Paper presented at the Specialists' Meeting on Accelerator Based Transmutation (PSI, 24-26 March 1992)

Overview on Nuclear Design Problems of Accelerator-based Transmutation Systems with Emphasis on Target Facilities and Their Interfaces with Accelerators

T. TAKIZUKA

Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken
319-11 Japan

INTRODUCTION

Recently, accelerator-based nuclear waste transmutation has been attracted much attention because of remarkable development in accelerator technology. Nevertheless, concepts of transmutation system proposed so far are limited in number and furthermore they are all in the stage of conceptual or pre-conceptual design study. They are also preliminary, and many challenging problems are left to be solved to detail designs and to establish the technical feasibility of their concepts.

In the absence of detailed design studies, it is premature to evaluate quantitatively the pertinent problems and to identify the priority technical issues due to their impacts on the system designs. The purpose of this paper is not to attempt to give a comprehensive surveyor critical review of generic nuclear design problems related to the accelerator-based transmutation systems. It is aimed at providing points to be discussed in this Specialists' Meeting.

To illustrate the design considerations of a practical system, a conceptual design of accelerator-based minor actinide transmutation plant(l) made at the Japan Atomic Energy Research Institute (JAERI) is briefly described as an example of the proposed systems. The plant transmutes about 250 kg of minor actinides by fission and produces 820 MW thermal power by using a 1.5 GeV proton beam with a current of 39 mA. Electric power of 246 MW is generated with a conventional stare turbine, and supplies sufficient electricity to power the accelerator.

Some problems arising from the design study are presented. Emphasis is placed on the problems related to the nuclear part of the plant design. The scope of this paper also covers such potential problems in other engineering design and in overall system design that may have significant impacts on system nuclear performance.

JAERI CONCEPT

A conceptual design study was made for a nuclear waste transmutation plant which consists of a high intensity proton accelerator and a sodium-cooled subcritical core with minor actinide alloy fuels and a tungsten target. The plant is designed to bum minor actinides from about 10 units of 3000 MWt LWR and to generate sufficient electricity to supply to its own accelerator.

Schematic diagram of the proposed plant concept is shown in Fig. 1. High current proton beam with the energy of 1.5 GeV is injected into the tungsten target region of the core. Heat generated in the target and the minor actinide fuels is removed by the forced flow of liquid sodium coolant. The heat is transported through primary and secondary coolant loops to a power conversion system, where it is converted to electricity.

ACTINIDE FUEL

The system uses metallic alloy fuel of minor actinides. The fuel consists of two alloy systems: Np-15Pu-30Zr and AmCm-35Pu-10Y. Actinide fuel slug with a diameter of 4 mm is sodium-bonded to the cladding of oxide dispersion strengthened (ODS) steel. The outside diameter of the cladding is 5.22 mm and the wall thickness, 0.3 mm. Figure 2 shows the fuel pin cell geometry. Active length of the fuel pin is 1.4 m. A gas vent mechanism is contained within upper section of individual fuel pin.

A pictorial view of the fuel assembly is presented in Fig. 3. Hexagonal wrapper tubes are eliminated in the assembly design. Fifty-five fuel pins are arranged on a uniform triangular pitch of 8.7 mm. The fuel pins containing Am and Cm are positioned on the outermost rows of the array.

Major design parameters of the fuel are presented in Table 1.

CORE/TARGET

As shown in Fig.4, the core consists of two region: the tungsten target region and the actinide fuel region. The tungsten target region of approximate form of right circular cylinder is installed in the center of the core. The target is surrounded by the annular actinide fuel region, which in turn is surrounded by radial and axial reflectors of stainless steel. A beam window is located right above the target region and is designed to be replaceable.

High energy protons are injected vertically downward through the window into the target region. The tungsten target acts as a spallation neutron source. Volume fraction of tungsten in the target is varied along the beam axis to shift the peak of spallation neutron flux toward the mid-height of the core. The actinide fuel assemblies and the target assemblies are cooled by upward flow of primary sodium coolant. Sodium temperature at the core inlet is 330 “C. The whole core is contained within a steel reactor vessel as shown in Fig. 5.

Core design parameters are summarized in Table 2.

The effective multiplication factor is about *0.9. The* core generates the thermal power of *820 MW* at the proton beam current of 39 mA. The average burnup is about 8%, about 250 kg of actinides, after one year operation at an 80% load factor.

Figure 6 shows the power density distribution in the core. The maximum power densities in the fuel and the target regions are about 920 W/cc and 360 W/cc, respectively. Temperature distribution along the fuel pin in the hot channel is shown in Fig. 7. Sodium temperature at the hot channel exit is 473 “C. The maximum temperature of the cladding is 528 “C and the *maximum fuel* center-line temperature is 890 “C.

The performance of the core is summarized in Table 3.

HEAT TRANSPORT AND POWER CONVERSION

The plant design is mostly based on the current state of technology for an LMFR plant. The basic plant arrangement is presented in Figs. 8 and 9. Figure 10 shows the schematic flow diagram of the heat transport and the power conversion systems.

The heat generated in the core is transported to the power conversion system through the primary and the secondary heat transport systems. The primary heat transport system consists of two sodium coolant loops; each has an intermediate heat exchanger (IHX) and a primary pump. The secondary system also consists of two loops; each has a steam generator (SG) and a secondary pump. Steam produced in the SGS is supplied to the power conversion system.

