DEVELOPMENT OF PROTON LINEAR ACCELERATOR AND TRANSMUTATION SYSTEM

M. Mizumoto, K.Hasegawa, H.Yokobori, H. Oguri, Y. Okumura, J. Kusano,
H. Murata, K. Sakogawa, M. Kawai, T. Nishida, T.Takizuka and H.Takada
Japan Atomic Energy Research Institute
Tokai–mura, Naka–gun, Ibaraki–ken, Japan, 319-11
81-292-82-6451

ABSTRACT

A conceptual design study has been carried out for an accelerator–driven minor actinide (MA) transmutation system with sodium–cooled subcritical reactor with actinide alloy fuel and spallation target of tungsten. In the present calculations, annual transmutation rate of about 250 kg of actinides and production of 820 MW thermal power are obtained by usinga 1.5 GeV proton beam with a current of 39 mA. The plant generates electric power of 246 MW with a conventional steam turbine, and supplies sufficient electricity to the accelerator. The solid target/core design is compared with a molten–salt target/core option.

The high intensity proton linear accelerator (ETA: Engineering Test Accelerator) with an energy of 1.5 GeV and an average current of 10 mA has been proposed by Japan Atomic Energy Research Institute, JAERI. In a course of the development, the R&D works for the low energy portion of the linear accelerator (BTA: Basic Technology Accelerator) with an energy of 10 MeV and a current of 10 mA are in progress.

I. INTRODUCTION

The JAERI is performing a long-term research and development works for partitioning and transmutation of minor actinides and long–lived fission products under a national program called OMEGA (Options Making Extra Gains from Actinides and Fission Products). The JAERI R&D includes the conceptual design study of accelerator–driven transmutation plant, the development of simulation code system, the spallation integral experiment and the development of a high intensity proton accelerator.

In the design study of transmutation plant, two system concepts are being investigated; solid system and molten–salt system[2]. In either system, an actinide–loaded subcritical core is driven by a high intensity (high-energy and high-current) proton linear accelerator and utilizes fast neutron spectrum to bum actinides efficiently. The design of the solid system is based on the current status of sodium–cooled fast breeder reactor technology. The engineering feasibility of the plant components such as fuel assembly, heat transfer system and beam window was investigated. The chloride minor actinide (MA) molten salt core has been studied simultaneously as another attractive option for the accelerator-driven transmutation system. The system has advantages in the continuous on–line processing of MA and reaction products and the capability to bum up some of the long–lived fission products in the moderated neutron flux region.

As compared with usual nuclear reactors, an accelerator–driven system does not required a critical condition, and therefore it has the significant advantage of large criticality safety margin. The thermal power of the subcritical core can be easily controlled by adjusting the power of incident proton beam.

The high-intensity proton linear accelerator (ETA: Engineering Test Accelerator) with a energy of 1.5 GeV and average current of 10 mA has been proposed by JAER1[3]. Various engineering tests will be performed using a high intensity accelerator for tbe transmutation system before actual plant has been constructed. The need for the development of such a high intensity proton linear accelerator (ETA) should be stressed for that purpose. Nuclear spallation reactions with high energy proton beams will also produce various intense beams, that can be utilized for other nuclear engineering applications. Those include material sciences, radio isotope productions, nuclear data measurements and other basic sciences with the proton, neutron and other secondary beams[1] in addition to nuclear waste transmutation.

The development of the Basic Technology Accelerator (BTA) has been carried out for the purpose of the mock-up test in the low energy portion of the ETA. The R&D's for main accelerator components such as high current hydrogen ion source, radio–frequency quadruple (RFQ), drift tune linac (DTL) and RF power source are in progress. The conceptual and optimization studies for the ETA were also performed concerning proper choice of operating frequency, high β structure, mechanical engineering consideration and RF source aspect in order to ensure low beam loss, hands–on–maintenance and low construction cost.

II. THE TRANSMUTATION SYSTEM

A. Design Concept of Solid Target/Core System

The detailed description of a transmutation target, neutronics calculation and power dissipation calculation has been published elsewhere Only the essential part of the scheme is described in the paper. Fig. 1 shows a conceptual flow diagram for an accelerator driven solid target system in combination with a subcritical reactor.

