4. Application

4.1 HIGH INTENSITY PROTON ACCELERATOR AND ITS APPLICATION (PROTON ENGINEERING CENTER)

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A plan called PROTON ENGINEERING CENTER has been proposed in JAERI. The center is a complex composed of research facilities and a beam shape & storage ring based on a proton linac with an energy of 1.5 GeV and an average current of 10 mA. The research facilities planned are OMEGA・Nuclear Energy Development Facility, Neutron Facility for Material Irradiation, Nuclear Data Experiment Facility, Neutron Factory, Meson Factory, Spallation Radioisotope Beam Facilty, and Medium Energy Experiment Facility, where high intensity proton beam and secondary particle beams such as neutrons, π-mesons, muons, and unstable isotopes originated from the protons are available for promoting the innovative research of nuclear energy and basic science and technology.

1. BACKGROUND

In '80s, a few of dawnlike activities have been made for high intensity proton accelerators to apply it to the nuclear fuel breeding and the incineration of high level radioactive waste.[1,2] After the partitioning and transmutation R&D program OMEGA was proposed by the Atomic Energy Agency(AEC) of Japan in 1988, JAERI has made an intensive work of the OMEGA program to study a transmutation system of minor actinides(MAs) with a proton accelerator as an option, and proposed the development of the high intensity proton linac, called Engineering Test Accelerator(ETA) with an energy of 1.5 GeV and an average current of 10mA.[3] In the course of the ETA development, since 1991, Research & Development(R&D) has been continued concerning the initial stage components; high brightness ion source, radio-frequency quadrupole linac(RFQ), drift-tube linac(DTL), and radio-frequency source(RF), as well as the conceptual design of the ETA collaborating with the LANL in USA.[4,5]

Besides, the potential possibility for applying the ETA to development of new nuclear energy production system and basic sciences has been discussed in addtion to the transmutation of MAs,[6] and recently an idea of Proton Engineering Center was proposed to apply the ETA for versatile purposes.[7]

2. OUTLINE OF THE PROTON ENGINEERING CENTER

Fig. 1 is a bird-eye figure based on a preconceptual layout of the PROTON ENGINEERING CENTER, which is composed of the ETA, a beam shape & storage ring, and seven research facilities as the following;

A. OMEGA・Nuclear Energy Development Facility,
B. Neutron Facility for Material Irradiation,

C. Nuclear Data Experiment Facility,
D. Neutron Factory,
E. Meson Factory,
F. Spallation Radioisotope Beam Facilty,
G. Medium Energy Experiment Facility.

Positive hydrogen of an average current of 10 mA and negative one of about a few mA are accelerated up to 1.5 GeV by the linear acelerator(ETA) with a length of about 1200 m. Positive ion beam of 1.5 GeV is mainly used in the OMEGA/Nuclear Energy Development Facility, and also that of 0.6 GeV extracted on the way for the Neutron Facility for Material Irradiation and the Medium Energy Experiment Facility. On the other hand, a part of negative hydrogen beam of 1.5 GeV is used for the Spallation Radioisotope Beam Facilty, while positive one is guided into the beam shape & storage ring to supply such a pulsed beam with various time structure as to meet various experimental requirements in the Nuclear Data Experiment Facility, Neutron Factory, and Meson Factory.

Beam sharing in the Proton Engineering Center and typical researches in the facilities are demonstrated in Fig.2. The beam intensity of the ETA is almost enough to supply it required from the facilities so that all of the experiments at each facility and each beam line are realized simultaneously.

3. ENGINEERING TEST ACCELERATOR(ETA)

The ETA is a proton linear accelerator, and consists of a high brightness ion source, an RFQ linac, a DTL and a high β linac as demonstrated in Fig.3. The principle parameters are given in Table 1.