Design parameters of the primary and secondary heat transport systems along with the auxiliary cooling system are listed in Table 4.

Steam raised in the SGs is supplied to a single turbine alternator to produce electricity. Saturated steam Rankine cycle is used for power conversion. The plant efficiency is about 30%, and the electric output of about 246 MW is produced. Table 5 presents the parameters of the power conversion system.

Electric power of about 146 MW is required to operate the 1.5 GeV -39 mA accelerator with an efficiency of 40%. The system is more than self-sufficient in terms of its own energy balance.

DESIGN PROBLEMS

Here, we assume a priori that system under consideration is designed at the following requirements:

(1) to use neutrons from spallation reaction for transmutation,
(2) to be specifically dedicated to waste actinide burning,
(3) to be self-sufficient in terms of energy balance, and
(4) to transmute actinides from about ten 3000 MWt LWRS.

Most of the proposed concepts of transmutation system make use of neutrons generated by spallation processes within targets bombarded by intense proton beam. Spallation reaction is a very efficient mean for neutron production, and spallation reaction and subsequent neutron reaction are used for transmutation of waste actinides. At present, this approach is considered to be most practical for realization of accelerator-based transmutation systems.

A transmutation system can be designed to be multipurpose by incorporating the capability of fuel conversion, breeding, electricity generation, or plutonium burning. Here, however, other purpose than the transmutation are viewed as not essential. A certain system can transmute long-lived fission products as well as actinides, but a system specific solely for fission product transmutation seems to be impractical.

The third requirement of positive energy balance imposes several constraints on system designs. Although power generation is not the primary purpose, systems are required to generate enough electricity for its own accelerator. To achieve a high efficiency of power conversion, system operating temperature should be high. This condition restricts a degree of freedom in the engineering designs, but it is similar to the case for power reactors. It is also required to produce sufficient heat in the core for power generation. The thermal energy produced per incident proton needs to be 4 to 8 times as large as energy of incident proton, depending on the efficiencies of the accelerator and the power conversion. This condition dictates that the subcritical core should have a considerably high neutron multiplication factor. In such a core, actinides are transmuted mostly by fission reaction in the same way as transmutation by a fission reactor.

The optimum scale of transmutation system will be decided considering various factors: the scale of available accelerator, the amount of accumulated actinides, the deployment strategy of transmutation systems, and so on. One 3000 MWt LWR generates waste actinides of about 25 kg annually. Transmutation of 25 kg/y actinides by fission produces about 80 MW thermal power. If we assume, for example, that one transmutation plant serves 10 units of 3000 MWt LWR, the thermal power of the plant in which fission dominates is determined to be about 800 Mw.

Another point to be considered from a system design perspective is actinide inventory. Smaller radioactive inventory is preferred for reason of safety.

NEUTRON SPECTRUM

The rate of actinide transmutation depends on whether it takes place in a fast or a thermal neutron flux. In a thermal neutron flux, fission of minor actinides is very small. They require several successive neutron captures and thereafter the daughter nuclides with large fission cross sections undergo fission. In a fast flux, on the other hand, most of minor actinides are fissionable with fission threshold in several hundreds keV range and their capture cross sections rapidly decrease above this energy region.

Clearly, fast flux is better suited to actinide transmutation application than thermal one. A very hard neutron energy spectrum is desirable. Another problem of minor actinide transmutation in a thermal flux is the generation of much higher mass number actinides (e.g., Bk and Cf). Even though their absolute amount is negligible small, they are very strong alpha and neutron emitters, leading to severe demands on the decay heat removal and the radiation shielding. Most of proposed concepts make advantage of fast neutron flux.

Recently, the Los Alamos National Laboratory (LANL) has proposed a unique concept, called the Accelerator Transmutation of Nuclear Waste (ATW). The LANL concept uses the extremely high thermal neutron flux of the order of 10^{16} n/(cm^{2}•s)[2]. In such a high thermal flux, actinide can be transmuted effectively by so-called two-step reaction.

Major advantages of the concept over fast flux systems are that it can transmute fission products effectively as well, and it can operate with a very small radioactive inventory. The system consists of a 150-mA class accelerator, a centrally located liquid lead (or lead-bismuth) flowing target, and a surrounding heavy-water blanket, as shown in Fig. 11. Actinides and fission products are loaded in the heavy-water blanket in forms of slurry and solution.

Possibly most challenging problems of the ATW system are radiation damage in target container material, processing and separation chemistry, and **upscaling** of accelerator. Frequent replacement of the target container maybe required during the plant life-time, but it **appears** to be **very difficult** to design a replaceable container.

Some problems arise from using heavy water at low **temperatures** in the range of 30-80 "C. Co-existence of low temperature heavy water and high temperature lead regions adds complexity to the container design. In the advanced ATW system, very **high** temperature (-775 "C) molten salt is used for **efficient** power generation, and it circulates through the heavy water blanket.

Recovery of the thermal energy deposited in the heavy water blanket seems impractical. Because the boiling point of heavy water is about 100 "C at the atmospheric pressure, substantial pressurization of the order of 10 MPa is required for high temperature **operation.** In accelerator-based transmutation systems, pressure boundary is necessarily irradiated by **high-**intensity proton or neutron flux, unlike in regular **reactors.** The system can not follow the design practice of existing thermal power reactors.

