COST / BENEFIT COMPARISON

FOR

45 MEV AND 70 MEV CYCLOTRONS

MAY 26, 2005

Conducted for:

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Office of Nuclear Energy, Science, and Technology
Office of Nuclear Facilities Management
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TABLE OF CONTENTS

EXECUTIVE SUMMARY

A cost/benefit study was conducted by *JUPITER* Corporation to compare acquisition and operating costs for a 45 MeV and 70 MeV negative ion cyclotron to be used by the Department of Energy in the production of medical radioisotopes. The study utilized available information from Brookhaven National Laboratory (BNL) in New York and from the University of Nantes in France, since both organizations have proposed the acquisition of a 70 MeV cyclotron. Cost information obtained from a vendor, Advanced Cyclotron Systems, pertained only to their 30 MeV cyclotron. However, scaling factors were developed to enable a conversion of this information for generation of costs for the higher energy accelerators.

Two credible cyclotron vendors (IBA Technology Group in Belgium and Advanced Cyclotron Systems, Inc. In Canada) were identified that have both the interest and capability to produce a 45 MeV or 70 MeV cyclotron operating at a beam current of 2 mA (milliamperes).

The results of our analysis of design costs, cyclotron fabrication costs, and beamline costs (excluding building construction costs) resulted in total acquisition costs of:

- $14.8M for the 45 MeV cyclotron, and
- $17.0M for the 70 MeV cyclotron.

Annual operating cost estimates for a 70 MeV cyclotron ranged between $1.9M and $1.1M; the large uncertainty is due to the lack of specificity in available data in comparing costs from BNL and the University of Nantes.

Overall power requirements (exclusive of facility heating and air conditioning) were estimated to be:

- 560 kW for the 45 MeV cyclotron, and
- 831 kW for the 70 MeV cyclotron.

Operational lifetime is expected to be in excess of 30 years for the main components of the accelerator.

Considerable scientific and economic benefits are gained in using the 70 MeV cyclotron compared to use of the 45 MeV cyclotron in terms of the variety and quantity of isotopes that can be produced. Selected examples of benefits in isotope production are discussed.

1. INTRODUCTION

1.1 Purpose and Scope

The Department of Energy's (DOE) Office of Nuclear Energy, Science, and Technology (NE) asked *JUPITER* Corporation (*JUPITER*) to conduct a cost comparison between 45 MeV and 70 MeV negative ion (H^-) cyclotrons to help support an NE decision on the potential purchase of an accelerator for the production of medical radioisotopes. We have conducted a survey of accelerator manufacturers and communicated with knowledgeable persons in the technical community to determine which vendors have the interest and capability to bid on such a machine. We have also developed some cost information and its bases.

For both the 45 MeV and 70 MeV H^- cyclotrons, we have:

- Identified vendors capable of supplying either or both machines.

- Developed cost estimates for an H^- cyclotron with two beam extraction ports. Each extraction port will have appropriate switching magnets and two target stations for a total of four target stations. Maximum current will be 2 mA.

- Estimated the baseline weekly operations cost for each machine running at a maximum energy (45 and 70 MeV, respectively). Power consumption has been estimated for:
  a) radio frequency (RF) source for 2 mA of beam current;
  b) base load power consumption for vacuum pumps, water cooling pumps ventilation blowers, etc.

- Estimated the operational lifetime of the cyclotron.

- Summarized the scientific and economic benefits derived from the purchase of a 70 MeV cyclotron.

1.2 Adaptation to Limits in Sources of Information

At the beginning of this study, it was established that the major credible vendors capable of producing a 70 MeV cyclotron are engaged in a competitive bidding process to supply the 70 MeV machine at the University of Nantes in France. The bidding phase of the competition is expected to be concluded in September 2005. Accordingly, those manufacturers are very reluctant to discuss specifications or costs with us at this time because information leakage could jeopardize their ability to be competitive. It is expected that they will be more forthcoming with cost and design information after September 2005.

We also communicated with authorities at the University of Nantes to explore the possibility of being included as an observer during the competitive discussions with bidders scheduled in August and September. We were informed (not surprisingly) that their procurement rules did not allow such outside observers. Prof. Jean-Francois Chatal at the University of Nantes indicated that they would be willing to share design and cost information with us following completion of the competitive discussions with bidders in September. In view of the lack of such credible sources for design and cost information, we have relied on the following:

- Summary design and cost information published in the document describing a plan to acquire a 70 MeV cyclotron by the University of Nantes in France, cited as *Lancement du project du Cyclotron de Nantes – Un grand equipement de recherché medicale pour la lutte contre le cancer*, dated September 30, 2004 (Reference 1).

- Information provided by BNL in their *March 2002 Business Operation Plan* for acquisition of a 70 MeV cyclotron, together with subsequent updates published in February 2004 (Reference 2).

- Limited design and cost information from Advanced Cyclotron Systems, Inc. based on their 30 MeV, 1 mA cyclotron.

- Development of scaling factors to enable the formulation of costs for a 45 MeV and a 70 MeV cyclotron based on costs of a 30 MeV machine.

- *JUPITER's* independent review of facility construction costs developed by BNL was conducted to validate their earlier information and help establish a common basis for comparing and reconciling cost figures generated by BNL, the University of Nantes, and those developed from communications with Advanced Cyclotron Systems, Inc.

