N/A	13.1
1993 - 1994	5.54	15.3	80.8	60.4
1994 - 1995	4.47	13.7	91.6	49.5
1995 - 1996*	6.20	22.9	92.7	68.9

* March - September, 1995.

availability is then expressed as a percentage of the total allocated patient treatment time (i.e. 9 hours per day) for which the machine is available for treatment. The machine utilization is expressed as the percent of scheduled one hour treatment sessions which are filled (i.e. a maximum of nine treatment sessions per day). Table 1 also lists the machine availability for each year since March 1993 and utilization since March 1992.

Table 2 is a summary of the total hours of downtime from March 1993 to September 1995 listed by the type of failure. The major item (23.4%) is a water leak problem which occurred in the vacuum chamber of the cyclotron. A water cooling pipe in the RF cavity which was damaged during manufacture developed a pin hole leak, the initial repair was inadequate causing a second failure which filled the vacuum cavity with water. Although repairs were completed within 48 hours in each case, 2 to 3 weeks were required to pump water vapor from the acceleration chamber. This mode of failure is regarded as an unusual occurrence and not the type of problem that might result from normal wear and tear of components. The next six causes of failure in Table 2, which are more likely to be the result of normal wear and tear account for 61.4% of the total downtime (or 80% if the water leak problem is excluded).

RF failures are a major contributor (17.1%); the fact that the RF-transmitter is a 105 MHZ commercial radio station unit has been useful since parts are readily available at short notice and advice is available 24 hours a day, seven days a week. We have also routinely used consultants from the NSCL to assist with RF problems. The magnet and the associated cryogenic system is also a major source of downtime (93.6 hours, in 31 months, 12.8% of the total). Initially a considerable amount of time was lost due to magnet quenches; the magnet/cryogenic control system has been upgraded to avoid such quenches and in the last 12 months of operation (Oct. 1994 - Sept. 1995) only 11 hours of downtime is attributed to magnet/cryogenic causes. During the early months of operation inexperience accounted for many of the problems and operator error was not uncommon (82.2 hours in 36 months, 11.2% of total). Many of these errors were associated with operation of the cryogenic system. Operator errors no longer contribute significantly to the downtime (3.1 hours in past 12 months, 2.2%). The other major source of problems is the multi-rod collimator; of the 64.7 hours of downtime nearly half (30.3 hours) have occurred in the last seven months. A recent major overhaul has resulted in improved performance and highlighted the need for more preventive maintenance.

Table 2 : Summary of downtime, March 1993 - September 1995

CAUSE	% OF DOWNTIME	HOURS
WATER LEAK PROBLEM	23.35	171.0
RF SYSTEM	17.07	125.0
MAGNET/ CRYOGENICS	12.78	93.6
OPERATOR ERROR	11.22	82.2
COLLIMATOR	8.83	64.7
SOURCE	5.94	43.5
THERAPY CONSOLE	5.68	41.6
UNSPECIFIED	4.03	29.5
X RAY SET	2.79	20.5
HYDRAULIC DOOR	2.39	17.5
POWER FAILURE	1.97	14.4
VACUUM	1.51	11.1
MISCELLANEOUS	2.44	17.9
TOTAL	100.00	732.5

Table 1 shows that over the three year period machine downtime is improving. Anticipating potential problems has not always been easy, but often when problems do arise, preventive maintenance proves to be effective. Maintaining an adequate spare parts inventory has also proved effective in minimizing downtime. The relative simplicity of the superconducting cyclotron makes it possible to keep many major spare components at a moderate expense. Such items include a spare magnet power supply, ion source power supply, gantry drive motor and turbo-molecular pumps. The main RF tube is interchanged every six montsh with the spare tube; 105 MHz RF tubes are available immediately and can be shipped overnight. For the NSCL custom-made electronics modules we are building spare direct replacement modules. The ion source and target assemblies are retractable through vacuum locks and spare assemblies are at present under construction.

Another important contribution to minimizing downtime has been the introduction of 24 hour alarms on certain key systems (beam chamber vacuum, cryostat vacuum, single and three phase power); the alarms sound in the hospital security office and personnel are immediately informed of faults.