By contrast, fast neutron system can make the advantages of experience in the design of current sodium-cooled fast **reactors.** Liquid sodium is an excellent heat **transfer** medium and its **high** boiling point allows **operation** at high temperatures without pressurization. Transmutation of fission products is ineffective in a **fast** flux. It is a challenging problem how to transmute them effectively in a **fast** system, if fission product **incineration** is also a requirement.

NEUTRON MULTIPLICATION FACTOR

The system performance is strongly affected by the degree of self-multiplication of neutron in the subcritical core. Effect of the neutron multiplication factor can be evaluated using the following simple equation:

$$N_{tot} = N_{spal} + N_{fis} = N_{spal} + S_h \cdot k_{eff} / (1 - k_{eff}) / \nu,$$

where N_{tot} : total number of nuclei incinerated per incident proton,

N_{spal} : number of **spallated** nuclei per incident proton,

N_{fis} : number of fissioned nuclei per incident proton,

S_h : number of neutrons generated by **spallation** reaction per incident proton,

ν : number of neutrons emitted per fission, and

k_{eff} : effective multiplication factor for fission neutron.

As the value of k_{eff} approaches to unity, N_{tot} increases rapidly. We assume that N_{spal} = 4, S_h = 40, **and** ν = 2.9. If&f= 0.9, $N_{tot} \approx 130$, and if $k_{eff} = 0.95$, $N_{tot} \approx$ **260. When** k_{eff} reaches 1, then the core becomes critical and requires no more proton current to drive the core.

As mentioned earlier, k_{eff} value should not be too low to meet the requirement of positive energy balance. We assume that the proton energy is 1.5GeV and the thermal energy released per fission is 200 MeV. A &value greater than -0.65 is required for 600/0 accelerator efficiency and 44% power conversion efficiency. Assuming more conservatively 40% and 30% efficiencies, k_{eff} should be greater than-0.8.

A high k_{eff} value offers substantial benefits for system designs. For a given actinide throughput, required proton current can be reduced by increasing the k_{eff} value. Reduction in required current allows to downscale the accelerator and to save the electric power consumption. Small current further minimizes the problems of radiation damage, thermal stress, and heat removal of beam windows.

A second benefit of a high k_{eff} value is to suppress the power peaking. Because the maximum thermal power is usually limited by local temperatures at or near the point of peak power density, a high k_{eff} value is beneficial to improve the overall performance. Also, it alleviates the need for frequent shuffling of fuel elements.

The reactivity of minor actinide fuel increases with the burnup. The extent of the reactivity swing can be controlled by adjusting the proportion of plutonium in the fuel. In liquid-fueled systems, the control of reactivity can be accomplished by means of continuous on-line fuel feeding and processing.

To assure not to become supercritical, a high k_{eff} core needs the high accuracy in the design data and method, and of course the fabrication to close tolerances. A low k_{eff} core can offer relatively large margins in design, fabrication, and operation, or can reduce the required accuracies more or less.

The degree of the subcriticality depends on designs. It should be determined by taking account the safety of the system. The JAERI concept chooses k_{eff} = 0.9-0.95. The near-term ATW system has a relatively low k_{eff} value (presumably -0.25), while the advanced ATW system has a value k_{eff} = 0.8-0.9. In the PHOENIX concept(6) shown in Fig. 12, proposed by Brookhaven National Laboratory (BNL), k_{eff} is selected to be around 0.9. Takahashi(5) has proposed a system operated at a slightly subcritical condition with k_{eff} = 0.99. With such a k_{eff} value very close to 1, a small-scale accelerator with 15-20 mA current and 1 GeV energy suffices to drive the 3300 GWt core.

Certainly, the core operating at a slightly subcritical condition can be viewed safer than the core of the regular reactor which always operates at the critical condition. However, there is an argument that the k_{eff} value should be chosen much less than 1, to be far away from usual reactor. At this time, there is no consensus among the community about the degree of the subcriticality for the accelerator-driven subcritical core. It is necessary to assess quantitatively the criteria for the choice of the proper&value.

DATA AND METHODS

One of the most important problems in the design studies of accelerator-based transmutation systems is that the design data and methods are insufficient. Their uncertainty affects the predicted system performance. The data and methods as such are beyond the scope of this paper. Here, we will discuss about the design requirements on the accuracy of the data and methods.

The accuracy of present nuclear data is considered to be satisfactory for actinide transmutation in LMFBRs where relatively small amount of actinide is added to the ordinary fuel. However, it is not satisfactory yet in actinide burner reactors(7). If we use actinide-enriched fuel in the near-critical core of the system, the accuracy of data available for minor actinides at low neutron energies is said not to be satisfactory as well.

In the accelerator-based transmutation system, the data and methods for high-energy nuclear reaction are more essential. The proton-induced spallation process in a target is the primary source of neutrons. In our design study, the nuclear reaction in the energy range above 15 MeV is calculated with a Monte Carlo simulation code NMTC/JAERI(8).

The most important quantity is the neutron yield of spallation reaction from the designer's standpoint. The recent survey(9) concluded that the neutron yield from the minor actinide target can be estimated in the error range of ±20%. With this level of confidence, it is possible to make approximate evaluation of the concept of an accelerator-based system. To make more accurate evaluation, further experiments and developments of code with more accurate nuclear data are required.