While the limitations in obtaining cost information from credible vendors resulted in the expenditure of more time and effort to collect and analyze useful information on cyclotron design features, performance, and costs, we believe the data is adequate to provide an approximate cost figure, and a reasonably good cost comparison between 45 MeV and 70 MeV cyclotrons. Further, two excellent vendors have been identified, operational costs are estimated, and comments are offered on operational lifetime. Information taken from earlier DOE documents on isotopes and their uses, and on scientific and economic benefit, are included here for completeness.

2. CYCLOTRON VENDORS

Two fully credible cyclotron vendors have been identified that have the capability to design and build either the 45 MeV or 70 Mev cyclotron. Both are at the top of the competition for procurement of the University of Nantes cyclotron (70 MeV, 150 mA beam current), which has very similar operational specifications compared to DOE expressed requirements[1]. These vendors are: 1) IBA Technology Group in Belgium, and 2) Advanced Cyclotron Systems, Inc. in British Columbia, Canada.

IBA is one of the world leaders in particle accelerator technology. Since 1986, they have developed and manufactured a full line of *PET* (positron emission tomography) and *SPECT*[2] cyclotrons, ranging from three to 30 MeV in energy.

Advanced Cyclotron Systems, Inc. was formed as a spin-off company of Ebco Industries in 1987 with the mandate to commercialize the scientific and technological advances in cyclotron, PET and radioisotope technologies developed at *TRIUMF*[3] over 25 years ago. It is one of the world leaders in cyclotron technology.

Contact information for these two vendors is provided below:

Name	**IBA Technology Group**
Address:	Business Office Chemin du Cyclotron, 3 1348 Louvain-la-Neuve Belgium
Telephone:	011-32-10475892
Fax:	011-32-10475847
e-mail:	info-tg@iba.be
Web site:	www.iba.be/root_tg/pages/IBATG_contact_us.htm
Contact:	Mr. Olivier van der Borght Vice President, Marketing
Telephone:	011-32-495-58-6852
e-mail:	vanderborght@iba.be

Name	**Advanced Cyclotron Systems, Inc.**
Address:	7851 Alderbridge Way Richmond, British Columbia Canada, V6X2A4
Telephone:	604-278-5578
Fax:	604-278-7230
e-mail:	info@advancedcyclotron.com science@advancedcyclotron.com
Web site:	www.advancedcyclotron.com/contactus.html
Contact:	Dr. Richard Johnson Program Manager
Telephone:	604-278-5578
e-mail:	dick@attglobal.net

[1] DOE is considering a 45 MeV or 70 MeV cyclotron with a negative ion beam current of 2 mA.
[2] SPECT is single photon emission computed tomography.
[3] *TRIUMF* is Canada's National Laboratory for Particle and Nuclear Physics.

Both Advanced Cyclotron Systems and IBA Technologies Group use very similar basic design features in their 30 MeV cyclotrons. Negative ions (either hydrogen or deuterium) are produced in a *multicusp* ion source and axially injected into the cyclotron. A high voltage alternating electric field, induced on a pair of electrodes (*dees*), cause repeated bursts of acceleration of the ions as they travel across the gap between the *dees* in an ever-widening circular trajectory under the influence of a fixed perpendicular magnetic field. Two beam extractor devices are located 180 degrees apart along the trajectory of maximum radius so that two beams can be extracted simultaneously. At these beam extraction points, electrons are stripped from the negative ions by passing the ions through a thin film pyrolytic carbon stripper foil. The proton or deuteron beams can then be directed to shielded cells for radioisotope production or conduct of nuclear experiments.

3. PURCHASE COST ESTIMATES FOR 45 MEV AND 70 MEV CYCLOTRONS

3.1 Basis for Analysis

Both IBA Technology Group and Advanced Cyclotron Systems have developed a standard design cyclotron to operate at a peak energy of 30 MeV with a beam current of 1 mA. Procurement of a cyclotron operating at a higher energy (45 MeV or 70 MeV) and a beam current of 2 mA would entail further design efforts with a corresponding increase in costs.

For estimating the cost of a 45 MeV or 70 MeV cyclotron, based on the cost of a standard 30 MeV, 1 mA cyclotron, one has to scale up the physical dimensions as well as the power requirements. For instance, the diameter of the cyclotron *dees* (as well as the diameter of the magnet face) is proportional to the maximum momentum of the accelerated particles (with some additional space added to accommodate the steel for the return yokes of the magnet), so the foot-print of the cyclotron must be scaled by about the ratio of the square root of the energies. Likewise the power must be scaled linearly with an increase in energy. For this comparison, the beam current is kept fixed at 1 mA. Estimates given here scale the fabrication details of a commercially available 30 MeV cyclotron to that for 45 and 70 MeV machines. A discussion of fabrication scaling factors is provided in Section 3.3 for the cyclotron, and in Section 3.4 for the beamlines. Cost considerations related to an increase in beam current are discussed later in this document. Besides the increase in fabrication costs, additional engineering design is required to produce manufacturing drawings for the 45 and 70 MeV cyclotrons; estimates of these design costs are discussed below.

