Conceptual Design Study of an Accelerator-based Actinide Transmutation Plant with Sodium-cooled Solid Target/Core

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ABSTRACT

Research and development works on accelerator-based nuclear waste transmutation are carried out at JAERI under the national program OMEGA. The preliminary design of the proposed minor actinide transmutation plant with a solid target/core is described. The plant consists of a high intensity proton accelerator, spallation target of solid tungsten, and subcritical core loaded with actinide alloy fuel. "Minor actinides are transmuted by fast fission reactions. The target and core are cooled by the forced flow of liquid sodium coolant. Thermal energy is recovered to supply electricity to power"& own accelerator.

The core with an effective multiplication factor of about 0.9 generates. the thermal power of 820 MW by using a 1.5 GeV proton beam with a current of 39 mA. The average burnup is about 8°/0, about 250 kg of actinides, after one year operation at an 80°/0 of load factor. With the conventional steam turbine cycle, electric output of about 246 MW is produced.

The design of the transmutation plant with sodium-cooled solid target/core is mostly based on the well-established technology of current LMFRs. Advantages and disadvantages of solid target/core are discussed.

Recent progress in the development of intense proton accelerator, the development of simulation code system, and the spallation integral experiment is also presented.

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A preliminary conceptual design study was made for an accelerator-based minor actinide transmutation plant which consists of a sodium-cooled subcritical core with actinides alloy fuel and a spallation target of tungsten. The core with an effective multiplication factor of about 0.9 is driven by a 1.5 GeV proton beam with a current of 39 mA, and generates the thermal power of 820 MW. The average burnup is about 8%, about 250 kg of actinides, after one year operation at an 80% of load factor. The plant produces an electric power of about 246 MW with the conventional steam turbine cycle, and supplies sufficient electricity to power its own accelerator. The solid target/core design is compared with a more advanced molten-salt target/core option.

Recent progress in the development of a simulation code system, the spallation integral experiment, and the development of a high intensity proton linear accelerator is also presented.

INTRODUCTION

The Japan Atomic Energy Research Institute (JAERI) is formulating a long-term research and development plan for partitioning and transmutation of minor actinides and long-lived fission products under a national program called OMEGA[1] (Options Making Extra Gains from Actinides and Fission Products). The JAERI R&D plan includes the conceptual design study of accelerator-based 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. In either system, an actinide-loaded subcritical core is driven by a high-energy, 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. On the other hand, the molten-salt system is a more advanced concept with the capability of continuous on-line processing. The goal of the study is to develop a feasible design concept of the accelerator-based actinide transmutation plant.

As compared with usual nuclear reactors, an accelerator-driven system does not require 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.

In this paper, a conceptual design of an accelerator-based actinide transmutation system with a sodium-cooled solid target/core is presented, and is compared with a molten-salt target/core option from the standpoint of system design. The description of the conceptual molten-salt system is given in the companion paper[2].

This paper also outlines the related R&D activities on accelerator-based transmutation; the simulation code development, the spallation experiment, and the development of an intense proton accelerator.

DESIGN CONCEPT

The proposed plant is designed as a dedicated system that transmutes about 250 kg of minor actinides per year by fission, which corresponds to the annual actinide production from about 10 units of 3,000 MWt light water reactors. The subcritical core is required to operate at an effective multiplication factor of around 0.9 or more to reduce the scale of proton accelerator and improve the energy balance of total system. Hard neutron spectrum is used to transmute actinides effective y by fission.

Schematic diagram of the proposed plant concept is shown in Fig. 1. The accelerator injects 1.5 GeV proton beam into the tungsten target located at the center of the core. The core is loaded with actinide alloy fuel. A large number of neutrons are released by spallation reaction in the target, and induce further fission reactions in the actinide fuel region. The core generates a thermal power of about 820 MW, and is cooled by the forced upward flow of sodium primary coolant. Heat is transported through the primary and the secondary loops to the power conversion system. In the energy conversion system, thermal energy is converted into electricity. A part of electric power is supplied to its own accelerator.

ACTINIDE FUEL

Metallic alloy of minor actinides is used as fuel. In order to maintain sufficiently high phase stability of alloy, the fuel is composed of two distinct alloy systems; Np-15Pu-30Zr and AmCm-35Pu-10Y. These alloy systems are proposed for a conceptual sodium-cooled actinide burner reactor[3]. Metallic fuel allows to implement a compact fuel cycle based on pyrochemical processes' and provides a hard neutron spectrum.