Table 1 Principle Parameters of the ETA

Energy	1500 MeV
Average current(H^+,H^-)	10 mA
Peak current	100 mA
Repetiton rate	50 Hz
Duty	10 %
Pulse width	1.0 ms

4. EXPERIMENTAL FACILITY

Table 2 represents a preliminary plan of the main parameters and experimental equipments of the facilities.

4.1 OMEGA and Nuclear Energy Technology Development Facility

A typical PWR of 3000 MWt produces about 25–30 kg of MAs having a long half-life per year.[8] Several concepts have been proposed for proton accelerator-based transmutation system of MAs by JAERI and others,[9] of which the examples are shown

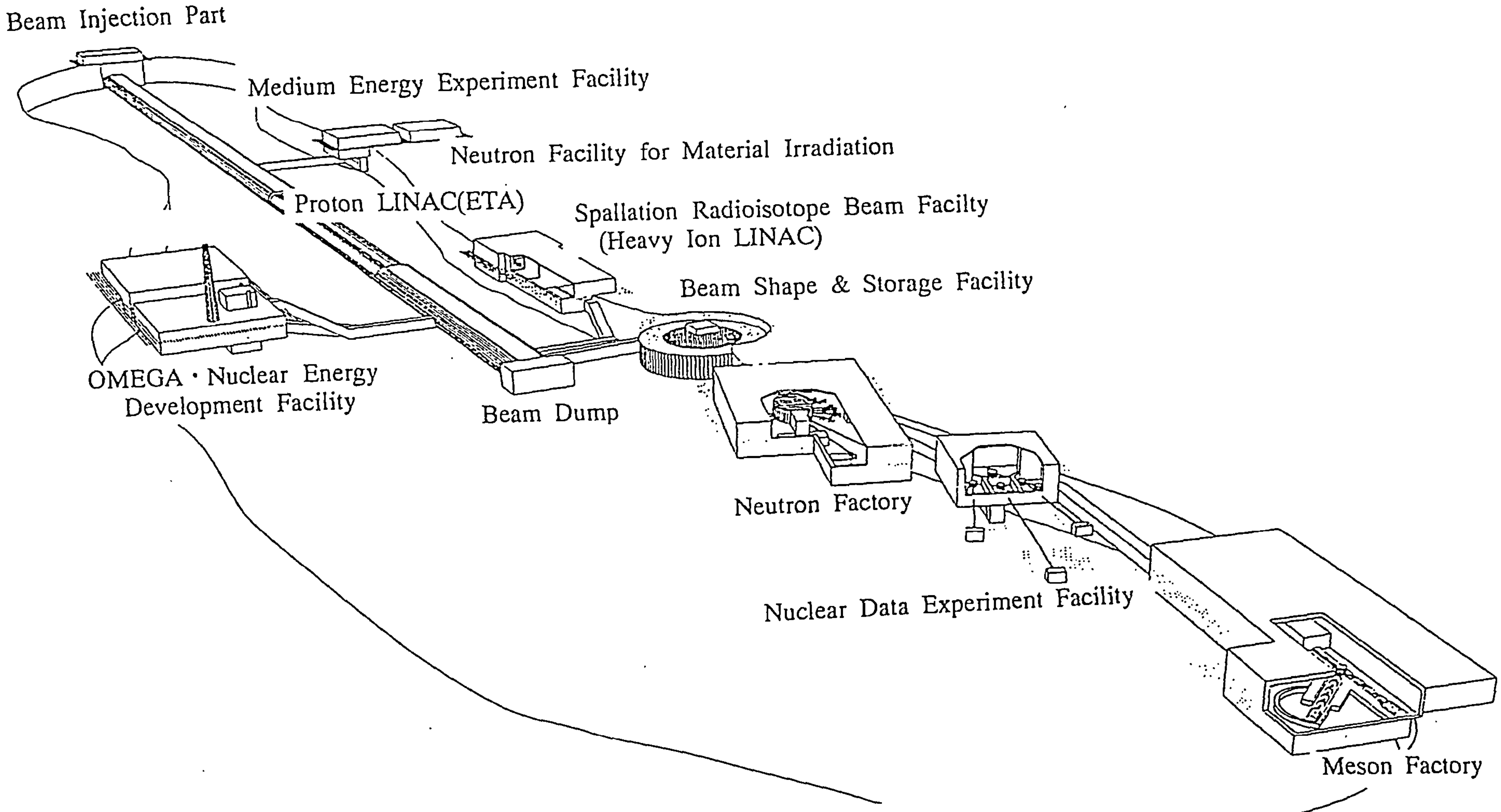

Fig.1 A Bird−Eye Figure of ETA and Research Facilities

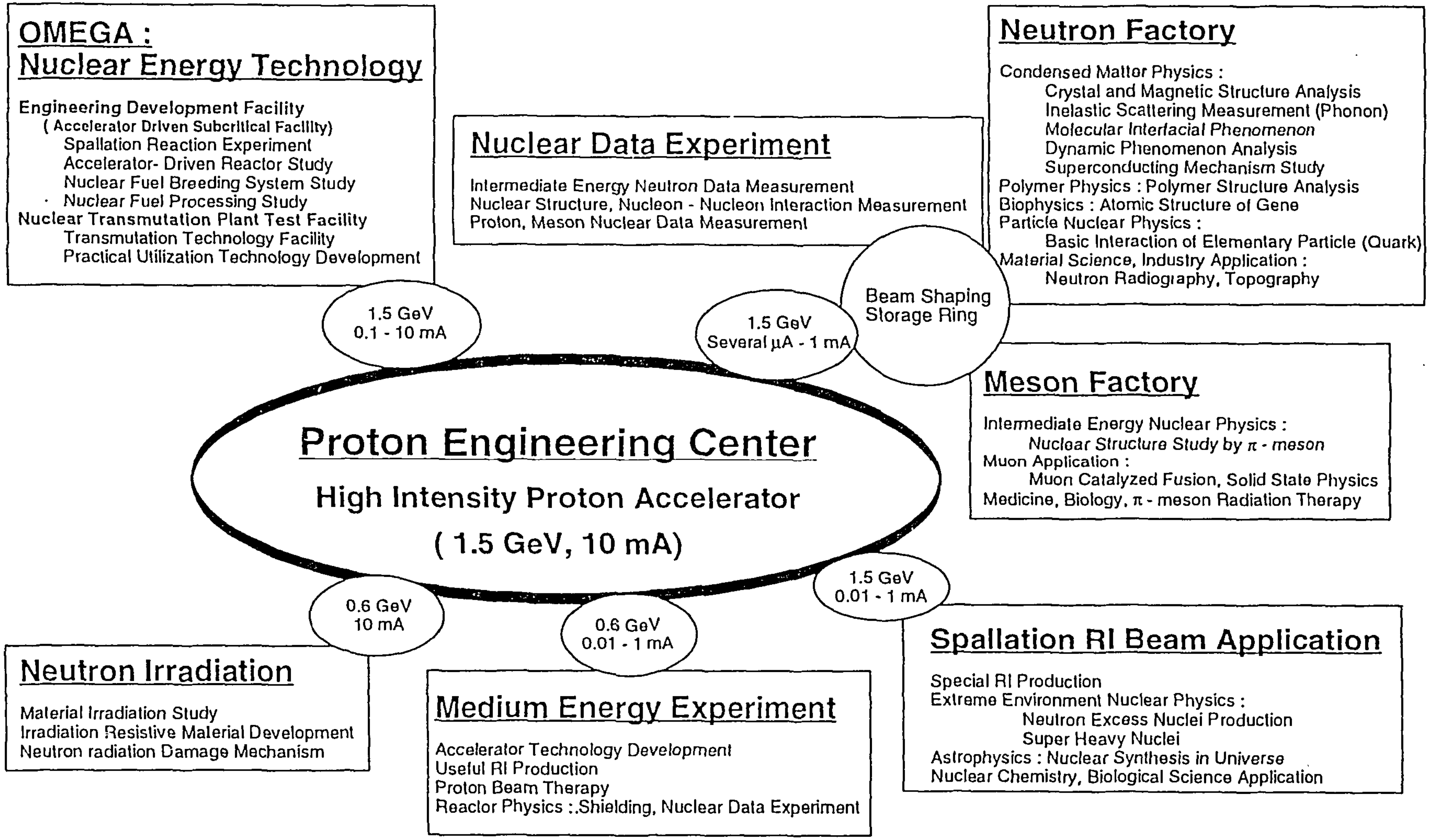

Fig.2 Facilities in Proton Engineering Center & Main Research Items

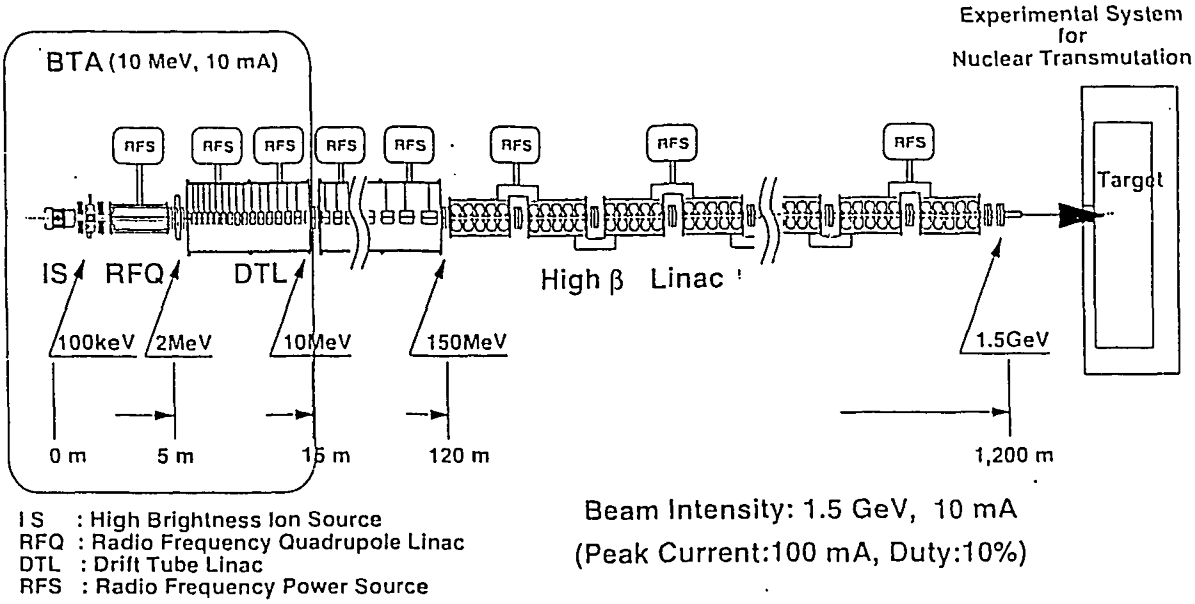

Fig.3 A Conceptual Layout of ETA(Engineering Test Accelerator)

in Figs.4, 5, and Tables 3, 4.[10)]

In this facility, two main experimental facilities; Enginnering Development Facility and Nuclear Transmutation Plant Test Facility, are expected to be consructed for the R&D for the OMEGA program aiming at transmutation of MAs and for the demonstration test of the transmutation plant. In the Enginnering Development Facility, various experiments are made to verify the design base of reactor physics and shielding of accelerator–driven