Present simulation calculations of complex spallation process are time-consuming. Even in earlier stage of design study, a considerable amount of computational work is required for survey calculations. If we can use effective cross sections instead of the Monte Carlo simulation of intranuclear cascade process without significant loss of accuracy, calculations at high energies can be made in similar way to that used for neutron transport at low energies. For efficient design study, it is expected to develop methods with such data.

There is a question how accurate is accurate enough. To answer this question, it is necessary to examine the sensitivity of system performance to the uncertainty of data and methods.

As well as the nuclear data, physical property data for minor actinide fuel are absolutely lacking. The uncertainty in fuel data also affects significantly to the transmutation rate of the system. Data of thermal conductivity and melting point of fuel are most influential. In the case of fluid fuel, specific heat also has a major influence.

There are also no data of damage in structural materials irradiated by high energy particles. Although they do not have direct effects on the transmutation rate, they are essential in the system designs.

CORE DESIGN

Actinide **fuel** maybe either solid or fluid. In case of solid fuel, core designs can be made based on the well-established technology of current **LMFRs. Combination** of pin-bundle type **fuel** element and sodium coolant offers many advantages, such as high power density, and high temperature operation under normal pressure. This approach is followed by both the **JAERI** concept and the PHOENIX concept.

Molten lead and lead-bismuth are considered as candidate coolants. These heavy liquid metals play both roles of coolant and target material. Previously, we compared a sodium cooled core and lead-bismuth cooled **core**[10]**.** Lead-bismuth cooling resulted in larger amount of **actinide** burned per proton current than sodium cooling. However, the transmutation rate in the core was lower, because of the inferior heat transfer capability of lead-bismuth as compared with sodium.

Other possible coolants are water and helium gas. Both heavy water and light water are widely used as reactor coolants. Since water is moderating material, it can not be used in fast neutron system. As already discussed, energy recovery is not practical with water cooling under normal pressure. Pressurization up to at least about 10 MPa is required for efficient power production, but this causes many **difficult** problems for accelerator-based systems.

Helium has many advantages as a coolant. Helium is chemically inert, it can be used at very high temperatures, and it **has** negligible ***effect*** on **neutronics.** However, fairly high pressure is required for effective heat removal from high power density core. Helium cooled reactors typically operate at pressure ranges of 4-10 MPa. Again, helium cooling **appears** to be **difficult** for **accelerator-based** systems.

The ATW concept uses liquid **fuel** in various forms: slurry, aqueous solution, and molten salt. **Liquid-fueled** system claims an advantage of the capability of continuous on-line processing and addition of **fuel.** ***This offers*** a mean of ***core*** reactivity control. There is little experience with fluid **fuel,** and many engineering problems are left unsolved.

JAERI has started the preliminary design study of a molten-salt fuel **concept**[11]**.** It **appears** difficult to reduce the total inventory of fluid-fueled ***system, because*** considerable volume of primary **fuel** fluid is contained in heat **exchangers,** circulator, and piping.

TARGET DESIGN

A variety of designs are conceivable for **spallation** targets. Target designs can be classified according to whether they contain actinide fuel or not. We refer to those with actinides as the "active" targets and to those without actinides as the "inactive" targets. The target of the PHOENIX concept is active in this sense, while the targets by JAERI and LANL are inactive.

The design of active target can be the same as that of fuel, then the target/core configuration is simplified. Both spallation and regular fission occur in the active target region. Thereby, heat generation tends to become much higher in the active target region than that of the core average. To suppress the local power peaking, the incident proton beam should be expanded. In the PHOENIX concept, the proton beam is expanded to irradiate evenly entire core.

Candidate materials for inactive target are lead, lead-bismuth, tungsten, etc. Tungsten has very high melting point, enabling high temperature operation. The inactive target adds complexity to the target/core configuration to some extent. The target acts only as a spallation neutron source. No regular fission takes place in the inactive target. Therefore, spallation reaction in the target does not directly to actinide transmutation. This, however, has a minor effect on the overall performance in the fission-dominated near-critical core.

The heat generation is much smaller in the inactive target. The inactive target can serve to suppress the core power peaking(12,13). In the core with a k_{eff} value close to unity, maximum power occurs usually at the center regardless the location of neutron source.

In terms of their physical form, targets can be divided into solid targets and fluid targets. The target of the JAERI concept is tungsten. A tungsten and lead solid target is examined by LANL(3) as an option to the ATW flowing lead target. The solid targets offer the possibility of tailoring the profile of source neutron distribution by varying the volume fraction of target *material.*

Cooling requirements for the solid target are essentially identical to those for the solid fuel. Forced convective cooling is considered to be imperative, even for an inactive target. The JAERI target is cooled by the primary sodium coolant, in the same way as the fuel. The LANL solid target is cooled by forced circulation of heavy water or helium gas. If helium is used at relatively low pressure, a penalty involved is an increase in the neutron leakage through the large diameter piping. With such a coolant as sodium, water, or gas, a beam window is required as a boundary between vacuum and coolant. The solid target should be designed to be replaceable for its severe damage.

Lead and lead-bismuth are leading candidate materials for fluid targets. Molten salts of heavy metal are potential candidates. Even if target liquid contains no actinides, forced circulation is required for heat removal. This makes the external cooling loop necessary. The total volume and mass of target material are considered to be much larger as compared with the case of solid target. Low vapor pressure liquids, such as lead-bismuth, lead, and certain molten salts offer the possibility of windowless design.