3. Cryogenic System

A detailed description of the cryogenic system has been published elsewhere[5]. A major limitation on the availability of the superconducting cyclotron is the "batch-fill" mode of operation used in maintaining the magnet coil at liquid helium temperatures. The coil is filled once a day (at ~ 05:30h) with approximately 75 liters of liquid helium to be ready for patient treeatment by 08:00h. This volume liquid is sufficient to allow machine operation until about 24:00h, when the level in the cryostat is so low that there is a risk of the magnet quenching in some orientations. Twenty-four hour availability of the cyclotron could be achieved by using a "continuous flow" method for supplying the cryogen. One limitation which has prevented previous serious consideration of this option has been the poor

Table 3 : The liquefier manufacturers' performance specifications for the liquefaction of pure helium gas.

COMPRESSOR TYPE	# OF COMPRESSORS	LIQUEFACTION RATE liters per hour			
		LN_2 PRECOOL		NO PRECOOL	
		60 Hz	50 Hz	60 Hz	50 Hz
Reciprocating compressor	1	12	22	6	6
"	2	26	22	12	10
"	3	34	28	15	15
Screw compressor	1	40	34	15	15

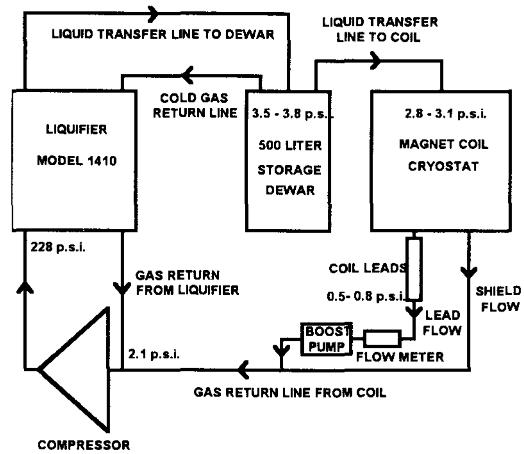
performance of the helium liquifier system. However, in Janaury 1995 after a major rebuild and system decontamination the system performed to its specification for the first time (Table 3). Even under these conditions liquefaction capacity is limited because of the need to maintain a low return line pressure (0.5 psi) to the compressor, in order to ensure sufficient cold gas flow thru the magnet leads in the cryostat. The normal and superconducting sections of the magnet power leads have insufficient overlap in this region and require cooling in order to avoid a magnet quench. Table 4 shows the liquifier performance with reduced return line (input) pressure at the compressors. Another problem is the large liquid helium losses in the present transfer line.

In July 1995 we performed a test to establish the feasibility of continuous flow operation. In order to boost the return line pressure to 2 psi while still maintaining adequate lead flow a small pump was installed in the lead flow line as shown in Figure 1. The liquefier was operated with two compressors and liquid nitrogen precool in which condition it can produce 22-24 liters per hour of liquid helium. The conditions for this test are shown in Fig. 1. By carefully adjusting the liquefier operating conditions

Table 4. Performance of the liquefier as a function of return line (compressor input) pressure.

# of Compressors	Return Line Pressure p.s.i.	Supply Pressure p.s.i.	Engine Speed r.p.m.	Liquefaction Rate liters/hour
1	0.5	195	80	3.5
1	2.0	211	95	5
2	0.7	218	185	7 - 9
2	1.8	222	220	10 - 14

Fig. 1 : Cryogenic system operating pressures during the continuous liquid helium flow test in July 1995.



it was possible to fill the cryostat with approximately 75 liters of helium and to maintain this level at a steady value. The pressures in the 500 liter liquid storage vessel, the cryostat coil and the return line in the steady condition are indicated in Fig 1. The level in the storage vessel remained approximately constant indicating that the full 22-24 liter/hour capacity of the liquefier was required to maintain this situation. In normal operating conditions (batch fill) liquid evaporates from the cryostat at a rate of approximately 2.5 liters per hour. This suggests that the liquid losses attributable to the transfer line are ~ 19-22 liters per hour. This is far in excess of the 2.5 to 4 liters per hour (10 to 15 W) specified for some commercially available helium lines.

Once a steady condition had been established and maintained for approximately one hour the next phase of the test was to rotate the cyclotron. The normal maintenance and fill position of the cyclotron is designated as 270^0. The cyclotron was rotated in the clockwise direction thru 0^0 and 90^0 to 180^0, and then returned to the 270^0 position. The result of the rotation was to set up a siphon action in the cryostat (~ 30-40 liters per hour) which resulted from the coil pressure rise which occurs during rotation. Attempts to stop the siphon were inconclusive, but the siphon action eventually stopped after approximately 15 liters of liquid had been lost. Repeated rotation tests showed that the liquid loss due to the siphon action decreased as the level of liquid in the cryostat was reduced. Eventually with liquid levels below about 40 liters the liquid losses during a 540^0 rotation were about three liters with, no evidence of a sustained siphon at the end of rotation. A rotation of 540^0 is typical of what might be expected in one hour on a typical treatment day.