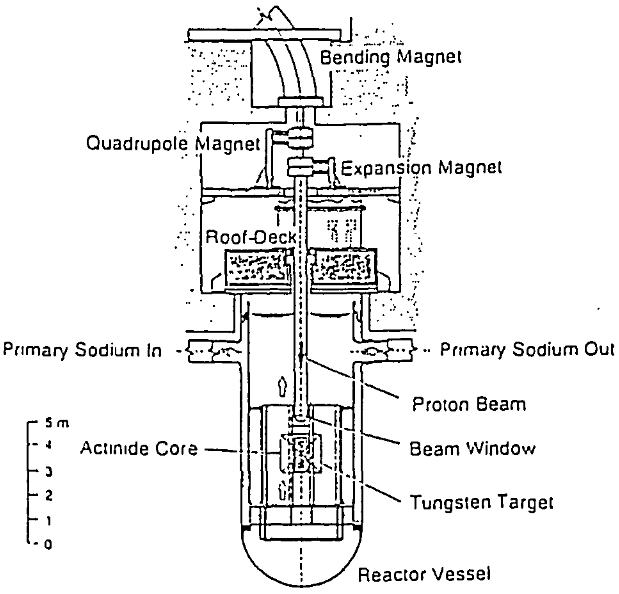

Fig.4 Solid Target/Core System

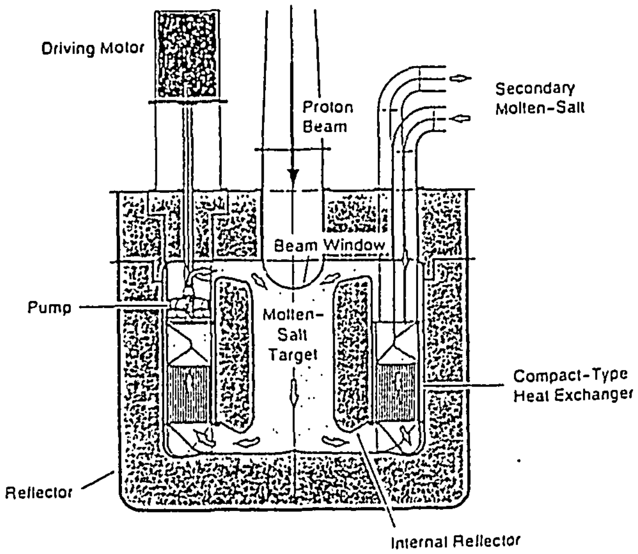

Fig.5 Molten Salt Target/Core System

Table 2 Features of Facilities in Proton Engineering Center

OMEGA · Nuclear Energy Development Facility

MAIN FACILITY	PRINCIPAL PARAMETERS	
Engineering Development Facility	Proton energy	1.5 GeV, 0.1 - 10 mA
	Apparatus	Accelerator driven subcritical assembly
		Spallation reaction experiment facility
		Fuel processing test facility
		Elementary technology development facility
	Floor plan	100 x 80 m^2
Nuclear Transmutation Plant Test Facility	Proton energy	1.5 GeV, 10 mA
	Experimental apparatus	Transmutation plant demonstration facility
	Floor plan	80 x 80 m^2

Neutron Facility for Material Irradiation

MAIN FACILITY	PRINCIPAL PARAMETERS	
Neutron Irradiation Facility	Proton energy	0.6 GeV, 10 mA
	Maximum flux	$2x10^{16}$ n/cm^2s
	Volume	1 - 2 litre
		(>100 dpa/y for SUS)
	Post Irradiation Experimental Facility	Neutron & muon probes
	Floor plan	50 x 50 m^2

Nuclear Data Experiment Facility

MAIN FACILITY	PRINCIPAL PARAMETERS	
Nuclear Data Measurement Facility	Proton energy	1.5 GeV, several μA – 1 mA
	Secondary radiations	neutrons, π
	Time of flight	50 - 100m(3 flights)
		20 - 50m(3 flights)
	Pulse width	~ns
	Floor plan	50 x 50 m^2

