Recycling and Recommissioning a Used Biomedical Cyclotron

L. R. Carroll and F. Ramsey
Carroll & Ramsey Associates
J. Armbruster
International Isotopes, Inc.
M. Montenero
Electronic Visions, Inc.

Abstract

Biomedical Cyclotrons have a very long life, but there eventually comes a time when any piece of equipment has to be retired from service. From time to time, we have the opportunity to help find new homes for used cyclotrons which, with relatively modest overhaul and refurbishment, can have many additional years of productive service, and thus represent a very valuable asset.

The reasons for retiring a cyclotron vary, of course, but in our experience it is often due to an institution's changing priorities or changing needs, rather than due to any fundamental age-related deficiency in the cyclotron itself. In this paper we'll report on the relocation and successful restoration of a used TCC CP-42 cyclotron, which was moved from M.D. Anderson Hospital in Houston to Denton, Texas in early 1998, where it is presently being used for R&D and commercial production of biomedical isotopes. Ownership of the machine has been transferred to the University of North Texas; facility, manpower, and operational resources are provided by International Isotopes, Inc.

ORIGINAL MOTIVATION AND GENESIS OF THE CP-42 CYCLOTRON

In a traditional, positive-ion cyclotron – exemplified by the CS-series of machines once built by The Cyclotron Corporation (TCC) of Berkeley, CA -- extraction of the beam is accomplished by means of an electrostatic channel. Inevitable beam loss at the entrance to the extraction channel, and consequent localized heating of extraction system components limits the amount of external beam that can be safely and reliably utilized.

Efficient, commercial-scale production of biomedical isotopes demands very high beam currents – much higher than can be easily extracted from a positive-ion cyclotron. Since *internal* (+) ion beam currents of the order of 100's of μA are easily achieved, commercial radiopharmaceutical producers often utilize internal targets, thus obviating the need to extract the beam.

However, operation of high-current internal targets carries a substantial price in that the cyclotron itself is subject to an intense, damaging neutron flux which can eventually lead to failure of major system components, as well as high-level, persistent, neutron-induced activation of the several tons of steel and copper comprising the main magnet. Neutron-induced activation also leads to persistent high levels of radiation in and around the cyclotron, making service and maintenance highly problematic.

Negative-ion Acceleration and Extraction

The initial concept and design of the CP-42 cyclotron was motivated largely by a desire to provide high beam current on targets which are external to -- and at a substantial distance from – the cyclotron itself, thereby mitigating the activation problems. This was accomplished by accelerating negative hydrogen (H-) ions and extracting the beam by means of charge-exchange in a thin foil. Utilizing this technique, an extraction efficiency of nearly 100% is achieved. Thus, the CP-42 was rated for an external proton beam current of 200 μA. over a range of energies from 10 MeV to 42 Mev, extracted from one of 9 separate beam ports.

In the early 1980's, TCC built five CP-42's: Four were intended for commercial-scale production of radiopharmaceuticals; one of the CP-42's was sold to the M. D. Anderson Hospital in Houston, TX for use in fast-neutron therapy for the treatment of cancer, funded by a research grant from the U. S. National Cancer Institute.

The Demise of TCC

Unfortunately, the scale and magnitude of the CP-42 development project severely strained the financial resources of the Cyclotron Corporation. The company went bankrupt in 1983, leaving all of the CP-42 installations in a state of partial completion. Fortunately, the projects were indemnified by an insurance company which immediately stepped forward to retain the pool of TCC technical personnel. One commercial customer elected to take a cash settlement instead of completing their project. That machine was subsequently shipped to Argentina and rebuilt under the supervision of the Cyclotron Group at KFK Karlsruhe. All of the other installations were eventually completed and accepted. All of the commercial CP-42 cyclotron installations are still operating to this day.