3.2 Design Costs

3.2.1 Energy-Related Design Costs

An estimate of the engineering design costs for converting existing 30 MeV fabrication drawings to fabrication drawings for the higher energy cyclotrons is given in Table 1 below, which shows a cost breakdown for various design activities, illustrating both estimated labor hours and cost. We have adopted a $100/hour average labor rate (fully burdened with indirect costs) for engineering design labor to convert the existing 30 MeV design to either a 45 Mev or 70 MeV design. At the estimated total required engineering labor of 12,000 hours, the total estimated design cost (including a contingency of $600,000) for either the 45 MeV or 70 MeV cyclotron is about $1,800,000.

While Advanced Cyclotron Systems recommended a design contingency of 100 percent, we believe that the figure of 50 percent shown in Table 1 is reasonable—unless there are serious problems in achieving a beam current of 2 mA. Further, if DOE decides to acquire a 70 MeV machine during the next couple of years, it will be able to take advantage of completed engineering work on the machine being procured at this time by the University of Nantes. The successful bidder will have to complete the design, and any subsequent purchase by DOE should trigger a significantly lower design cost if DOE purchases a similar machine from the winner. If DOE decides to purchase a machine from the losing vendor, we believe the 50 percent contingency is more than adequate since even the losing vendor would have completed some preliminary design work as part of the current competition for the University of Nantes machine. Considering this, design costs for the DOE cyclotron might be reduced significantly below the figure shown in the Table, even with a need to raise the beam current from the 1.5 mA Nantes design to the 2 mA specified by DOE.

Table 1 – Estimated Design Costs[4] for Cyclotrons of Various Energies

Design Elements	Cyclotron Peak Energy			
	45 MeV		70 MeV	
	Labor Hours	Cost ($K)	Labor Hours	Cost ($K)
Physics Design	4,000	400	4,000	400
Magnet Detail	2,000	200	2,000	200
RF Design	2,000	200	2,000	200
Vacuum Detail	2,000	200	2,000	200
Beamline Detail	2,000	200	2,000	200
Subtotal	12,000	1,200	12,000	1,200
Contingency (50%)		600		600
Total Design Cost		**1,800**		**1,800**

3.2.2 Design Considerations for Higher Beam Currents

Recent upgrades on Advanced Cyclotron System's TR30 cyclotron allow a maximum beam current in excess of 1.2 mA to 1.5 mA[5]. Development of beam current capabilities in excess of that value are underway at Advanced Cyclotron Systems, but have not yet been achieved. While the TR30 multicusp negative ion source used in the beam injector is capable of 15 mA current at the injector input, significant losses are realized in the injection and acceleration process. Technical problems associated with higher beam currents relate principally to the need for short injection lines and development of a strong focusing accelerator to overcome electrostatic space charge effects that tend to blow up the beam cross section[6] beyond the physical space allowed between the accelerating *dees*. A solenoid focusing lens and a pair of axially rotated quadrupole focusing magnets in the injector are used to help mitigate beam blow-up at the front end of the accelerator. Development of strong focusing within the accelerator is more difficult. Containment of the ion beam beyond the accelerator needs to be within the diameter of the beam tube[7] or collimators, and pairs of axially rotated magnetic quadrupole lenses in the beamlines are used for this purpose. The ability to achieve higher beam currents will depend greatly on development of improved strong focusing within the accelerator, and on improved design and increased effectiveness of focusing magnets.

3.3 Cyclotron Fabrication Costs

Table 2 below summarizes the scaling factors needed to estimate the additional material and power required for cyclotron operation at the higher energies, as well as to determine the fabrication costs for the 45 MeV and 75 MeV cyclotrons, based on the standard 1 mA beam current, 30 MeV design of Advanced Cyclotron Systems.

[4] Developed following guidance from Advanced Cyclotron Systems, Inc.
[5] Note that the design beam current for the 70 MeV cyclotron at the University of Nantes is 1.5 mA.
[6] In the TR30 cyclotron, the beam spot size is generally 24 mm vertical by 10 mm horizontal.
[7] The nominal beam tube bore is 90 mm for the TR30 cyclotron.

Table 2 – Scaling Factors[8] for Adjustment of Costs for Cyclotrons of Various Energies

Subsystem	Cyclotron Peak Energy		
	30 MeV	**45 MeV**	**70 MeV**
Steel/Copper	1.0	1.50	2.00
Electrics (PS)	1.0	1.25	1.50
RF Power	1.0 (at 62.4 kW)	1.40 (at 90 kW)	2.10 (at 132 kW)
Ion Source Injection System	1.0	1.00	1.00
Vacuum System	1.0	1.50	2.00
Fabrication Scaling Factor	**1.0**	**1.20**	**1.40**
Fabrication Costs	**$8.0M**	**$9.6M**	**$11.2M**

The RF power scaling factors shown above take into account power required to excite the accelerating *dees* plus the beam loading power, together with a 20 percent contingency in total required power, respectively, for each energy. The final row provides an estimate of the costs for higher-energy cyclotrons derived by multiplying appropriate fabrication scale factors by the commercial cost of the 30 MeV cyclotron. The nominal budgetary cost[9] for a 1 mA, 30 MeV commercial cyclotron is $8,000,000. Accordingly, the anticipated commercial fabrication costs for higher every machines are:

- $9.6M for a 45 MeV cyclotron, and
- $11.2M for a 70 MeV cyclotron.

Design costs as well as beamline costs (discussed below) are added to these figures to arrive at the final price in Section 3.5.