Neutron Factory

MAIN FACILITY	PRINCIPAL PARAMETERS	
Slow Neutron Facility	Proton energy	1.5 GeV, 0.1 - 1 mA
	Beam channel	20
	Neutron energy	10^{-7} - 10 eV
	Pulse width	<200 ns
	Peak flux	10^{17} n/cm^2s
	Floor plan	100 x 100 m^2
		20 x 20 m^2

Table 2(continued)

Meson Factory

MAIN FACILITY	PRINCIPAL PARAMETERS	
μ Facility	Proton energy	1.5 GeV, 0.1 - 1 mA
	Beam channel	28
	μ energy	10 keV - several 10 MeV
	Pulse width	50 - 20 ns
	Beam intensity	10^7 - 10^9 /s
π-meson Facility	Beam channel	3
	π-meson energy	0.5 - 1 GeV/c
ν Facility	Beam channel	1
	Floor plan	150 x 60 m^2 (μ) 50 x 80 m^2 (π) 30 x 50 m^2 (ν)

Spallation Radioisotope Beam Facilty

MAIN FACILITY	PRINCIPAL PARAMETERS	
Spallation RI Production Facility	Proton energy	1.5 GeV, 0.01 - 1 mA
	Target/Ion source	300 kV
Heavy Ion Linac	Energy	10MeV/u
	Accelerated ion	proton - Uranium
	Beam intensity	1 ppA - 1μpA
	Floor plan	100 x 40 m^2 (Linac) 50 x 50 m^2 (Experiment)

Medium Energy Experiment Facility

MAIN FACILITY	PRINCIPAL PARAMETERS	
Experiment Facility	Proton energy	0.6 GeV, 0.01 - 1 mA
	Beam channel	RI production Multi-purpose
	Floor plan	50 x 60 m^2

Beam Shape & Storage Ring

MAIN FACILITY	PRINCIPAL PARAMETERS	
Shaping - Storage Ring	Proton energy	1.5 GeV, 0.1 - 1 mA
	Ring length	200 m
	Pulse width	<20 ns for meson <200 ns for neutron
	Floor plan	100 x 80 m^2

subcritical system, and further for developing the spallation target system and the beam window and so forth which are essential technology for making the transmuation system realized. Besides, this facility is also expected to be used for the R&D of hybrid energy production and fuel breeding reactor system using proton accelerators.

The Nuclear Transmutation Plant Test Facility should be constructed for demonstrating the total enginnering system based on the results in the Engineering Dvelopment Facility.

Table 3 Design Parameters and Operating Condition for Solid Target/Core System

Fuel	Metal Alloy Np-15Pu-30Zr AmCm-36Pu-10Y
Target	Soild Tungsten
Primary coolant	Liquid sodium
Actinide inventory	3160 kg
Multiplication factor(k_{eff})	0.89
Spallation neutrons(z)	40 n/p
Proton beam	1.5 GeV - 39 mA
Thermal power(W)	820 MW
Burnup	250 kg/y(8.0% per year)
Power density	930 MW/m^3 (Max.) 400 MW/m^3 (Avg.)
Temperature, Core Inlet/Outlet	330/430 °C
Coolant maximum velocity	8 m/s

Table 4 Design Parameters and Operating Condition for Molten Salt Target/Core)

Fuel	Chloride salt $64NaCl-5PuCl_3-31MACl_3$ (MA: Np, Am, Cm)
Target	Chloride salt
Primary coolant	Chloride salt
Actinide inventory	5430 kg
Multiplication factor(k_{eff})	0.92
Spallation neutrons(z)	38 n/p
Proton beam	1.5 GeV - 25 mA
Thermal power(W)	800 MW
Burnup	250 kg/y(4.6% per year)
Power density	1660 MW/m^3 (Max.) 310 MW/m^3 (Avg.)
Temperature, Core Inlet/Outlet	650/750 °C
Coolant maximum velocity	3.6 m/s

4.2 Neutron Facility for Material Irradiation

To confirm the integrity of materials for fast neutron irradiation is very important to endorse the life and safety of nuclear plants. In this context, fast neutron irradiation facility for materials is an essential one for developing fission and fusion reactors, and several fission reactors have been constructed for material irradiation testing. However, no accelerator-based fast neutron irradiation facility, so far, has been constructed, although a couple of ideas have been proposed using d-Li reaction neutrons[11] and spallation neutrons[12,13] from deutron and proton accelerators.