The CP-42 at Houston was intended primarily as a tool for the treatment of cancer using fast neutrons. In time, however, the outcome of clinical trials demonstrated results which were not substantially better than those achieved by well-managed photon therapy. Interest in the use of neutron therapy by researchers and funding agencies waned .....

In the 1980's positron-emission tomography (PET) began to emerge as an essential tool for biomedical research, with significant potential as a clinically-useful diagnostic imaging modality. During this period the Houston CP-42 had also been used for the production of PET / biomedical isotopes. Unfortunately, the CP-42 was just too big and expensive a machine to operate for cost-effective, hospital-based PET, and was eventually shut down and moth-balled.

TRANSFER OF OWNERSHIP

The administration at M.D. Anderson Hospital were looking for a way to remove the CP-42 from the premises, since the now-idle cyclotron was taking up valuable space in the hospital. They arranged for a transfer of ownership to another institution in the University of Texas System -- the University of North Texas (UNT) at Denton. Facility, manpower, and operational resources were to be supplied by International Isotopes, Inc. (I^3), a new start-up Company just entering the Radioisotope and radiopharmaceutical production business, who would be leasing the CP-42 system from the university. In the fall of 1997, Carroll & Ramsey Associates (CRA) were contacted by Dr. Joe Beaver, vice President for System Development at I^3.

CRA was asked to provide technical assistance and project supervision for dismantling the Houston CP-42 and moving it to the I^3 facilities in Denton, as well as helping to rebuild and re-commission the machine. The intention was to utilize the cyclotron for targetry and process development and validation while the primary accelerator facility at I^3 – the former injector Linac from the recently-canceled Super-Conducting Super-Collider Project -- was being refurbished and upgraded to adapt and "ruggedize" the injector Linac for eventual high-duty-cycle commercial service as I^3' s main isotope-producing accelerator.

The process of dismantling and moving the CP-42 was initiated under the direction of Mr. Robert Wetzel, senior project manager at I^3. We first conducted a careful review and reconnaissance of the M.D. Anderson facility with consideration for heavy lifting, maneuvering in close quarters, access, floor loadings, etc. A walk-through and planning session with the owners, riggers, and I^3 personnel was conducted in the weeks prior to the actual move.

Dismantling and loading the CP-42 onto five trucks required 10 days. A crane was brought in for 3 days to lift the cyclotron, power supplies and ancillary equip-ment from the basement through an access hatch-way in an adjoining parking lot with relatively minor disruption to the everyday hospital routine.

RE-ASSEMBLY AND SYSTEM TEST

When the CP-42 arrived at the I^3 facility in Denton, the vault intended to house the cyclotron hadn't yet been built, so the machine was assembled on the floor of a warehouse in order to evaluate and repair – as needed – all of the power supplies, mechanical subsystems, vacuum system, RF system, etc.

Since the Cyclotron Corporation had long-since gone bankrupt, the former owners of the CP-42 may have felt (albeit incorrectly) that they had nowhere to turn for outside technical assistance. During the previous years of service at M.D. Anderson there had been many ad hoc field changes and "repairs" which were well-intentioned, but not always optimum in their implementation. However, as a matter of CRA company policy, we proceeded under the premise that – with certain very specific exceptions – the original design concept of the CP-42 was sound, and that our primary goal would be to repair worn or damaged parts, and to restore the system to as close to the original factory configuration as possible.

The major exceptions were: 1) implementation of an improved high-voltage Dee insulator design; 2) changes to the ion-source water-cooling concept plus changes in various other aspects of the mechanical assembly and alignment of the ion source, and 3) a complete revision and replacement of the computer-aided operator-control interface, including substitution of a PC - based control console for the original DEC Model PDP-1103 computer, substitution of PLC's and other off-the-shelf components (such as stepper-motor control cards, etc.) for the original TCC-designed subsystem control modules.