3.4 Scaling Factors[10] for Beamline Costs

A similar scaling can be done for the beamlines (deflecting magnets and vacuum system, including roughing pumps and cryogenic ion pumps, valves, vacuum tubes, etc.), and Table 3 below indicates the scaling that can be applied for estimation of beamline costs. Four beamlines leading from a 30 MeV cyclotron has a budgetary cost of about $3M[11].

[8] Based partially on input from Advanced Cyclotron Systems.
[9] Information provided by Advanced Cyclotron Systems
[10] Based on manufacturer's input
[11] Based on quotation from Advanced Cyclotron Systems.

Table 3– Scaling Factors[12] for Beamline Fabrication Costs

Subsystem	Cyclotron Peak Energy		
	30 MeV	45 MeV	70 MeV
Steel/Copper	1.0	1.50	2.0
Electrics (PS)	1.0	1.25	1.5
B.L. Fab. Scaling Factor	**1.0**	**1.20**	**1.4**
Beamline Fab. Costs	**$3.0M**	**$3.4M**	**$4.0M**

Using results from Table 3 above leads to an estimate of beamline costs of:

- $3.4M for the 45 MeV cyclotron beamlines, and
- $4M for the 70 MeV cyclotron beamlines.

3.5 Summary of Costs

The overall acquisition costs will be given by the sum of the design costs, cyclotron fabrication costs, and beamline costs. This corresponds to costs of:

$1.8M + $3.4M + $9.6M = $14.8M for the 45 MeV cyclotron, and

$1.8M + $4.0M + $11.2M = $17.0M for the 70 MeV cyclotron.

These estimates are summarized in Table 4 below. Assumptions are explained in the discussions above.

Table 4 – Summary of Total Estimated Costs for the Cyclotron System

Cost Element	Cyclotron Peak Energy		
	30 Mev	45 MeV	70 MeV
Cyclotron Design Cost	0	$1.8M	$1.8M
Cyclotron Fabrication Cost	$8.0M	$9.6M	$11.2M
Beamline Fabrication Cost	$3.0M	$3.4M	$4.0M
Total Acquisition Cost	**$11.0M**	**$14.8M**	**$17.0M**

Note: Costs for irradiation targets and radiochemical processing of the irradiated material are not included.

Design of irradiation targets usable for the higher beam currents of 2 mA will present a greater challenge in terms of cooling requirements and target lifetime. Likewise, shielding requirements and concerns for worker radiation exposure will be increased because of the higher radiation field (largely due to activation

[12] Developed following guidance from Advanced Cyclotron Systems, Inc.

of material in beamline components and the concrete shielding) at the higher energy of 70 MeV. The amount of change will require detailed assessment since the energy spectrum of neutrons and gammas produced in proton beam interactions will cause activation in those components and materials that will be different at the higher energies.

3.6 Comments on Purchase Cost Differences Between a 45 MeV and a 70 MeV Cyclotron

From Table 4 in Section 3.5, we note the difference of $2.2M out of a total of approximately $17M between the estimated purchase price of a 45 MeV and a 70 MeV cyclotron—corresponding to a 13 percent higher cost for the 70 MeV machine. Let us now consider the combined cost of the cyclotron and the building that houses it. Refer to the analysis in Appendix A that provides results of an independent review of costs for the BNL-proposed 70 MeV cyclotron, and Appendix B which provides an overview of various costs associated with 70 MeV cyclotrons. When the cost of the building is combined with the cyclotron purchase price (amounting to a total of about $37M), this cost difference becomes less than six percent of the total.

The 70 MeV cyclotron could be housed in a building of size and complexity that is similar to that for a 45 MeV cyclotron. There would be a small increase in the size of the cyclotron vault (a few feet in lateral dimension) to accommodate the larger main magnet and larger accelerating electrodes. The beam line system would not be changed significantly. The main change would be reflected in the need for larger switching and focusing magnets and increased radiation shielding. The intensity of radiation produced by higher energy protons on a target increases more rapidly than a linear dependence, and is influenced by the cross section (probability of nuclear interaction) with material around the target. However, an increase in concrete shielding thickness results in an exponential decrease in radiation intensity for gamma rays; the attenuation for neutrons is more complex because of the combined processes of neutron thermalization (scattering) and capture, and will require careful design in order to optimize shielding. Nevertheless, the increase in shielding thickness for the 70 MeV cyclotron is not expected to be large. Therefore, incremental costs for the 70 MeV cyclotron and building will likely not exceed a factor of 10 percent higher than that for the 45 MeV cyclotron.

4. BASELINE OPERATING COSTS

4.1 Operational Cost Estimates by BNL and by University of Nantes

Cyclotron operational costs have been projected by both BNL[13] and the University of Nantes[14] for their proposed 70 MeV cyclotron facilities. These projections relate only to accelerator operations, and not to radioisotope processing and distribution; they are summarized and compared in Table 5 below.

Table 5 – Summary of Annual Operating Cost Estimates for University of Nantes and BNL Cyclotrons

Cost Element	Univ. of Nantes	BNL
Salaries – Cyclotron Operations	$643.6K	$583.6K (2.7 FTEs)
Other Operational Costs	$1,287.2K	$468K
Total Operational Cost	**$1,930.8K**	**$1,051.6K**

Note: Costs for processing and shipping radionuclide products are not included.