A comparison of neutron flux and corresponding irradiation volume is demonstrated among typical existing and planned neutron irradiation facilities in Table 5. As an intensity of average 10 mA of 0.6 GeV protons is available in the present facility as shown in Fig.3, the neutron intensity above 0.4 MeV is about 5x10^{14} n/cm^{2}s at 10 cm and 5x10^{15} n/cm^{2}s at 1 cm estimated from the EURAC's design for Pb target, which is about one-order higher than that of IFMIF in the ratio of flux-volume.[14]

The present facility is expected to be used for material researches as a powerful pulsed neutron source to complement ion-beam accelerators and fission reactors for material irradiation and researches.

Table 5 Typical Existing and Planned Neutron Irradiation Facilities

Reactor		
	JMTR(JAERI)	ϕ=4 x10^{14} n/cm^2 s
	HIFR(ORNL)	ϕ=1.4x10^{15} n/cm^2 s (30dpa/y for SUS)
	HIFR-RB(ORNL)	ϕ=7 x10^{14} n/cm^2 s (10dpa/y for SUS)
	ORR(ORNL)	ϕ=3.0x10^{14} n/cm^2 s (4dpa/y for SUS)
	ANS(ORNL)	ϕ>1.4x10^{15} n/cm^2 s (planned)
Accerelator		
	IFMIF	Li target E_d=35MeV, Beam current=250mA Continuous operation(CW) ϕ=1.5x10^{14} n/cm^2 s V = about 1 litre
	EURAC(ISPRA)	Spallation target(Pb) E_p=0.6GeV, Beam current=6mA Quasi-pulse operation 2x10^{16} n/cm^2 s (max 320dpa/y for SUS) V = 1-2 litre(>100dpa/y for SUS)
	ETA	Spallation target(Pb) E_p=0.6GeV, Beam current=10mA Pulse operation 2x10^{16} n/cm^2 s (maximum) V > 1-2 litre(>100dpa/y for SUS)

ϕ:neutron flux, V:irradiation volume

4.3 Nuclear Data Experiment Facility

In this facility, versatile experimental data are measured to verify theoretical models and directly for special purposes with respect to protons and neutrons from 20 to 1500 MeV, π-meson, and various secondary particles produced by protons and neutrons. For example, Koning[15] summarizes the data requirements for accelerator-based transmutation as Table 6.

The necessity for intermediate-energy nuclear data libraries up to a few GeV is increasing not only for accelerator-based transmutation, but also in medical field, fusion material research, space exploration research, and fundamental nuclear science. Nevertheless, the present status of intermediate-energy nuclear data is far from the level required in the quality and quantity, furthermore, the experimental facilities are completely insufficient worlwidely.

The Nuclear Data Experiment Facility is expected to become an international center of excellence in nuclear data research, in addition to the production of qualified nuclear data.

Table 6 Requirements for Evaluated Nuclear Data File for Accelerator-Based Transmutation

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Energy range covered
- a data library from 0 to about 100 MeV
- a reference data library from 20 to 1500 MeV
- an activation/transmutation library from 0 to 100 MeV

Materials
- Targets :Ta, W, Pb, Bi
- Actinides :^{238}U, ^{237}Np, ^{238}Pu, ^{241}Am, ^{243}Am, ^{244}Cm, ^{245}Cm
- Shielding & Reactor:H, C, N, O, Na, Mg, Al, Ar, K, Ca, Cr, Mn, Fe, Co, Ni, Cu Zn, Zr