BEAM WINDOW

The beam window is probably the most critical component in the accelerator-based transmutation system. The major difficulties are caused by radiation darnage and heat generation. Radiation damage by high energy particle is not fully understood.

Radiation damage can be alleviated by expanding the beam diameter at the window. Enlarging the window diameter needs a proportional increase in the window thickness to withstand the pressure difference across the window. As a result, the maximum temperature and the thermal stress in the window can not reduced by increasing the diameter. In the JAERI concept, the design pressure difference is 0.25 MPa. The maximum allowable pressure difference is estimated to be about 2 MPa for the hemispherical window of ODS steel under uniform irradiation.

Window material should have high irradiation resistance, high creep-rupture strength, high thermal conductivity, and good compatibility with coolant. Candidates are ferritic steels, vanadium alloys, SiC, C/C composites, etc.

The beam window should be designed to be replaceable. Multi-wall structure may be required to provide means for detection of window failure.

As noted above, the windowless design maybe possible with lead, lead-bismuth, etc. However, it seems a difficult problem to contain the radioactivity.

ACCELERATOR INTERFACE

The role of the accelerator is to provide a beam with sufficient intensity to produce a required neutron source strength. There is a trade-off between its energy and current. LANL has optimized the accelerator parameters for both the near-term and the advanced ATW systems to minimize construction and operation costs[(4)]. Because the proton energy affects the target dimension, the shielding requirements, and the cooling of beam window, energy-current should be optimized taking these factors into account.

Design of the beam transport system becomes quite different depending on whether the target is arranged vertically or horizontally. For the horizontal target, the interface can be straight forward. The vertical target needs a series of beam bends in the beam transport system. In the PHOENIX concept and the ATW solid target option, the beam is incident horizontally. The ATW windowless liquid target is inevitably arranged vertically. The JAERI concept employs vertical target because this arrangement markedly simplifies the window/target/core configuration. Horizontal arrangement imposes a number of difficulties.

To reduce the window damage, it is necessary to expand the beam cross section area and to flatten the intensity profile. The undesirable beam tails also needs to be removed.

Thermal power of a subcritical core is controlled by adjusting the beam current or energy. A proton accelerator can be electrically controlled much faster than the mechanical movement of the control rods. The time required for beam shutdown is probably within few ms.

Change in beam intensity causes a problem. Beam trip imposes a large thermal shock. The consequence of beam trip should be considered. If the multiple cores are driven by time-shared beam, they suffer from high frequency thermal shock. Small fluctuations of beam intensity may be inevitable due to the instability in ion source. It should be assured that beam fluctuations do not affect adversely.

The design of radiation shielding is more complicated than the case of regular reactors, because it involves much higher energies and there is a large diameter beam transport system.

Design measures should be provided to prevent the radioactivity from escaping into the accelerator in case of window failure.

Modem high-intensity accelerators claim their high reliability. Accelerator availability can be well above 70% including planned beam-off time. The highest possible availability is desirable for overall system operation.

SUMMARY

A conceptual system for accelerator-based minor actinide transmutation is designed. 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 for the accelerator.

Design problems of accelerator-based transmutation systems, such as neutron spectrum, neutron multiplication factor, data and methods, core design, target design, beam window, and accelerator interface, are discussed from the viewpoint of engineering.

ACKNOWLEDGEMENT

The author would like to thank to Drs. T. Nishida, M. Mizumoto, and H. Yoshida for their valuable discussions. The collaboration of Mitsubishi Atomic Power Industry, Inc. for the plant design is also acknowledged.

REFERENCES

1. T. TAKIZUKA et al., "Conceptual Design of Transmutation Plant," Specialist Mtg. on Accelerator-driven Transmutation Technology for Radwaste and Other Applications, Stockholm, 24-28 June 1991.
2. E. D. ARTHUR, "Introduction to Accelerator-driven Intense Thermal Neutron Source - Advantages for Transmutation and other Applications," ibid.
3. M. W. CAPPEILLO, et al., "Target/Blanket Conceptual Designs for the Los Alamos Accelerator Transmutation of Nuclear Waste (ATW) Concept," ibid.
4. S. SCHRIBER, "Intense Proton Accelerator forTransmutation Neutron Source," ibid.
5. H. TAKAHASHI, "A First Breeder and Incineration Assisted by a Proton Accelerator," ibid.
6. G. J. VAN TUYLE, et al., "The PHOENIX Concept, Proposed Transmutation ofLong-lived Radioactive Wastes to Produce Electric Power," BNL 52279, 1991.
7. T. MUKAIYAMA et al., "Higher Actinides Transmutation using Higher Actinide Burner Reactors," Int. Conf. on Physics of Reactors: Operation, Design and Computation, Marseille, 23-27 April 1990.
8. Y. NAKAHARA and Y. TSUTSUI, "NMTC/JAERI, A Simulation Code System for High Energy Nuclear Reaction and Nucleon-Meson Transport Processes," JAERI-M 82-198, 1982.
9. H. TAKAHASHI, "Survey of Codes Relevant to Design, Engineering and Simulation of Transmutation of Actinide by Spallation (The Cost Estimation of Accelerator for Incinerator and the Problem of Radiation Hazard)," OECD/NEA report, to be published.
10. T. TAKIZUKA et al, "A Study of Incineration Target System," 5th Int. Conf. on Emerging Nuclear Energy Systems, Karlsruhe, 3-7 July 1989.
11. Y. KATO, et al., "Accelerator Molten-salt Target System Transmutation of Long-lived Nuclides," Specialists' Mtg. on Accelerator-based Transmutation, PSI, 24-26 March 1992.
12. H. TAKADA et al., "A Conceptual Study of Actinide Transmutation System with Proton Accelerator (1) Target Neutronics Calculation," 2nd Symp. on Advanced Nuclear Energy Research - Evolution by Accelerators, Mite, 24-26 January 1990.
13. T. TAKIZUKA et al, "A Conceptual Study of Actinide Transmutation System with Proton Accelerator (2) Target Thermal Hydraulics," ibid.