The University of Nantes data was taken from Reference 1, while the BNL data was derived from Reference 2, and presented here with the following adjustments: BNL's published cost of $170K for Trades Labor was added to their cost of $256K for salaries of 2.7 FTEs. We note that these figures did not include Laboratory G&A indirect cost mark-up (at 37%); this G&A mark-up was added to the sum of the trades labor and salaries to yield a total of $583.6K shown in Table 5 above.

We note that the cited operating staff of 2.7 FTEs is reasonable for a facility of this type for a one-shift operation, and projecting about 50 weeks per year of operation. The Other Operational Costs principally represent services of maintenance workers and health physics monitors as well as material and supplies (including power costs). Costs for processing and shipping of radioisotopes are not included here, but are expected to be larger by a factor of five or six. While the operational costs for cyclotrons at the University of Nantes and at BNL differ by almost a factor of two, this difference may be reconcilable with more information on the detailed make up of the cost elements and the fringe, overhead, and G&A indirect rate structures employed at the two facilities.

While the above differences are not yet resolved, we believe they provide a range of operating costs over which projections might be made. Accordingly, a notional annual operating cost of $1,500,000 might be adopted—corresponding to weekly operating costs of $28,846 per week, including fully burdened salaries. The apparent ± 50 % uncertainty in this estimate could be due to unresolved differences in cost sharing with other activities, such as radioisotope processing or with health physics or administrative services.

4.2 Power Requirements

Power requirements have been examined for 30 MeV, 45 MeV, and 70 MeV cyclotrons. Building on the detailed data available for the Advanced Cyclotron Systems Model TR30 cyclotron, operating at a

[13] Reference 2, cited in page 3.
[14] Reference 1, cited in page 2.

maximum energy of 30 MeV, we have scaled power requirements for the higher energy machines. Power is scaled linearly with increases in energy; accordingly, for those subsystems whose performance is related to energy increases, we have used a scaling factor of 1.5 for the 45 MeV cyclotron, and 2.33 for the 70 MeV cyclotron. For those subsystems whose performance are relatively independent of energy increases, we have used 1.0 for the scaling factor for both the 45 MeV and the 70 MeV cyclotrons.

Table 6 - Scaling Factors and Power Requirements for Subsystems Supporting Cyclotrons of Various Energies

Subsystem	Description	Scaling Factors			Power Requirements (kW)		
		30 MeV	45 MeV	70 MeV	30 MeV	45 MeV	70 MeV
Cyclotron	Main Magnet P/S	1.00	1.50	2.33	57.50	86.25	133.98
	Probes	1.00	1.50	2.33	2.00	3.00	4.66
	Hydraulic Pump	1.00	1.50	2.33	15.00	22.50	34.95
	Current Amplifiers	1.00	1.50	2.33	1.00	1.50	2.33
RF System	Amplifier (Low Current)	1.00	1.50	2.33	65.00	97.50	151.45
	Amplifier (High Current)	1.00	1.50	2.33	100.00	150.00	233.00
	Power	1.00	1.50	2.33	1.00	1.50	2.33
Ion Source	Isolation Transformer	1.00	1.00	1.00	25.00	25.00	25.00
	Solenoid	1.00	1.00	1.00	7.50	7.50	7.50
	Ground Region	1.00	1.00	1.00	2.60	2.60	2.60
Vacuum	Cryopump Comp. (2)	1.00	1.00	1.00	6.00	6.00	6.00
	Vacuum Forepump	1.00	1.00	1.00	3.00	3.00	3.00
	Vacuum Gauge Cont.	1.00	1.00	1.00	2.00	2.00	2.00
Beamlines	Combination Magnet P/S (2)	1.00	1.50	2.33	19.00	28.50	44.27
	Switching Magnet P/S (2)	1.00	1.50	2.33	19.00	28.50	44.27
	Quadrupole (6) P/S	1.00	1.50	2.33	45.00	67.50	104.85
	Steering Magnets P/S (4)	1.00	1.50	2.33	2.00	3.00	4.66
Water System	Pumps, etc.	1.00	1.00	1.00	19.00	19.00	19.00
Control System	Computer System	1.00	1.00	1.00	4.00	4.00	4.00
RMS/Safety	PLC c/w UPS System	1.00	1.00	1.00	2.00	2.00	2.00
TOTAL					**397.60**	**560.85**	**831.85**

Note: Figures do not include power for facility air conditioning or heating.

Table 6 above shows the resulting compilation of power requirements for all three accelerators, with a total power requirement of:

- 560.85 kW for the 45 MeV cyclotron, and
- 831.85 kW for the 70 MeV cyclotron.

5. ESTIMATE OF OPERATIONAL LIFETIME

The cyclotron is a relatively durable instrument, consisting of an ionized hydrogen injector as a source of protons, power supplies, a large magnet, accelerating electrodes (*dees*), and a vacuum system (roughing pumps, cryogenic ion pumps, valves, and beam pipes). The basic main magnet, *dees,* and beamline system will have an operational life exceeding 30 years, and they represent by far the greatest portion of the cost. Ancillary components such as switches, gauges, power supplies and pumps may be replaced at intervals of several years, depending on manufacturer's warranty and maintenance practices. Most of the minor subsystem components would be repaired or replaced, as needed. This view is supported by extensive experience with operation of other accelerators.