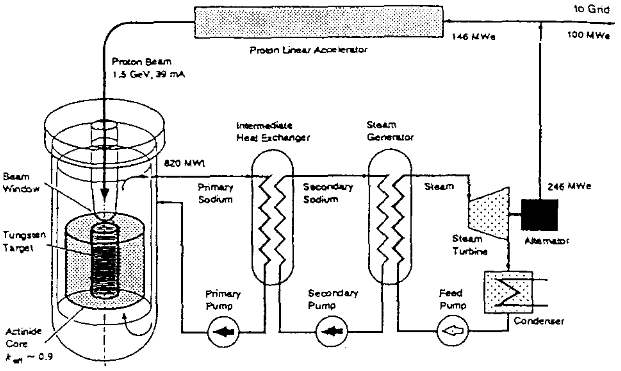

Fig.1 A Concept of Accelerator-Driven **Actinide** Transmutation Solid Target/Core System

The target and fuel assembly in the reactor proposed are similar to that used for the common fast breeder reactor with the sodium coolant[3]. Primary nuclear spallation reactions and the subsequent particle transport processes were simulated using the NMTC/JAERI code[4] for the neutron energy range above the cutoff energy of 15 MeV. Below this energy, a three dimensional Monte Carlo transport codes, MORSE-DD and TWOTRANS-2, were used.

The maximum power densities in the fuel and target regions are calculated to be about 930 MW/m^3 and 360 MW/m^3, respectively. Thermal hydraulics calculations were performed to assure that the fuel and the cladding temperature stay below the maximum allowable temperature (900 “C in actinide fuel and 725 ‘C in cladding). The calculated maximum thermal output powers were 820 MW. Accordingly, the averaged power densities were 400 W/cc for the incident proton beam current of 39 MA. Table 1 summarizes the operating conditions and characteristics of this accelerator transmutation system.

Table 1. Operating Conditions of the Accelerator-Driven Transmutation Solid Target/Core System

Proton beam energy	1.5 GeV
Proton beam current	39 MA
Actinide inventory	3160 kg
k_{eff}	0.89
No. of neutrons	40 n/p
No. of fission (>15MeV)	0.45 f/p
(<15MeV)	100 f/p
Neutron flux:	4x10’^{5}n/cm^{2}s
Mean neutron energy	690 keV
Burnup	250 kg/y(8%/y)
Thermal output	820 MW
Power density (max)	930 MW/cm^3
(ave)	400 MW/cm^3
Maximum temperature	
output	473 “c
Fuel	890 “C
Clad	528 “C
Electric output	246 MW

From these calculations, the spallation neutrons and the subsequent induced fission neutrons can transmute the MA produced by nearly ten LWR (Liquid Water Reactor) in a sodium cooled subcritical assembly. As a by-product, this system can be used to produce excess electric power of about 246 MW, a part of which can be used to operate the proton accelerator.

B. Design Study of Molten-Salt Target/Core System

A preliminary conceptual design study is performed on an 800 MWt molten-salt core/target as an advanced option for an accelerator–driven nuclear waste transmutation systems. Chloride salt with a composition of $64NaCl-5PuCl_3-31MACl_3$ (where MA represents Np, Am and Cm) is chosen for the molten salt system based on the consideration mainly about actinide solubility.

The molten–salt core system is calculated to have a maximum power density of 1660 MW and the core averaged power density of 940 MW/m^3, exceeding the maximum value of the solid system. The power density, however, is not a limiting factor for the performance of the molten salt core because no solid components are contained in the core. In the molten–salt system, the most difficult heat removal problem appears instead in intermediate heat exchanger.

If the design condition had followed a conventional design approach with external shell-and-tube type heat exchanger, removal of 800 MW thermal power would require the total fuel volume much larger than 6 m^3 and hence >10,000 kg actinides, leading to an unacceptably low actinide bumup, that is, < 2 %/y. Highly efficient heat exchangers are needed in the molten-salt system to reduce the total volume of the primary loops. The main aim in the present design of the molten–salt system is to minimize the total actinide inventory by incorporating compact type heat exchanger within a reactor vessel. This approach results in a reasonable actinide inventory of 5430 kg, about 1.7 times larger than that of the solid system and a moderate power density of 310 MW/m^3 average over the entire primary volume.

C. Comparison between the Solid and Molten-Salt System

Although the design of the molten-salt system has not yet been detailed to the same extent as the solid system design, comparison of the characteristics between the solid and molten–salt system is made as shown in Table 2, illustrating their relative advantages and disadvantages from the standpoint of system design.