Projectile
- Neutron, Proton

Data for neutrons and protons
- (n,xn),(n,xγ) double differential cross section
- Neutron and photon yields
- Products yields as a function of energy
- (n,fission) cross section

4.4 Neutron Factory

This facility is proposed to use slow neutrons for condensed matter physics, polymer physics, biophysics, particle nuclear physics, and other applications. The proton beam firstly is introduced into the beam shape & storage ring from the ETA to produce the pulsed beam having various time structure required in the Neutron Factory, and after that the pulsed proton beam with an enegy of 1.5 GeV and the maximum current of 1 mA bombards neutron targets to generate pulsed neutrons from 10^{-7} to 10 eV. The proton beam of 1.5 MW, which is a little bit greater than that of the SINQ(Swiss Intense Neutron Source "Quelle") under construction and smaller than 5 MW of the ESS(European Spallation Source) planned, could generate a peak neutron flux of about 10^{17} n/cm^{2}s-eV which is several hundreds times higher than that of JRR-3M, and the intense neutrons are expected to be available for developing new scientific fields such as time-dependent behavior in biology and material sciences.

In this facility, various experimetal researches can be performed simultaneously using more than 20 beam lines, which looks like a research factory using neutrons.

4.5 Meson Factory

This facility is composed of muon channels, π-meson chinnnels and a beam dump for neutrino experiment. A model of the meson factory is the Meson Arena in the JHP(Japan Hadron Project)[16]. Muon beams from about 10 keV to several 10 MeV are produced by thin targets using pulsed proton beam from the beam shape & storage ring, and are provided for various experiments through the beam lines equipped around the targets. The muon intensity is 2-3 orders stronger than those in the exsisting muon facilities of LAMPF, TRIUMF, and ISIS. The intense muon beam is powerful not only for the μCF(muon-catelyzed fusion) and as a probe of the μSR(muon spin resonance), but it is expected that a new field of muon science is developed as a meson factory.

4.6 Spallation Radioisotope Beam Application Facilty

Various radioisotopes will be produced via spallation process by bombading a target with proton beam of 1.5 GeV. In this facility, the produced radioisotopes are seperated using an ISOL(Isotope Seperator on Line), and then accelerated up to 10 MeV/nucleon by a heavy ion linac, which is the same concept with the Exotic Nuclei Arena in the JHP.

It is thought that the present facilty develop a new frontier in nuclear structure investigation with respect to super-heavy elements and astrophysics based on the advanced research at the Tandem-Booster[17] of JAERI.

4.7 Medium Energy Experiment Facility

Proton beam of 0.6 GeV is guided to the facility to do complemental experiments for proton beam of 1.5 GeV and to develop the technology of proton beam applications for medicine and industry. Specially, it is expected that the intense proton beam is powerful for massive-production of radioisotopes tabulated in Table 7 which are useful for therapy, diagonosis, and industrial applications.

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Table 7 Useful Radioisotopes Produced by Proton Accelerator

$^{68}\mathrm{Zn(p,2n)}^{67}\mathrm{Ga}$	:Diagonosis of tumor
$^{203}\mathrm{Tl(p,3n)}^{201}\mathrm{Pb} \rightarrow {}^{201}\mathrm{Tl}$	:Diagonosis(Sacnning) of myocardium
$^{111}\mathrm{Cd(p,n)}^{111}\mathrm{In}$	:Scintigraphy of brain
$^{127}\mathrm{I(p,5n)}^{123}\mathrm{Xe} \rightarrow {}^{123}\mathrm{I}$	:Therapy of thyroid
$^{16}\mathrm{O}(\mathrm{p},\alpha)^{13}\mathrm{N}$	:Positron tomography(PET)
$^{14}\mathrm{N}(\mathrm{p},\alpha)^{11}\mathrm{C}$	:Positron tomography(PET)
$^{58}\mathrm{Ni(p,pn)}^{57}\mathrm{Ni} \rightarrow {}^{57}\mathrm{Co}$	:Calibration source, Mossbauer

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