6. LIST OF ISOTOPES AND THEIR USES THAT REQUIRE A 45 MEV OR 70 MEV PROTON ACCELERATOR[15]

6.1 List of Isotopes Produced by Accelerators of Various Energies

Benefits derived from operation of a 70 MeV cyclotron instead of one at a lower energy is illustrated by the ability to produce some isotopes that cannot be produced at the lower energies. Table 5 below groups isotopes into three categories: (1) those that can be made in a 30 MeV cyclotron; (2) a 45 MeV machine; and (3) finally, a 70 MeV machine. It follows that whatever can be made by a 30 MeV machine, can also be made by a 45 MeV machine, and that a 70 MeV machine can produce all the isotopes listed in this table. Half-lives for these isotopes are also listed, and the isotopes are ranked according to the length of the half-life from shortest to longest.

Although a 30 MeV cyclotron, of which several are currently owned and operated by various private sector isotope-producing facilities, is not under consideration by DOE, a list of isotopes that can be made by this machine is included for completeness. Table 7 below illustrates a 60 percent increase in the number of radioisotopes of interest that can be produced by a 70 MeV accelerator compared to a 45 MeV machine.

Table 7 – List of Isotopes Produced by Proton Accelerators of Various Energies

30 MeV		45 MeV		70 MeV	
Isotope	**Half-Life**	**Isotope**	**Half-Life**	**Isotope**	**Half-Life**
Cu-64	12.7 h	Zn-62	9.2 h	Fe-52	8.3 h
Y-86	14.6 h	Co-55	17.5 h	Xe-122	20.1 h
Cu-67 *	2.58 d	Hg-195m	41.6 h	Mg-28	21 h
Sc-47	3.35 d	Bi-206	6.2 d	Ba-128	2.43 d
I-124	4.2 d			Cu-67 *	2.58 d
Tc-96	4.28 d			Ru-97	2.79 d
Xe-127	36.4 d			Sn-117m	13.6 d
Y-88	106.7 d			Sr-82	25.4 d
Ge-268	271 d				

6.2 Uses of Isotopes Produced by a 70 MeV Proton Accelerator

The following is a list of some of the potential uses for isotopes produced by a 70 MeV proton accelerator. Active research is generally not being done with these isotopes due to their lack of availability. However, some research has been performed with them and the following uses are briefly tabulated here.

[15] Adapted from an earlier DOE document.

- *Iron-52.* Parent generator for manganese-52, a positron emitter used for Positron Emission Tomography (PET) diagnostics. Iron-52 itself is a positron emitter and is also used as an iron tracer for the study of red blood cell formation and brain uptake.
- *Xenon-122.* Parent generator for iodine-122, a positron emitter used for PET brain blood-flow (perfusion) studies.
- *Magnesium-28.* Used as a magnesium tracer. Magnesium is an important biochemical element. Also an analog to calcium and can be used for bone studies.
- *Barium-128.* Parent generator for producing positron-emitting cesium-128, a potassium analog. It is a PET isotope that has been used for heart and blood flow imaging.
- *Copper-67.* Radioimmunotherapy. This isotope can be made in a 30 MeV cyclotron using a different reaction mechanism. However, the yield is small compared to the yield at 70 MeV. Also attaining high specific activity material is a problem due to the presence of stable environmental copper being introduced during chemical process of the target. (DOTA[16] and TETA[17] are labeled with this; TETA is more Cu specific than DOTA, which will pick up any metal, Cu, or otherwise.)
- *Ruthenium-97.* A gamma emitter that is used for imaging cerebrospinal fluid and blood flow in liver.
- *Tin-117m.* A gamma emitter that has potential use for bone pain palliation.
- *Strontium-82.* Parent generator for producing positron-emitting rubidium-82, a potassium analog used for heart imaging. As a PET isotope, it is used to generate 3D images of the heart to see where blockage occurs.

6.3 Uses of Isotopes Produced by a 45 MeV Proton Accelerator

The following isotopes require a cyclotron capable of attaining a proton beam energy of 45 MeV.

- *Zinc-62.* Parent generator of copper-62, a positron-emitter, used for the study of cerebral and myocardial blood flow.
- *Cobalt-55.* Used for imaging both by SPECT and PET. As a PET isotope it is used to image damaged brain tissue after stroke.
- *Mercury-195m.* Parent in generator system for producing gold-195m, which is used in cardiac blood pool studies.
- *Bismuth-206.* Tracer used to study the biological distribution of bismuth.

[16] DOTA is tetraazacyclododecanetetracetate.
[17] TETA is the chelating agent 1,4,8,11-tetraazacyclotetradecane-1,4,8,11-tetraacetic acid.

7. SCIENTIFIC AND ECONOMIC BENEFITS VALIDATING THE INCREMENTAL COSTS ASSOCIATED WITH THE PURCHASE AND OPERATION OF A 70 MEV CYCLOTRON

The 70 MeV cyclotron under consideration is expected to serve as a dedicated facility for production of radioisotopes on a 50-week per year basis. This dedicated service is not available at any other DOE facility. The scientific and economic benefits validating the incremental costs associated with the purchase and operation of a 70 MeV cyclotron, over and above those attainable from a 45 MeV cyclotron are substantial. It will be able to produce a host of radioisotopes not achievable using a 45 MeV accelerator; some examples are summarized below:

- The ability to achieve significantly higher yields of 2.58 day half-life copper-67, which is important in radioimmunotherapy. Copper-67 has been used in limited clinical trials as a therapeutic isotope when conjugated to monoclonal antibodies. However, these trials have been adversely affected by the limited availability of the isotope. Reliable production by a dedicated 70 MeV cyclotron would enable its broad application to patients in need of such therapy.