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
Pin#Assembly	55
Pin Pitch	8.7 mm

Table 2 Core design parameters

Proton Beam Energy	1.5 GeV
Diameter	400 mm
Target	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		3160kg
k_{eff}		0.89
Neutron#Proton		40
Fission#Proton	(>15 MeV)	0.45
	(<15 MeV)	100
Neutron Flux		4×10^{15} n/cm$^2\cdot$s
Mean Neutron Energy		690 **keV**
Burnup		250 **kg/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**		
Outlet 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
Turbine Inlet Temperature	285 “C
Electric Output	246 MW
Efficiency	30%

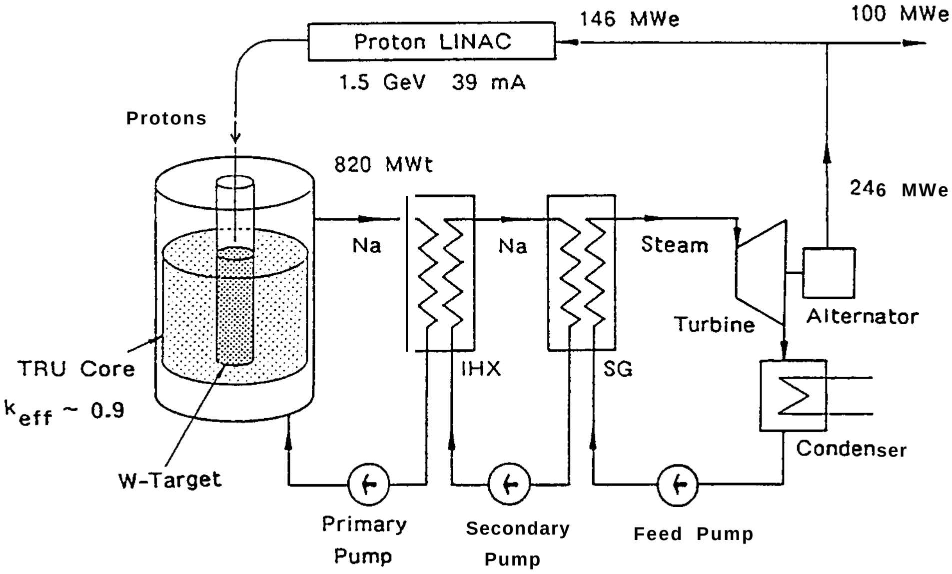

Fig. 1 Conceptual flow diagram of actinide transmutation plant

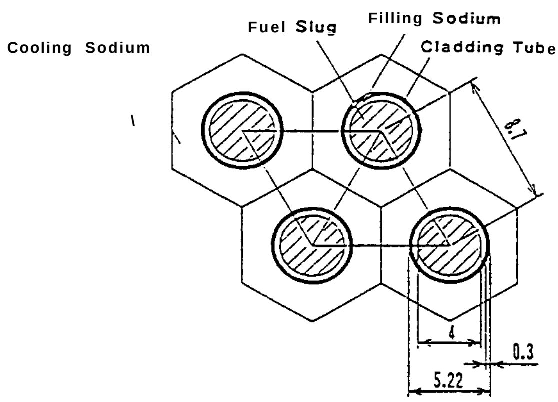

Fig. 2 Fuel pin geometry

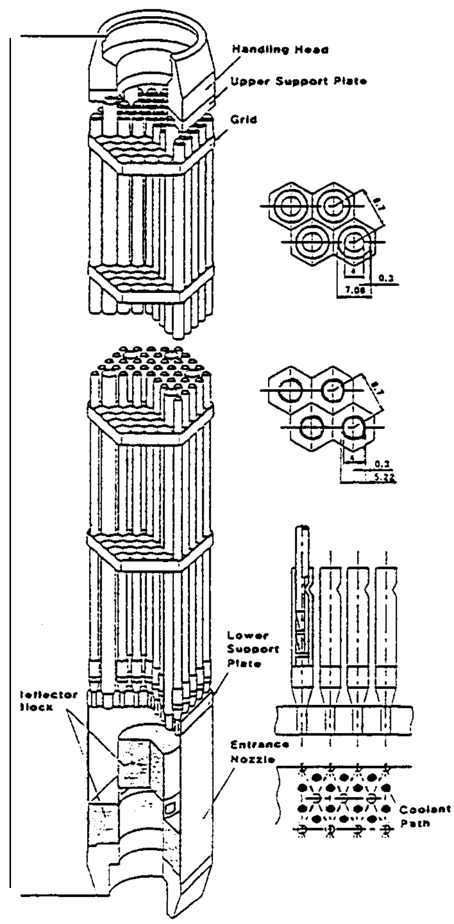

Fig. 3 Fuel assembly

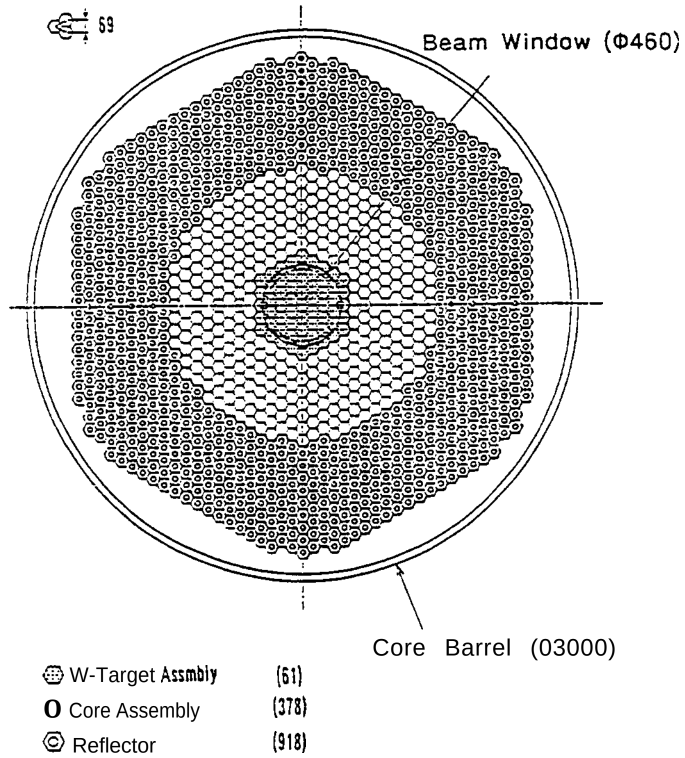

Fig. 4 Core configuration