In the design, maximum fuel temperature is limited to 900 'C, because of low melting-point of minor actinide alloy. Actinide fuel slug with a diameter of 4 mm is sodium-bonded to the cladding made of oxygen dispersion strengthened (ODS) alloy. The outside diameter of the cladding is 5.22 mm, and the thickness is 0.3 mm. Fuel design parameters are summarized in Table 1.

A pictorial view of the fuel assembly is shown in Fig. 2. To ensure adequate fuel cooling during the out-of-core handling operation, the assembly design has several unique features; the structure members are six tie-rods near the comers rather than a hexagonal wrapper tube, number of fuel pins per assembly is as small as 55, pitch of the fuel pin array is as wide as 8.7 mm, fuel pins containing Am and Cm are arranged on the outermost row of the army while Np-containing pins are arranged on the inner rows.

Active length of the fuel pin is 1.4 m. Each fuel pin contains a gas vent mechanism and upper reflector in its upper section. Because of relatively wide fuel pin spacing, grid type spacers are employed rather than wirewrap spacers. Sodium coolant enters the assembly from the entrance nozzle at the bottom, and flows upward through the space between fuel pins, and exits from the handling head at the top.

TARGET/CORE

The core consists of two regions; the tungsten target region and the actinide fuel region. The target region is located in the center of the core. The target consistsof61 target assemblies, which together form an approximate right circular cylinder, with a diameter of about 0.4 m and a height of 1.4 m. The target assembly has the same cross sectional dimensions as theactinide fuel assembly.

The target region is surrounded by the annular actinide fuel region, 1.4 m in outside diameter and 1.4 m in height. The fuel region is made up of 378 fuel assemblies. Around the fuel region is reflectors made of stainless steel. Thickness of upper and lower axial reflectors is 0.4 m, and side reflector thickness is 0.6 m.

High energy protons are injected vertically downward through the beam window into the target. The tungsten target acts as the spallation neutron source. The volume fraction of tungsten in the target is varied along the beam axis to produce a desirable shape of high energy neutron flux distribution from the target. The target is inactive, or it does not contain any fissile or fissionable materials. This eliminates the power peaking at the core center, and thus considerably flattens the core power distribution.

The whole core including the reflector is contained within a steel reactor vessel as shown in Fig. 3. The vessel diameter is about 4.6 m and the height is about 14 m. The reactor is o f loop' type. Primary coolant sodium enters the vessel from the inlet nozzle, and then flows downward through annular space between the vessel and the core barrel into lower plenum. Then, it turns upward, removes the heat from fuel and target during its passage through the core, and exits from the vessel through the outlet nozzle.

A vertical tube for beam path is inserted into the reactor vessel down to just above the target region in the core. The bottom end of the tube is the beam window made of ODS alloy. The beam window has a form of hemispherical shell and is cooled by the upward impinging sodium flow from the target exit.

Core design parameters are summarized in Table 2. The volume of active core is about 2 m^3. Maximum coolant flow velocity through the active core is limited to 8 m/s to avoid the possibility of flow-induced vibration of fuel pins. Core inlet sodium temperature is selected to be 330 "C. This somewhat lower coolant temperature than levels in standard sodium-cooled reactors helps to achieve a high core power density, or a high transmutation rote, at the expense of decreasing the power conversion efficiency.

Figure 4 is the calculated power density distribution in the core. The core generates a thermal power of 820 MW for the 1.5 GeV and 39 mA proton beam. 800 MWt is generated in the actinide fuel region and 20 MWt in the tungsten target region. In the fuel region, the maximum power density is about 920 M W/m^3 and the average power density about 400 MW/m^3. The maximum power density in the target regions is about 360 MW/m^3.

The calculated temperature distributions along the fuel pin in the hot channel is shown in Fig. 5. Sodium coolant temperature at the hot channel exit is 473 "C. The maximum temperature of the ODS alloy cladding is 528 "C. This value is well below within its design limit of 725 'C. The maximum fuel center-line temperature is 890 'C, which is very close to the maximum allowable temperature of the actinide alloy fuel. This indicates that the peak fuel temperature determines the maximum power in the core.