- Production of magnesium-28 as a magnesium tracer.

- Production of iron-52 for use as an iron tracer and as a positron emitter.

- Production of strontium-82 which is a parent in the generator system for producing the positron-emitting rubidium-82, a potassium analog.

- Production of ruthenium-97 for application in treating hepatobiliary function, as well as localization of tumors and inflammation.

- Production of xenon-122, which is the parent in the generator system for production of positron-emitting iodine-122.

- Production of barium-128, the parent in the generator system for producing the positron-emitting cesium-128, a potassium analog.

These benefits cannot be realized using a 45 MeV accelerator, and they have the potential of affecting the life and health of many people. More than 12 million nuclear medicine procedures are performed annually in the United States, and about one-third of all patients admitted into U.S. hospitals undergo at least one medical procedure that employs the use of medical isotopes. A difference of less than 10 percent in the total acquisition cost of the 70 MeV cyclotron facility (combining the cost of the accelerator and its building) is a small price to pay for such a wide-reaching benefit.

APPENDIX A — INDEPENDENT COST REVIEW OF A 70 MEV CYCLOTRON FACILITY

This is a summary of an independent cost review for the proposed 70 MeV Cyclotron Isotope Research Center (CIRC) at Brookhaven National Laboratory (BNL). This independent estimate was conducted to convert the March 2002 BNL cost estimate to current-day 2005 costs and to enable its comparison with current projections for the 70 MeV cyclotron at the University of Nantes in France.

Comparisons were made with information provided in the BNL Business Operations Plan (BOP), dated March 2002, for the CIRC facility, Project No. 04-CH-106. The BOP contained a facility overview, site plan for adding onto Building 801, a floor plan and a summary level cost estimate. It is recognized that the BNL cost estimate was modified and updated subsequently to utilize a refurbishment of Building 912 NW at a cost of $4.1M—less than half the $8.73M figure offered in the 2002 estimate. We have continued to use the 2002 cost figures in this review since more detail was available to support an independent review and enable comparisons with the University of Nantes facility.

The review cost estimate was developed using material unit costs from R.S. Means and Richardson Engineering cost estimating manuals, labor rates from Page labor estimating hours and costs from similar types of construction projects at various DOE sites.

The major differences are in the Construction Facilities and Contingency calculation. We observe that the BNL estimate may not consider the construction complexity for this type of structure and its confined construction site being adjacent to an existing facility. Operations in that adjacent structure may be affected during the construction's scheduled duration.

The BNL estimate combines contingency dollars for construction and technical activities. We could not judiciously separate the BNL cost, so both contingencies are shown in the review estimate for comparison of the total cost.

Table A-1 below summarizes the elements of the total project costs for the CIRC Project at BNL. Our review estimate accepts and contains the following site estimate costs for Technical Facilities:

- Cyclotron/Beam Line Equipment at $13,610,000.
- Target Systems at $430,000.
- Target Handling and Radioisotope Transport System at $550,000.
- Instrumentation/Controls/Safety Interlocks at $520,000.
- High Radiation Water System at $1,040,000.

Table A-1 – Comparison of an Independent Cost Review for the Proposed BNL 70 MeV Cyclotron

DESCRIPTION	BNL ESTIMATE (See note below)	REVIEW ESTIMATE FY2007 Dollars
BUILDING DESIGN PHASE		
Conventional Facilities	$1,160,000	$1,263,814
Technical Facilities	$930,000	$979,225
Conventional Design PM Costs	$300,000	$420,722
Sub-Total – Building Design Cost	**$2,390,000**	**$2,663,761**
BUILDING CONSTRUCTION PHASE		
Conventional Facilities	$8,140,000	$9,899,104
Construction Management	$280,000	$450,000
Insp., Des. & Project Liaison, Checkout & Accept.	$310,000	$120,850
Subtotal – Building Construction Cost	**$8,730,000**	**$10,469,954**
TECHNICAL FACILITIES		
Cyclotron / Beamline / Vacuum / Support Equipment	$13,610,000	$13,610,000
Target System	$430,000	$430,000
Target Handling & Radioisotope Transport System	$550,000	$550,000
Instrumentation/Controls/Safety Interlocks	$520,000	$520,000
High Radiation Water System	$1,040,000	$1,040,000
Subtotal – Technical Facilities	**$16,150,000**	**$16,150,000**
OTHER COSTS		
Project Management	$2,400,000	$1,895,873
Health, Safety	$640,000	Included in Constr. Facilities above
Subtotal – Other Costs	**$3,440,000**	**$1,895,873**
TOTAL – ACQUISITION COST	**$27,920,000**	**$28,515,827**
CONTINGENCIES		
Design Phase	$370,000	$262,996
Construction Phase	$5,820,000	$3,211,089
Technical Phase	Included above	$4,013,275
TOTAL – CONSTRUCTION CONTINGENCY	**$6,190,000**	**$7,487,361**
TOTAL – LINE ITEM COST	**$36,500,000**	**$38,666,948**

Note: We have assumed that the BNL estimate is expressed in FY2007 dollars. The summary estimate in the BNL BOP, dated March 2002, Page 10, contains a footnote stating "The annual escalation rates assumed for FY2001 through FY2007 are 2.5, 2.6, 2.1, 2.5, 2.9, 2.8 and 2.6 percent, respectively, using DOE FY2004 Guidance, January 2002 Update." Also, Appendix I, Page 18 of the BOP, shows production to start in 2007.