Table 2. Solid and Molten-Salt System Designs Comparison

	Solid system	Molten-salt system
Fuel	Metal alloy Np-15Pu-30Zr AmCm-35Pu-10Y	Chloride salt $64NaCl-5PuCl_3-31MACl_3$ (MA:Np,Am,Cm)
Target	Solid tungsten	Chloride salt
Primary coolant	Liquid sodium	Chloride salt
Actinide inventory	3160 kg	5430 kg
k_{eff}	0.89	0.92
Spallation neutrons	40 n/p	38 n/p
Proton beam	1.5 GeV -39 mA	1.5 GeV -25 MA

Thermal power		
	820 MW	800 MW
Burnup	250 kg/y (8.0%/y)	250 kg/y(4.6 %/y)
Power density		
(Maximum)	930 MW/m^3	1660 MW/m^3
(Average)	400 MW/m^3	310 MW/m^3
Temperature		
(Core inlet)	330 “C	650 “C
(Core outlet)	430 “C	750 “c
Maximum velocity		
	8 m/s	3.6 m/s

In the solid system, two actinide alloys (Np-15Pu-30Zr and AmCm-35Pu-10Y) are used as a fuel for the subcritical core, target material for the proton beam is solid tungsten, and primary coolant is liquid sodium. On the other hand, the molten salt acts both as fuel and as a target material, and also serves as coolant simultaneously in the system. This simplifies the core/target system configuration.

Numbers of spallation neutrons per incident 1.5 GeV proton are about the same for the both systems. The proton beam current estimated for the molten-salt system is 25 rnA, about two thirds of that for the solid system. The difference in the beam current reflects the difference in the neutron multiplication factors in the subcritical cores. The coolant temperature in the molten-salt core is higher by 320 “C as compared to the solid core. It is preferable to operate the molten-salt core in 550 - 650 ‘C range, because the eutectic melting point is estimated to be about 450 “C. The reduction of the heat exchanger volume, however, requires a high temperature operation, ranging from 650 to 750 “C. With such a high operating temperature, a power conversion efficiency around 4570 become feasible with a super critical steam cycle, which can improve the total energy balance of the system. Nevertheless, material problems may become more serious as the increase in operating temperature.

Although the actinide in the primary molten-salt loops other than the core region occupies a considerably large fraction of the total inventory compared to the solid system as mentioned above, molten–salt system offers several attractive features for the design of transmutation system. The main advantage over the solid system is the capability of the continuous on-line separation of fission products and spallation products from the fuel. Furthermore, process of actinide fuel fabrication is not required for the molten-salt system. Core melt–down accident can be avoided because the molten-salt is ready to be dumped from the core in case of emergency.

D. Simulation Code Development and Integral Experiment

A computer code system bas been continuously developed for tbe design of the accelerator driven transmutation system[6]. In the code system, NMTC/JAERI code simulates the proton–induced nuclear spallation and subsequent internuclear transport process for energies above 15 MeV. It also calculates high energy fission reaction as a competing process with evaporation. Neutronic calculation below 15 MeV is carried out using transport codes, MORSE-DD and TWOTRANS-2. The time evohrtion process of transmutation produces is calculated by SPCHAIN code in the higher energy range above 15 MeV and by ORIGEN-2 code below 15 MeV. The code system has been upgraded and improved by incorporating current models and methods.

Spallation integral experiments have been carried out in order to obtain data on nuclide production to estimate tbe yields of neutrons and spallation products, and to evaluate the validity of the simulation code system’. The 500 MeV booster proton synchrotrons facility at the National Laboratory for High Energy Physics (KEK) is used for the experiments. Proton beam was injected into a cylindrical assembly made for lead, with a diameter of 600 mm and a length of 1000 mm as shown in Fig. 2. A lead/tungsten target was installed in the center of the lead assembly. The activation samples were Al, Fe, Ni and Cu cylinders with dimensions of 6 mm in diameter and 4-10 mm in length. These samples encapsulated in 8 mm diameter metallic can were inserted in the 10 mm diameter holes drilled through the assembly along the beam axis at various radial positions. The numbers of induced activities in the samples were obtained by measuring gamma–rays with a 100 cc Ge-detector. Experimental results were compared with prediction by NMTC/JAERI code.