The core operating parameters are given in Table 3. The core inventory of minor actinide is about 3,160 kg. The effective neutron multiplication factor k_{eff} is calculated to be 0.89. For an incident proton, approximately 40 neutrons are emitted by spallation reactions in the target region. About 100 fissions are induced per proton in the fuel region. Assuming a load factor of 80%, the actinide burnup is approximately 250 kg, or 8%, after one year operation. A fairly hard neutron spectrum with an average neutron energy of 690 keV is achieved in the core.

HEAT TRANSPORT AND POWER CONVERSION SYSTEMS

Heat transport and power conversion systems in the plant design is based on the current state of technology for a sodium-cooled fast breeder reactor plant. The primary heat transport system consists of two sodium coolant loops. Each primary loop has an intermediate heat exchanger and a primary pump. The secondary system also consists of two sodium loops with each having a steam generator and a secondary pump. Steam produced in the steam generators is supplyed to the power conversion system.

A primary reactor auxiliary cooling system (PRACS) consist of two NaK loops. This system is provided as an independent means of removing core afterheat. The core afterheat is ultimately rejected from the air coolers to natural draft of atmospheric air through stacks.

In the power conversion system, steam raised in the steam generators drives a single turbine alternator to produce electricity. Because of the relatively low coolant temperature for a sodium-cooled system, the steam condition is similar to that of a conventional light water reactor plant. The plant efficiency is roughly 30% and therefore the electric output is about 246 MW.

Assuming an efficiency of 40% for the 1.5 GeV, 39 mA proton accelerator, electric power required to operate the accelerator is about 146 MW. This means that the proposed system is more than self-sufficient in terms of its own energy balance, having capability to supply some 100 MW surplus electricity to the external grid.

Parameters of the heat transport and power conversion systems are summarized in Tables 4 and 5, respectively.

COMPARISON WITH MOLTEN-SALT SYSTEM

A preliminary conceptual design study is being conducted on an 800 MWt molten-salt core/target as an advanced option for an accelerator-based nuclear waste transmutation system at JAERI[2]. Chloride salt with a composition of 64NaC1-5PuC1$_3$-31MAC13 (where MA represents Np, Am, and Cm) is chosen for the molten-salt system based on the consideration about actinide volubility and nuclear characteristics.

The study is at a very early stage, and several design problems with the molten salt are still left unsolved especially in the areas of separation chemistry and material compatibility. Therefore, the design of the molten-salt system has not yet been detailed to the same extent as the aforementioned solid system design. In this section, comparison of these two concepts is made to illustrate their relative advantages and disadvantages from the standpoint of system design. Table 6 compares their characteristics.

In the solid system, two actinide alloys of Np-15Pu-30Zr and AmCm-35Pu-10Y are used as 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 target material, and at the same time it also serves as coolant in the molten-salt system. This significantly simplifies the core/target system configuration.

Molten state of fuel salt offers several attractive features for the design of transmutation systems. 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, rather laborious process of actinide fuel fabrication is not required for the molten-salt system. Core melt-down accidents can be impossible as the molten fuel is *ready* to be dumped from the core in case of emergency, which may add a high degree of safety.

In the solid system, the design limit of peak fuel temperature determines the maximum power density of 930 MW/m^3 and hence the core thermal power of 800 MW. The molten-salt core has a much higher maximum *power* density of 1660 MW/m^3 and even the core averaged power density is 940 MW/m^3, exceeding the maximum value of the solid system. The power density is not yet a limiting factor for the performance of the molten-salt core because no solid components are contained in the core. Although a very high power density is achievable in the molten-salt core, this should not be interpreted as meaning that the molten-salt system can entirely circumvent the heat removal problem that determines the actinide transmutation rate. In the molten-salt system, the heat removal problem usually appears instead in intermediate heat exchangers, and it can become still more difficult. The actinide contained in the primary molten-salt loops other than the core region occupies a considerably huge fraction of the total inventory. If the design had followed a conventional design approach with external shell-and-tube type heat exchangers, 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 burnup much less than 2 %/y. Obviously, highly efficient heat exchangers are needed in the molten-salt system to reduce the total volume of the primary loops, unlike the case of the solid system. The present design of the molten-salt system aims at minimizing the total actinide inventory by incorporating compact type heat exchangers 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 averaged over the entire primary volume.