The following are assumptions associated with our Review Estimate.

- The review estimate covers all general construction including site work, building structure and associated mechanical/electrical utilities.
- The estimated cost comparison is for general construction only but does contain Construction Management and Project Management (CMPM) costs for the total project. The reviewer was unable to ascertain the division of costs for CMPM in the site estimate. Thus, the review estimate contains both costs to validate the site estimate.
- Site work will be performed within a confined area.
- The structure will be constructed using 5,000 psi concrete, laced steel reinforcing and integrated concrete floor and roof.
- Roof to be an elastomeric thermal and moisture protection system.
- Armored type floor covering with access floor in the control room.
- Radio Frequency shielding in the cyclotron vault.
- All walls painted with nuclear grade paint.
- The mechanical systems will have HEPA filtering.
- All electrical components will be explosion proof.
- The cyclotron vault will contain a bridge crane.
- All doors will be 3-hour fire rated flush steel.
- Blast resistant doors or building accessories are not part of the estimate.
- Cyclotron and associated controls, components and power supply are not part of the review estimate.

The contingency estimate used in Table A-1 above was derived from a weighted/probability contingency analysis calculation developed by the reviewer; results are summarized in Table A-2 below.

Table A-2 – Results of Contingency Analysis.

Description	Estimated Cost	Contingency Percent (Rounded)	Contingency Cost (Rounded Dollars)
Engineering, Design and Inspection (Construction)	$1,263,814	12%	$148,182
Engineering, Design and Inspection (Technical)	$979,225	12%	$114,814
Improvement to Land	$318,760	15%	$48,345
Building	$9,456,831	27%	$2,575,509
Utilities	$123,513	20%	$24,136
Construction Support (Construction and Project Management)	$2,967,789	19%	$563,099
Special Process Equipment	$16,150,000	25%	$4,013,275
TOTAL	**$31,280,707**	**24%**	**$7,487,361**

The relative weight and probability score determinations for construction were derived from the type of construction, complexity of the project design, design completeness, market conditions, and method of accomplishment. Determinations for the technical, special process equipment were derived from the specification completeness, quality accuracy, price accuracy and method of accomplishment.

The independent review resulted in a total cost estimate ($38,666,948) that is higher than the BNL estimate ($36,500,000) by $2,166,948, or 5.6 percent. The main contributions to this difference appear to be in the construction cost and in the contingency.

APPENDIX B — OVERVIEW OF COSTS FROM VARIOUS ESTIMATES FOR A 70 MEV CYCLOTRON FACILITY

An overview of cyclotron facility costs, using input information from various available sources is useful in that it can serve as a basis of confidence in estimates, and suggest areas for further investigation. Here, we list available cost information derived from documents or communications from the University of Nantes, BNL, *JUPITER's* independent review of BNL's 2002 cost estimate[18], and costs derived from scaling an Advanced Cyclotron Systems' 30 MeV cyclotron to a machine operating at either 45 MeV or 70 MeV.

Table B-1 – Overview of Various Costs Among the University of Nantes[19] Cyclotron, Proposed BNL Cyclotron and Costs Developed From Scaling of ACS Information

Item/Parameter	U. of Nantes	BNL	Independent Review of BNL Costs	Developed From Scaling of ACS Information
Cyclotron		$13,610,000		$17,000,000
Building		$22,890,000	$25,056,948	
Total Acquisition Cost of Building and Cyclotron	$38,616,000	$36,500,000	$38,666,948	
Estimated annual cost of operation (excluding salaries)	$1,287,200	$468,000		
Estimated Annual Salaries	$643,600	$583,600		

The University of Nantes' information does not provide a cost break-down between the cyclotron and the building; it only provides overall costs, and an estimate of operational costs with salaries listed separately. We note in Table A-2 below that the comparisons of total acquisition costs at both University of Nantes and BNL are quite good (within about 5 percent). While the estimated cost of a 70 MeV cyclotron developed from scaling up of Advanced Cyclotron Systems' costs of their 30 MeV cyclotron is significantly higher (by about 20 percent), we believe the scaling process may have resulted in somewhat higher figures than could be obtained through a competitive bid.

The large discrepancy in operational costs are probably due to differences in shared costs with other activities at the facility, and probably can be reconciled with access to additional detailed information from the two facilities.

Generally, this overview of estimated costs provide a fair degree of confidence in estimated overall costs for acquisition of a 70 MeV cyclotron.

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[18] While BNL's 2002 estimate was revised later and showed about a $4M reduction in building cost (based on a proposal to refurbish Building 912 NW instead of adding onto Building 901), the BNL 2002 projections were useful because of the greater detail available to us and comparisons with similar construction at the University of Nantes.

[19] Information taken from an English translation of a French document: *Lancement du project du Cyclotron de Nantes – Un grand equipement de recherché medicale pour la lutte contre le cancer*, dated September 30, 2004 (Reference 1).