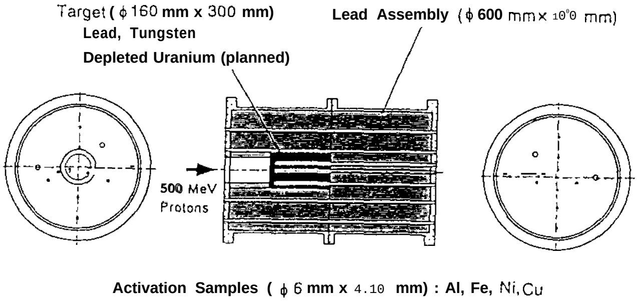

Fig.2 A Lead Assembly for Spallation Integral Experiment

III. ACCELERATOR DEVELOPMENT

The conceptual layout of the Engineering Test Accelerator (ETA) is shown in Fig. 3. In the case of high intensity accelerator, it is particularly important to minimize beam losses to avoid damage and activation of the accelerator structures. Because the beam quality and maximum current are mainly determined by the low energy portion of the accelerator, the accelerator (BTA) is designed and will be built[8] as a first step in the ETA development.

The basic specification of BTA is given in Table 3. Because of the high beam current and high duty factor, heat removal problem from the accelerator structures is an important issue for the mechanical design. Temperature distribution and thermal stresses are carefully studied with the three dimensional modeling codes. The beam energy for the BTA is chosen to be 10 MeV in order to avoid proton induced reactions in accelerator structural materials where the Coulomb barriers are barely exceeded. The acceleration frequency of 201.25 MHz is selected both for RFQ and DTL mainly due to the relatively manageable heat removal problem and the availability of RF source

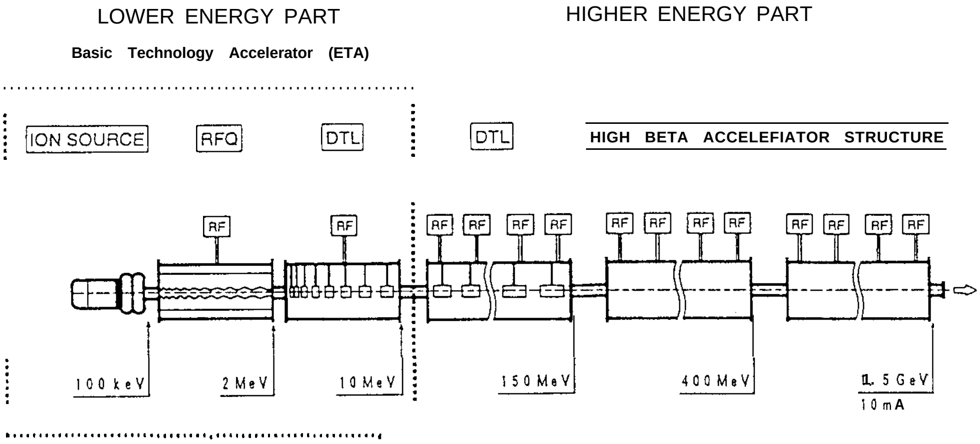

Fig.3 A Conceptual Layout of ETA and BTA

Table 3. A Basic Specification of BTA

Operation mode	pulse
Duty factor	10 %
Output energy	10 MeV
Average beam current	10 mA
Peak beam current	100 mA

A. **Ion** source

Fig. 4 shows a prototype of ion source[9] which was constructed in collaboration with the group of the NBI (Neutral Beam Injectors) Heating Laboratory for Fusion Research. The source consists of a multicusp plasma generator and a two stage extractor. The dimension of the plasma chamber is 20 cm in diameter and 17 cm in length. The chamber is surrounded by10 columns of SmCo magnets with the field strength of about 2 kG at the inner surface. The other basic specifications for the source are given in Table 4.