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 mA, about two thirds of that for the solid system. The difference in the beam currents reflects the difference in the neutron multiplication factors in the subcritical cores.

The coolant temperature in the solid core is lower by 320 "C as compared to the molten-salt core. It maybe preferable to operate the molten-salt core in 550-650 "C range, provided that the eutectic melting point is about 450 °C. The requirement to decrease the heat exchanger volume leads to a higher temperature range from 650 to 750 "C. With such a high operating temperature, a power conversion efficiency around 45% becomes feasible by using 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 temperature.

SIMULATION CODE DEVELOPMENT AND SPALLATION INTEGRAL EXPERIMENT

A computer code system is being developed for the nuclear design of the accelerator-based transmutation system at JAERI. 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 MORSE-DD and TWOTRAN 2 codes. The time evolution process of transmutation products is calculated by SPCHAIN code in the higher energy range above 15MeV and by ORIGEN-2 code below 15 MeV. The code system has been continuously upgraded and improved by incorporating current models and methods. The disagreement in the mass yield predictions by NMTC/JAERI and HETC/KFA2 was examined(4), and it was shown that the discrepancy was mainly due to the difference in the estimation of the width of post-fission yield curve.

Spallation integral experiments[s] are underway in order to obtain data on nuclide production, to estimate. the yields of neutrons and spallation products, and to investigate the validity of the spallation simulation code NMTC/JAERI. 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 of lead, with a diameter of 600 mm and a length of 1000 mm (Fig. 6). A target was installed in the center of the lead assembly. Target materials used so far are lead and tungsten. Experiments with a target of depleted uranium is also planned. 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 encased in 8-mm-diameter metal capsules were inserted in the 10-mm-diameter holes drilled through the assembly along the beam axis at various radial positions. The numbers of induced reactions in the samples was obtained by measuring gamma-rays with a 100 cc Ge-detector. Experimental results were compared with prediction by NMTC/JAERI code. The agreement was generally fairly good, but there were significant discrepancies on the centerline of the assembly. It is inferred that these discrepancies are attributed to the high energy nucleon streaming through the gap between the samples and the assembly.

INTENSE PROTON ACCELERATOR DEVELOPMENT

JAERI has proposed to construct a high intensity proton linear accelerator for the purpose of performing various tests for accelerator-based nuclear waste transmutation and other possible nuclear engineering applications(6). The proposed accelerator having a final energy of 1.5 GeV and an average current of 10 mA is called Engineering Test Accelerator, ETA. Conceptual layout of ETA is shown in Fig. 7. ETA consists of an ion source, a radio frequency quadrupole (RFQ), drift tube linacs (DTLs), high-beta acceleration structures, and RF sources.

In cases of high energy and high current beam acceleration, it is of particular importance to minimize beam losses to avoid resultant damage and activation of accelerator structures. The beam quality and current are mainly determined by the low energy portion of the accelerator. So, as a first step toward the construction of ETA, a proton accelerator with an energy of 10 MeV and an average current of 10 mA is developed for the meek-up test of the low energy portion. This 10 MeV-10 mA accelerator is called Basic Technology Accelerator, BTA.

Research and development works for the prototype accelerator componentsare in progress. A 100 keV- 120 mA multi-cusp ion source was fabricated and tests are proceeding satisfactorily. Design of the prototype RFQ and DTL have been almost completed. One of the most critical problems in the mechanical design is heat removal from theaccelerator structures because of the high beam current and duty factor. The high power model tests for the RFQ and DTL will be started in FY 1993.

The conceptual studies for ETA are also underway in collaboration with the Los Alamos National Laboratory (LANL). These studies involve design optimization for the operating frequency, the energy configuration, and the type of high-beta structure of ETA based on beam dynamics and mechanical engineering considerations.

Figure 8 shows the schedule of the program for the intense proton accelerator development at JAERI. BTA will start operation in FY 1997. Construction of ETA is planned to commence in FY 1998, and its operation is expected to start in FY 2003.

SUMMARY

A conceptual design of an accelerator-driven actinide transmutation plant with a sodium-cooled target/core are presented. The proposed plant transmutes about 250 kg of minor actinides per year with a 1.5 GeV, 39 mA proton accelerator and generates enough electricity y for the accelerator. The solid target/core design is compared with a more advanced molten-salt option from the standpoint of system design. JAERI activities on simulation code development, spallation integral experiment and development of intense proton linear accelerator are outlined.