Overhaul of Major System Components

The magnet and vacuum tank were dis-assembled in order to clean and polish all the O-ring surfaces which form the main vacuum seal between the upper and lower pole base and pole-tip plates. This required removal of the magnet hills, the vacuum tank, pole tip plates, plus the upper magnet coil, since that is held in place by the upper pole-tip plate and the upper portion of the vacuum tank. (The lower coil could stay in place.)

All four of the Varian VHS-10 vacuum diffusion pumps were overhauled and rebuilt using Vendor-supplied repair kits. Major repairs and replacement of worn parts were also implemented on the mechanical backing pumps. After refurbishment, repairs, and final leak-checking were completed, a base pressure in the 10^{-7} torr range was achieved.

All of the major power supplies and systems were 'stripped to the bone' to check for loose or corroded electrical wiring connections as well as any leaks in plumbing connections.

New Control System

By the time the system was decommissioned at M. D. Anderson Hospital, it had not been run for several years. The documentation was in disarray and many sections were missing. The control computer system had been modified from the original PDP 1103 system supplied by TCC and, although the computer system was still functional, the source and support disks were not readable. Inability to modify the control system for the new installation essentially rendered it useless.

When the CP-42 arrived in Denton the basic vacuum control system, comprising a control panel and a Texas Instruments "5TI" programmed-logic controller was quickly reassembled and placed into operation to maintain vacuum until a new control system concept was devised.

The control requirements were evaluated along with the existing system hardware components. The original PDP 1103 computer had already been replaced by an ensemble of microcomputers, but most of the original proprietary TCC distributed control bus was still in use. 5TI PLC's were still being used throughout the system for interlocking functions and vacuum controls.

It was decided that the new system would use a standard personal computer (PC) with LabView^{tm} as the graphical user interface. This would allow reasonable ease of programming and interfacing with other hardware. Moreover, I^3 was already using LabView for various other laboratory and control applications, so this would help maintain a degree of standardization and uniformity within the company.

Due to unavailability of parts, the 5TI PLC's were replaced with contemporary Modicon^{tm} PLC's linked to the PC with Modbus Plus^{tm} communications. The new PLC's would handle the interlocking functions, and also provide most of the I/O for LabView. Additional I/O cards were installed in the PC for interfacing to the control encoder knobs, beam current monitoring and Beam-line power supply control and monitoring.

In the Main Magnet supply, only the closed loop analog portion of the controls was re-used. A PLC was used to provide all control and monitoring signals. Another PLC was used for miscellaneous interlocks, beam-line interlocks and controls, variable extractor controls, and harmonic coil controls. Additional PLC's were used for a redundant Personnel Access and Safety System and for Target Transfer and Handling controls. The Magnet Supply itself was taken apart, components inspected and tested, and then reassembled. It was then connected to the Magnet and tested on the warehouse floor prior to permanent installation in the new facility. The Anode Power Supply and Ion Source Supply were treated in a similar manner, but could not be fully tested until all the systems were installed in an acceptable climate-controlled environment. After initial overhaul and after lengthy and thorough operational testing, the original power supplies (main magnet, RF, and ion source) have proven to be sound.

Only one major failure occurred -- a high-voltage line-isolation transformer in the RF power supply shorted out. Fortunately, a vendor was found who was able to re-build the transformer on a priority schedule. Most other problems were mechanical in nature such as worn motor gearing, control linkages, etc. Other problems occurred in the initial start-up of the RF system, but these proved to be largely due to lack of good environmental controls while construction of the facility was still underway. Once the room temperature and -- most importantly -- the humidity were brought under control, the system has been operating very reliably.

Vault Design and Construction

While repairs to the CP-42 were underway, designs for the vault were evaluated . After weighing the overall costs, advantages, and disadvantages of various designs against the mission at hand (this being intended more as a tool for "R&D" rather than a dedicated "production" facility), I^3 chose to build a single, large room to house the cyclotron, beamlines, and targets. Based upon the intended target products and estimated beam currents, it was determined that a wall thickness of six feet and a roof thickness of four feet would be sufficient to reduce the radiation fields outside the vault to less than 0.5 mR/hr in any uncontrolled area. It was also planned that supplementary shielding would be installed directly around the target stations to further reduce radiation fields. In any case, radiation measurements would be performed under actual operating conditions to verify that the shielding was sufficient and, if necessary, additional shielding would be installed.