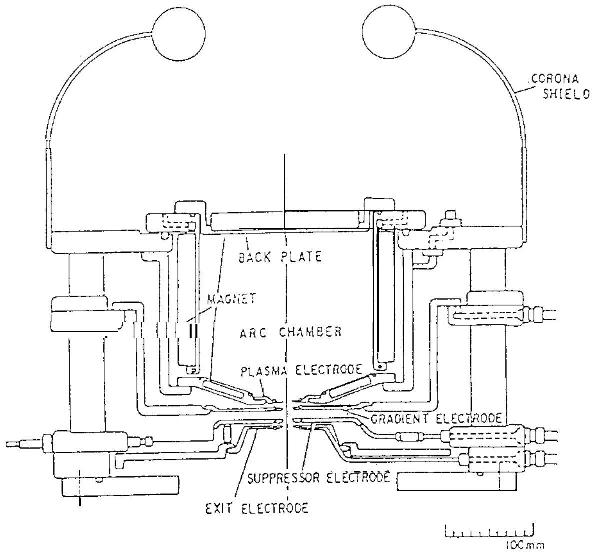

Fig.4. ACross-Sectionrd View of Ion Source for BTA

The high brightness hydrogen ion of 140 mA was extracted using the 100 kV high voltage-power supply. The beam profile was measured with a multi-channel calorimeter and the observed normalized emittance was about 0.45 πmm.mrad (9070). The proton ratio and impurity were also obtained to be 80 % and less than 1 % respectively by a Doppler shifted spectroscopy method.

Table 4. High Brightness Ion Source Parameters

Energy	100 keV
Current	120 mA
Duty factor	C w
Emittance	0.5 πmm.mrad (normalized 100%)
Proton ratio	>90 %
Impurity	<1 %

B. RFQ

The design study forthe RFQhasbeen made forafour vane type resonator and the frequency of 201.25 MHz[10]. The peak current of 110 mA and duty factor of 10 % were chosen. Two dimensional machining of the vane (circular cross section of the tip) for the RFQ was examined and its effects were estimated with the modified PARMTEQ code[11]. The undercutting of the vanes and power losses at the end region were studied with the MAFIA codes. The temperature distribution and thermal displacement were estimated with the three–dimensional finite element code of ABAQUS. The RFQ parameters are given in Table 5.

The machining of the vanes and RFQ tank have been completed and the ports for RF coupler and vacuum devices are being fabricated by the Sumitomo Heavy Industries, LTD.. The electromagnetic field measurement will be carried out soon.

Table 5. RFQ Parameters

Frequency	201.25 MHz
Energy	0.1-2 MeV
Beam current	110 mA
Duty Factor	10 %

Synchronous phase		-90°--35°
Vane voltage		0.113 MV
Focussing parameter B		7.114
Number of cell		181
Cavity diameter		36.6 cm
Vane length		334.8 cm
Quality factor (Q)		13000 (100% Q)
Wall loss power		432 kW (60% Q)
Beam power		209 kW
Normalized emittance		
LEBT Input		
(loo%)	x,y	0.05 πcm.mrad
(rms)	x,y,	0.0083 πcm.mrad
RFQ Input		
(98%)	x,y,	0.085 πcm.mrad
(rms)	x,y:	0.0123πcm.mrad
RFQ Output		
(rms)	x:	0.0203πcm.mrad
(rms)	y:	0.0187πcm.mrad
(rms)	z:	0.0027πMeV.rad

C. DTL

A resonant frequency, magnetic field strength and heat removal problem were investigated for DTL under the various mechanical constraints. A hollow conductor type coil with 5x5 mm^2 was chosen for focussing magnet. Configuration of quadruple magnet is optimized under the condition on the coolant water (temperature rise 25 °C in the coil, pressure drop 5 kgf/cm^2 and velocity 3.4 m/s). The beam dynamics design calculations for the DTL have been made using the computer code PARMILA[11]. The MEBT consisting of four quadruple magnets and one buncher is considered between RFQ and DTL to obtain matching. The DTL parameters are given in Table 6. The hot test model with 9 cells, among which the #l drift tube and the one at the front end plate are installed with actual quadruple magnets, is being fabricated by Mitsubishi Heavy Industries, LTD.. The magnetic field strength and center position, and higher harmonic field components have been measured with the conventional rotating search coil technique.

Table 6. DTL Parameters

Frequency	201.25 MHz
Energy	2-10 MeV
Beam current	100 mA
Average field	2.0 MV/m
Tank diameter	89.3 cm
Tank length	564.9 cm
Cell length	9.86-21.55 cm
g/L	0.234-0.’293
DT outer diameter	20 cm
DT inner diameter	2cm
Synchronous phase	-30°
DT cell number	36
Focus magnetic field	80-35 T/m
Q	69800
Wall loss	720 kW
Beam power	800 kW
Emittance	
x(rms)	0.048 πcm.mrad
y(rms)	0.035 πcm.mrad
z(rms)	0.0053 πMeV.rad

D. RF source

Three sets of 201.25 MHz RF sources with 1 MW peak class amplifier are required (641 kW for RFQ and two 760 kW for DTL) for BTA. The tetrode tube 4CM2500KG (EIMAC), which was originally developed for fusion plasma heating, is used with multistage amplifier configuration. The RF source was designed and one set of the amplifier is being manufactured by the Sumitomo Heavy Industries, LTD.. The high power amplifier (HPA) is driven by a 60 kW intermediate amplifier (IPA of RS2058CJ) which is fed by a master oscillator and a 3 kW solid state drive amplifier. The accelerator voltage and phase control loop with an accuracy of <0.1 % in amplitude and <10 in phase are being prepared. The high power test for HPA is underway.