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

(4) T. Nishida et al., "Benchmark Study on Computational Model in the Accelerator-based Transmutation Simulation Code," OECD/NEA Specialists Meeting on Accelerator-based Transmutation, PSI, Würenlingen/Villigen 1991

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Table 1 Fuel design parameters

Fuel Composition	Np-15Pu-30Zr
	AmCm-35Pu-10Y
Slug Diameter	4.0 mm
Clad Material	ODS Steel
Outer Diameter	5.22 mm
Thickness	0.3 mm
Active Length	1400 mm
Pins/Assembly	55
Pin Pitch	8.7 mm

Table 2 Core design parameters

Proton Beam Energy	1.5 GeV
Diameter	400 mm
Target	Solid Tungsten
Fuel	Actinide Alloy
Active Core Volume	2 m^3
Length	1.4 m
coolant	Sodium
Velocity	8 m/s
Inlet Temperature	330°C

Table 3 Operating condition

Proton Beam Current		39 mA
Actinide Inventory		3160 kg
Multiplication Factor		0.89
Neutrons/Proton		40
Fissions/Proton	(>15 MeV)	0.45
	(<15 MeV)	100
Neutron Flux		4×10^{15} n/cm^2·s
Mean Neutron Energy		690 keV
Burnup		250 kg/y (8 %/y)
Thermal Output		820 MW
Power Density	Maximum	930 MW/m^3
	Average	400 MW/m^3
Linear Rating	Maximum	61 kW/m
Maximum *Temperature*		
Coolant		473 °C
Fuel		890 °C
clad		528 ‘C

Table 4 Heat transport systems

Primary System		
No. of Loops		2
Fluid		Na
Temperature	IHX in/out	430/330 'c
Components		IHXs, Primary Pumps
Secondary System		
No. of Loops		2
Fluid		Na
Temperature	SG in/out	390/290 °C
Components		SGS, Secondary Pumps
PRACS (Primary Reactor Auxiliary Cooling System)		
No. of Loops		2
Fluid		NaK
Components		Air Coolers, EM Pumps

Table 5 Power conversion system

Cycle	Saturated Steam Cycle
Turbiie Inlet Temperature	285 'C
Electric Output	246 MW
Efficiency	30%

Table 6 Solid and Molten-Salt System Designs Comparison

	Solid System	Molten-Salt System
Fuel	Metal Alloy	Chloride Salt
	Np-15Pu-30Zr	64NaC1-5PuC1$_3$-31MAC13
	AmCm-35Pu- 10Y	(MA: Np, Am, Cm)
Target	Solid Tungsten	Chloride Salt
Primary coolant	Liquid Sodium	Chloride Salt
Actinide Inventory	3160 kg	5430 kg
Multiplication Factor	0.89	0.92
Spallation Neutrons	40 n/p	38 n/p
Proton Beam	1.5 GeV-39 mA	1.5GeV-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