The partially re-built CP-42 was then moved into place and the vault built around it. The inner wall of the vault was assembled using traditional wood frame construction techniques. In addition, polyethylene beads were placed between the wall studs to enhance neutron shielding. After pouring a concrete footer, the 6 ft. thick main shielding walls were constructed by dry-stacking concrete blocks. An interlocking pattern was used to help assure that there were no direct seams through the wall. The vault roof was constructed using "Glue Lam" beams, each 10 ½" X 24 ¾" X 34 ft. place on 18" centers over ¾" plywood sheets. Polyethylene beads were also placed between the roof beams to enhance neutron shielding. Concrete blocks were then stacked on top of the roof platform using an interlocking pattern. All penetrations (ducts, wire-ways, etc.) through the shield wall were constructed to eliminate line-of-sight paths. Inside the accelerator vault, all of the power and control cabling, plus hoses and plumbing for system cooling, were installed under a raised "computer" floor. A maze -- also constructed of concrete block -- provides access to the interior of the vault. The final "trimming" of the maze was established from radiation measurements during initial operation of the CP-42. All entrances to the vault and maze are controlled with the Personal Access Safety System (PASS).

OPERATIONAL RESULTS

First internal beam was achieved on October 22, 1998, approximately one year after the initial contact between I^3 and CRA, and approximately 8 months after arrival of the CP-42 at the Denton Facility. The first target irradiation was on Feb. 12, 1999. Target runs are now done routinely -- "on demand" -- to meet the needs of the radio-chemistry department. Until additional system upgrades are implemented, and until certain critical back-up spare parts fabricated or procured, beam currents are normally limited to 100 uA, with occasional excursions to higher levels.

The first product was to be ^{201}Pb / ^{201}Tl, so the first extractor and beamline were positioned for a nominal 28 MeV, based on equilibrium orbit data derived from original magnetic field measurements done at the factory. The final position for the extractor (a fixed "pop-up" extractor) was determined experimentally by measuring the energy of the extracted beam using the stacked foil method. Construction of a thallium target had proceeded concurrently with the project of rebuilding of the CP-42. Once the correct position for the extractor was found, the beam exit angle was established and the beamline and its target station fixed in place.

Next came rebuilding and installation of the Variable-Energy Extractor (VEA) and its beamline. This required a great deal of careful mechanical assembly, alignment, and testing to insure smooth and repeatable operation. A data base of extractor locations versus energy was developed from equilibrium orbit data. Once the VEA and its beamline were in place, beams of various energies (15, 18, 20, and 30 MeV) were extracted to a probe in the "Combo" steering magnet on the exit of the accelerator. Beams of 15 and 18 MeV were also transported to a beam-stop at the end the beamline. Two additional beamlines (16 and 18 MeV) were subsequently installed and are currently in use for isotope production. In calendar 1999, the CP-42 was operated for 16,161 uA-hours in 65 separate runs. In calendar 2000, the CP-42 has been operated (as of Nov 1, 2000) for 24,251 uA-hours in 136 separate target runs.

Acknowledgment

In addition to those named previously, we wish to acknowledge the invaluable help and encouragement from I^3 senior staff and, in particular, Dr. Homer Hupf.

Postscript

According to information just made public, as of November 15, 2000, International Isotopes, Inc., has ceased operations on their Linear Accelerator. That machine has been shut down and staff have been let go. At this time, I^3 is actively seeking a buyer for the linear accelerator and its facility.

The CP-42 cyclotron is still being operated for research and production purposes, and is producing various products such as ^{18}F, ^{123}I and ^{201}Tl.