E. High β linac

The accelerator cavities and rf system for high β structures dominate the construction cost for ETA. The conceptual and optimization studies for the ETA are performed concerning proper choice of operating frequency, energy configuration, type of high β structure based on the beam dynamics and mechanical engineering considerations in collaboration with Los Alamos National Laboratory. RF source aspects on the trade-offs between large and small amplifiers are investigated. The preliminary specification for the ETA high β linac is given in Table 7.

Table 7. A Specification of High β linac

Beam energy	1.5 GeV
Beam current	10 mA
Beam power	15 MW
Maximum beam loss	<1nA/m
Total average RF power	37 MW
Overall length	1300 m

IV. SUMMARY

A conceptual design studies of an accelerator driven actinide transmutation plant with a sodium cooled target/core have been carried out. The proposed plant transmutes about 250 kg of minor actinide (MA) per year with a 1.5 GeV, 39 mA proton accelerator and generate enough electricity for the accelerator. The solid target/core design is compared with a molten-salt option from the stand point of system design.

The R&D works with the design and construction of prototype accelerator structures (Ion source, RFQ, DTL and RF source) for high power test (hot model) are in progress. For the high power test, measurements of the electric and magnetic characteristics of tbe accelerator structure are underway with the single unit of high power RF source prepared. Problems of heat dissipation and heat removal in the structure are carefully studied. The detailed design works for BTA construction are followed in the next stage based on the results of the R&D works.

ACKNOWLEDGMENT

The authors would like to thank Dr. Y. Kaneko and Dr. Hiraoka for their encouragement and support in the present work. They are also indebted to all the collaborators in Accelerator Engineering Laboratory and Nuclear Spallation Study Group for valuable discussions and suggestions.

REFERENCE

1. Y. Kaneko, "The Intense Proton Accelerator Program", The 2nd Int. Symp. on Advanced Nuclear Energy Research, Mite, 1990, p 25.

2. T. Takizuka et al., "Conceptual Design Study of an Accelerator–based Actinide Transmutation Plant with Sodium–cooled Solid Target/Core", the 2nd OECD/NEA Information Exchange Meeting on Partitioning and Transmutation of Actinides and Fission Products, ANL, Argonne, 1992

3. T. Mukaiyama et al., "Conceptual Study of Actinidc Burner Reactor", 1988 Int. Reactor Physics Conference, Jackson Hole 1988.

4. Y. Nakahara et al., "NMTC/JAERI A Simulation Code System for High Energy Nuclear Reactions and Nucleon-Meson Transport Processes", JAERI–M 82-198 (1982)

5. H. Katsuta et al., "A Continuous Transmutation System for Long-lived Nuclides with Accelerator–Driven Fuel Targets", the 2nd OECD/NEA Information Exchange Meeting on partitioning and Transmutation of Actinides and Fission Products, ANL, Argonne, 1992.

6. T. Nishida et rd., "Benchmark Study on Computational Model in the Accelerator–based Transmutation Simulation Code," OECD/NEA Specialists' Meeting on Accelerator-based Transmutation, PSI, Würenlingen/Villigen 1991.

7. H. Takada et al., "Production of Radioactive Nuclides in a Lead Assembly with 500 MeV Proton", ibid.

8. M. Mizumoto et al.,"High Intensity Proton Accelerator for Nuclear Waste Transmutation", 1992 Lineae Accelerator Conference Proceedings, 1992 August 24-28, Ottawa, Ontario, Canada, C. R.Hoffman Editor, AECL-10728, p.749–751.

9. Y. Okumura et al., "Development of A High Brightness Ion Source for the Proton Linear Accelerator (BTA) at JAERI", ibid. p.645-647

10. K. Hasegawa et al.,"Design Study on An RFQ for The Basic Technology Accelerator in JAERI", ibid. p.314–316

11. Los Alamos Accelerator Code Group, "Computer Codes for Particles Accelerator Design and Analysis", LA–UR–90–1766, 1990.