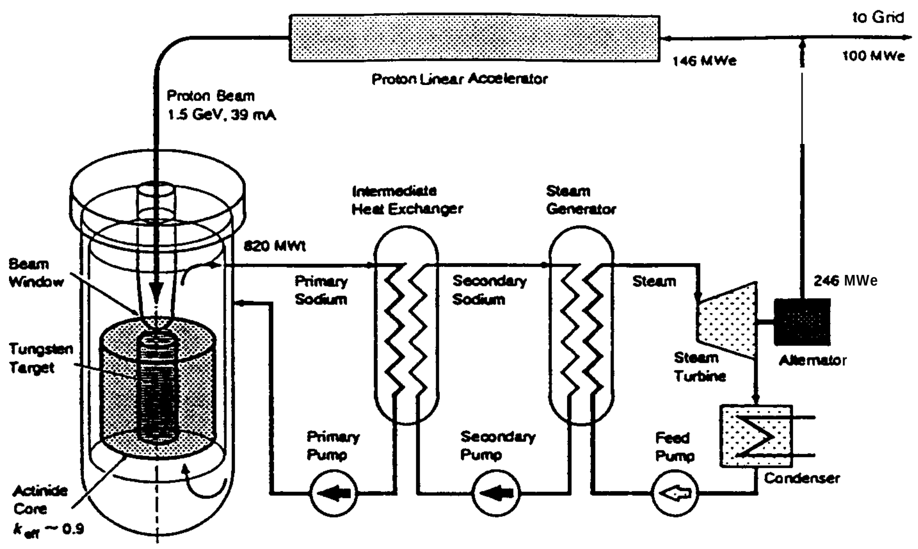

Fig. 1 Concept of Accelerator-based Actinide Transmutation System

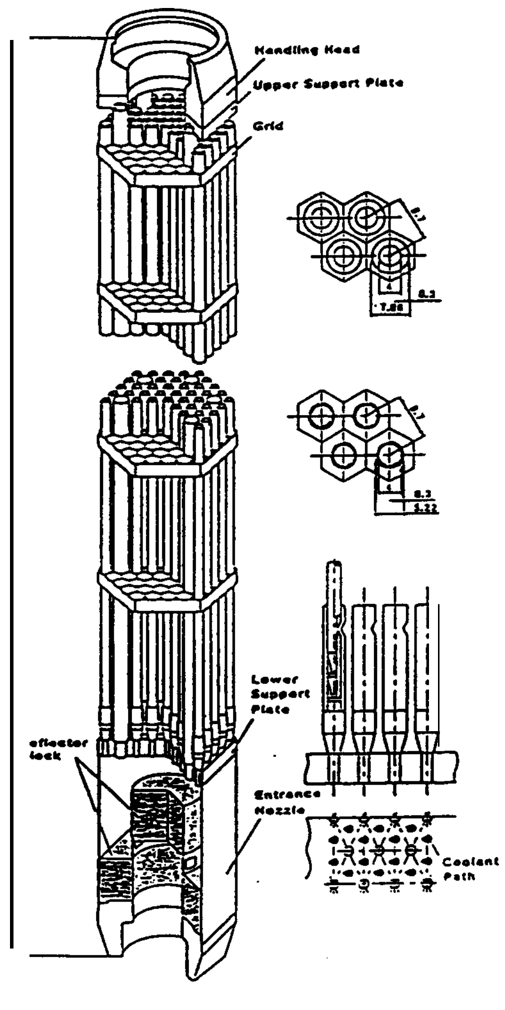

Fig. 2 **Actinide** Fuel Assembly

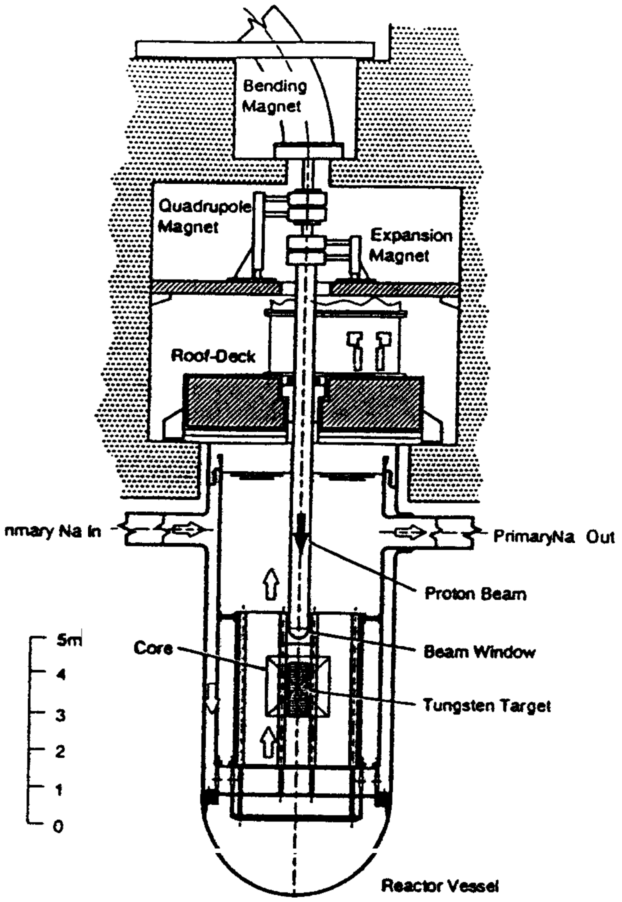

Fig. 3 ‘ **Sodium-cooled** Solid Target/Core

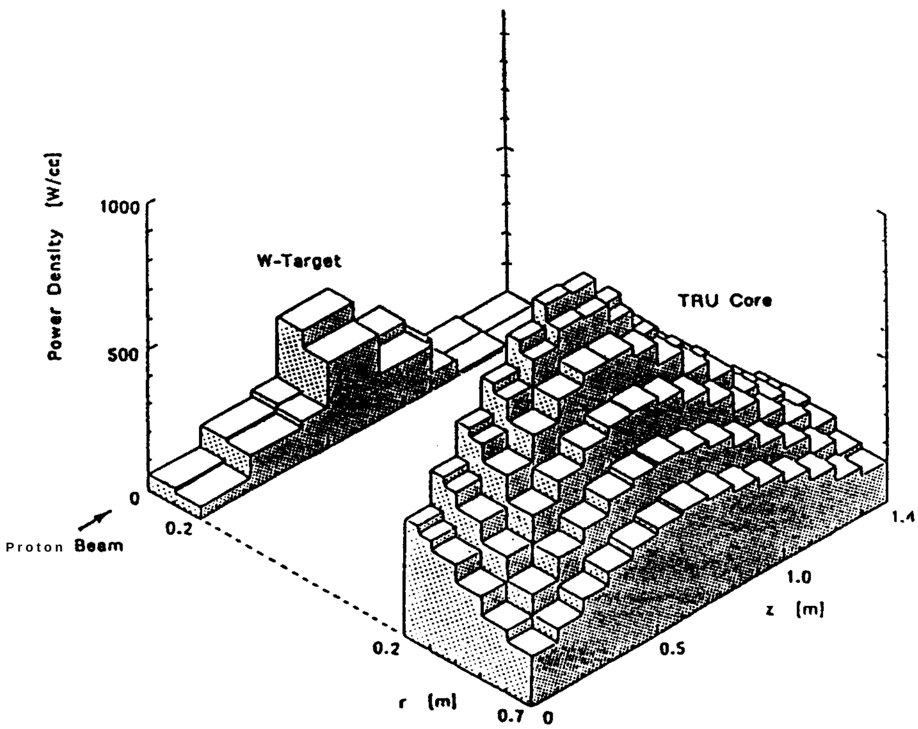

Fig. 4 Power Distribution