These tests indicate that it would be feasible to establish a continuous flow mode of operation for the cryostat, with the existing system although the present liquefying capacity (24 liters/hr max.) is marginal. This could be overcome by (1) improving the transfer line to reduce losses and/or (2) installing an additional reciprocating compressor or replacing the existing two compressors with a single screw compressor. The need for liquid nitrogen pre-cooling depends on how much the liquidhelium requirements could be reduced by installation of an improved helium transfer line between the helium storage dewar and the coil cryostat.

4. Therapists' Exposure.

Detailed records of the exposure of radiotherapists (radiation therapy technologists, radiographers) , engineers and physicists have been kept since the start of the program. Not only are staff issued film badges which are processed by a commercial dose monitoring organization, but they also wear electronic dosimeters with instantaneous dose read outs. In this way the exposures received by all personnel can be monitored and recorded on a daily basis.

The radiation exposure received by the radiotherapists can best be expressed in terms of the exposure per therapist per field treated. At the end of each day the therapists record the total exposure received during the day and the total number of fields they have treated. Between January 1993 and May 1995 the average exposure per therapist per field was 8.0 μSv (0.8 mRem). This figure is somewhat higher than the 5 μSv value reported by several other institutions [6,7] and the 4 μSv per field reported by Risler *et al* [8] at the University of Washington. This later value is estimated to be ~2 μSv per therapist per field, since at any time two therapists are sharing the dose per field.

In order to reduce the therapist dose, arrangements have been made which allow the gantry and collimator to be rotated from outside the room. Storage for the polystyrene blocks used in the multirod collimator has also been moved outside the treatment room. These changes have lead to a reduction in the exposure to ~6 μSv per therapist per field in recent months. The greater exposures in the Harper facility may be attributed to several sources. These include:

(1) the use of a steel counterweight / beam stop on the cyclotron gantry, which intercepts the beam in relatively close proximity to the isocenter (2m).

(2) The use of a gantry mounted x ray set for producing port films of the patient. This x ray set is mounted at an angle of 60^0relative to the neutron beam axis and a double exposure technique is used to produce an x ray image of the patient anatomy and a neutron image of the collimator field shape. This process is time consuming.

(3) Many of the patient set-ups involve complex field arrangements, such as non-coplanar beams which are also time consuming. Most of the prostate patients (which represent 65 - 75 % of patients treated) require complex field set ups.

There are 24 radiotherapists in the Gershenson Radiation Oncology Center at Harper Hospital and they rotate through all the treatment machines in the department (1 cyclotron and 4 linacs). It is only during the neutron therapy rotation that we expect the therapists to receive measurable exposures. Since many of the therapists are young women of childbearing age a major concern is potential fetal exposure. In the U.S.A. the National Council on Radiation Protection and Measurements (NCRP) recommends, " a monthly equivalent dose limit of 0.5 mSv (50 mRem) to the embryo-fetus (excluding medical and natural background radiation) once the pregnancy is known." [9] This translates into 5 mSv (500 mRem) limit during the whole of the gestation period. In order to conform with this recommendation no therapist who is known to be pregnant is assigned to work on the cyclotron and no therapists are allowed to accumulate a dose in excess of 5 mSv (500 mRem) during an assignment. At the present load level we expect each therapist to rotate through the cyclotron approximately twice in a three year period which would give an average annual exposure of 3.33 mSv (333 mRem) per therapist over the three year period. At maximum load we would expect this to rise to 5 mSv (500 mRem) per annum.

5. Conclusions.

The superconducting cyclotron at Harper Hospital has proved to be a reliable source of fast neutrons for radiation therapy. To further improve the availability of the accelerator for clinical and research applications it would be advantageous to develop a continuous liquid helium system. Such a system would permit 24 hour use of the facility. Tests have shown that such a system is feasible. The therapist exposure levels experienced in this facility are a little higher than those experienced in most other facilities (by ~20%). However, these levels are still much below the maximum permissible dose level of 50 mSv (5 rem..).

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