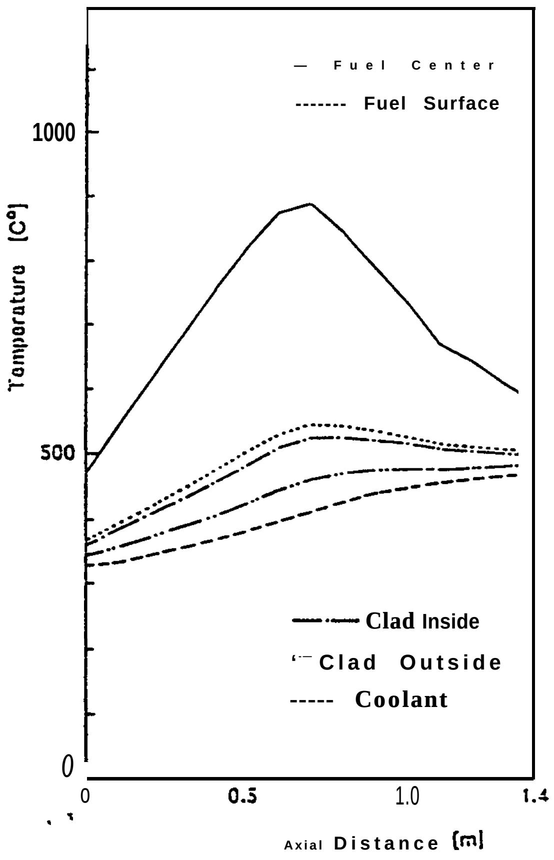

Fig. 5 Temperature Distribution along Hot Channel

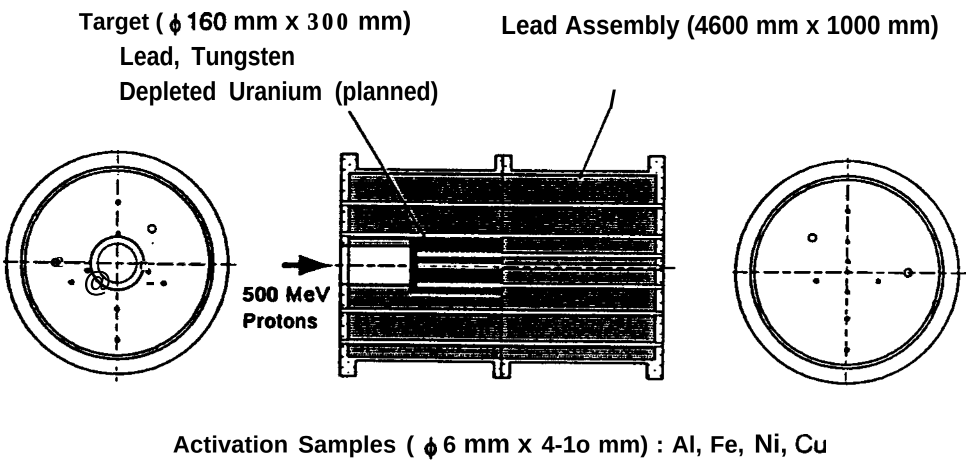

Fig. 6 Lead Assembly for Spallation Integral Experiments

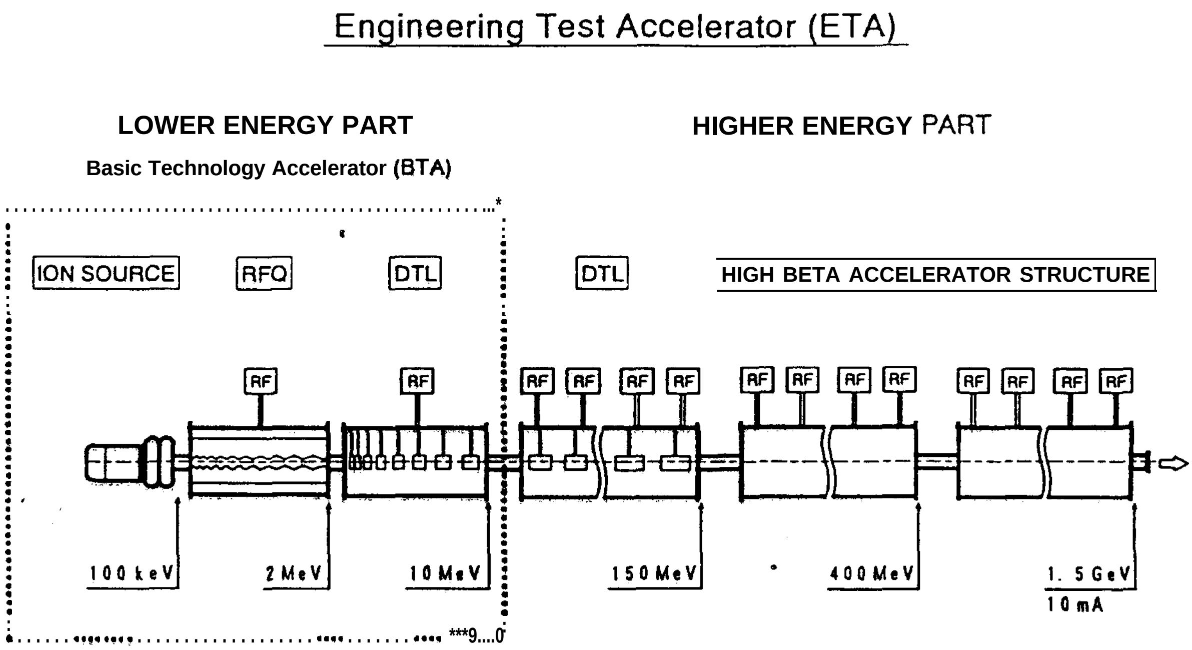

Fig. 7 Conceptual Layout of ETA

(Nov. 5, 1992)

Fiscal Year	1991 92 93 94 95 96 97 98 99 2000
Development of Accelerator Technology	
(1) R&D	Ion Source, RFQ, DTL, RF Source (1991–93)
(2) Basic Technology Accelerator (BTA) (10 MeV-10 mA].	Design, Assembly, Fabrication, Beam Test (93–96); Operation (96–2000)
(3) ETA Building	Design, Construction (93–95)
Engineering Test Accelerator (ETA) [1.5 GeV-10 mA]	optimization Study; Design; Construction

Fig. 8 Schedule of Intense Proton Accelerator Development program