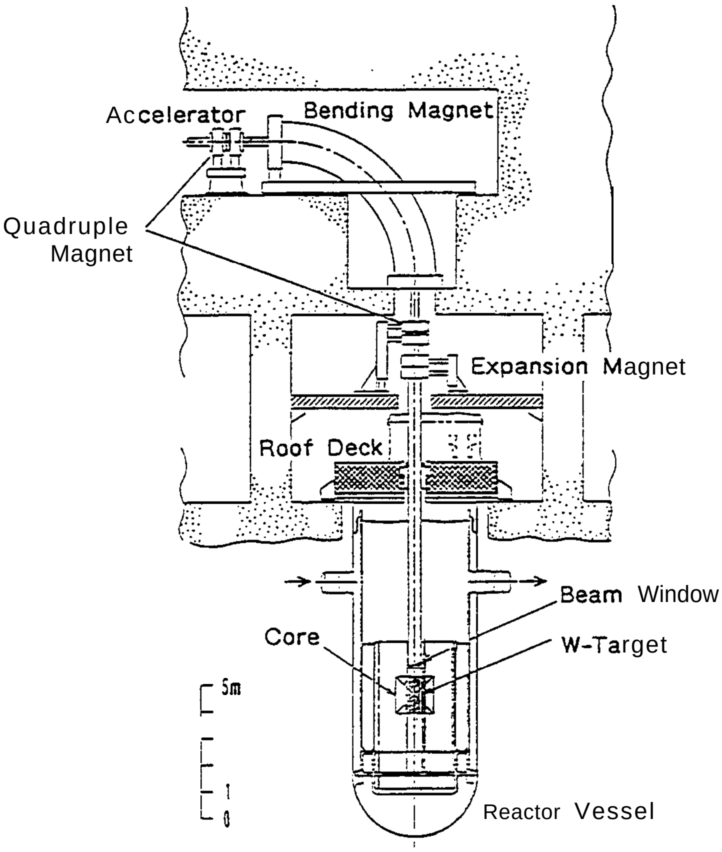

Fig. 5 Reactor

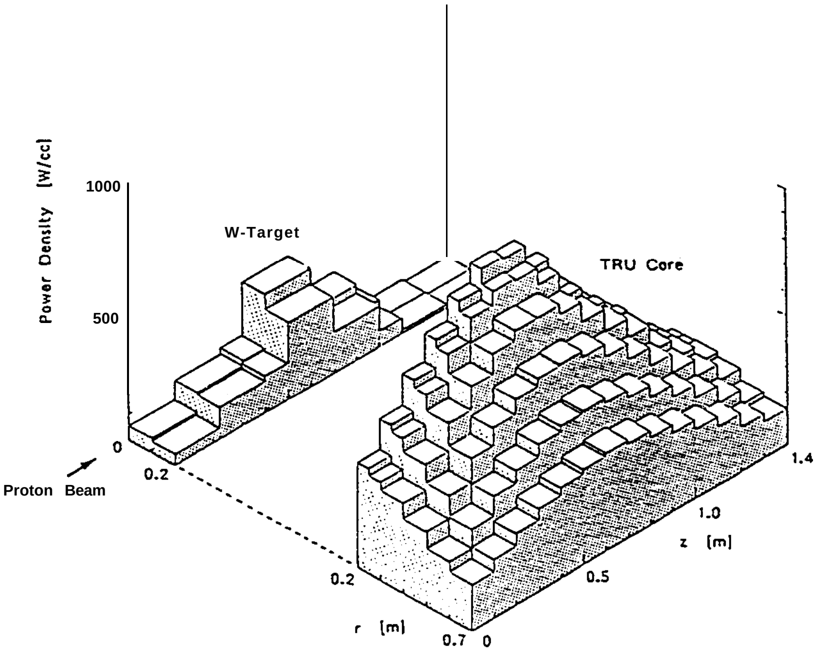

Fig.6 Corepower distribution

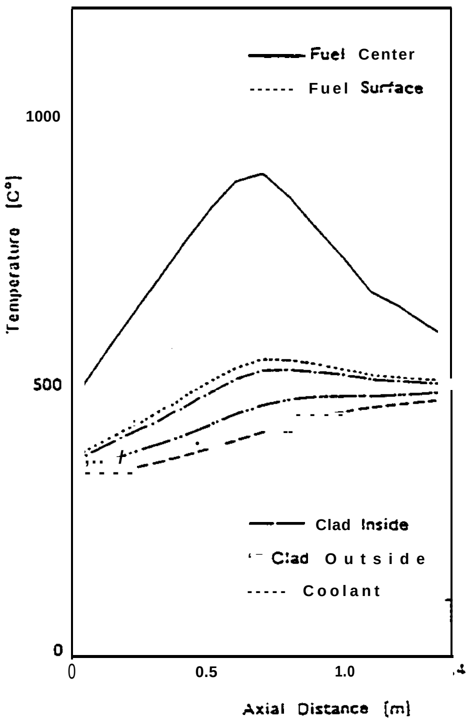

Fig. 7 Temperature distribution along hot channel

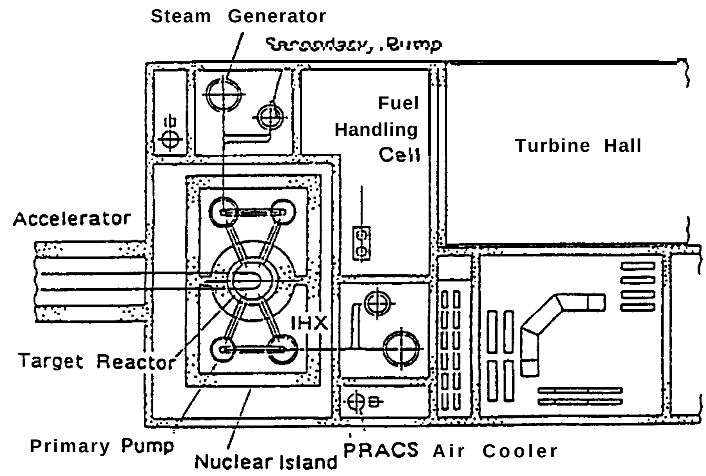

Fig. 8 Plant arrangement (plan)

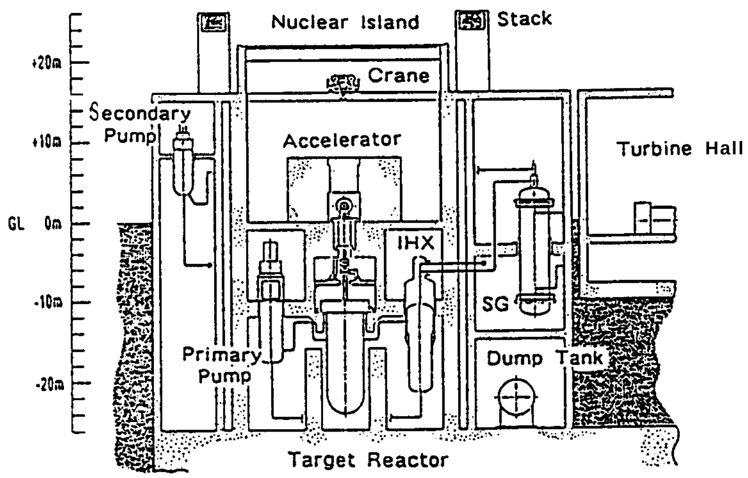

Fig. 9 Plant arrangement (section)

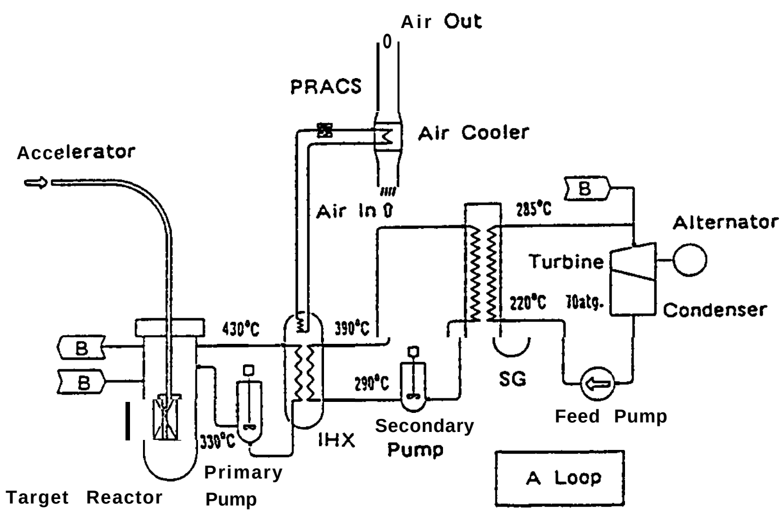

Fig. 10 Schematic flow diagram of plant

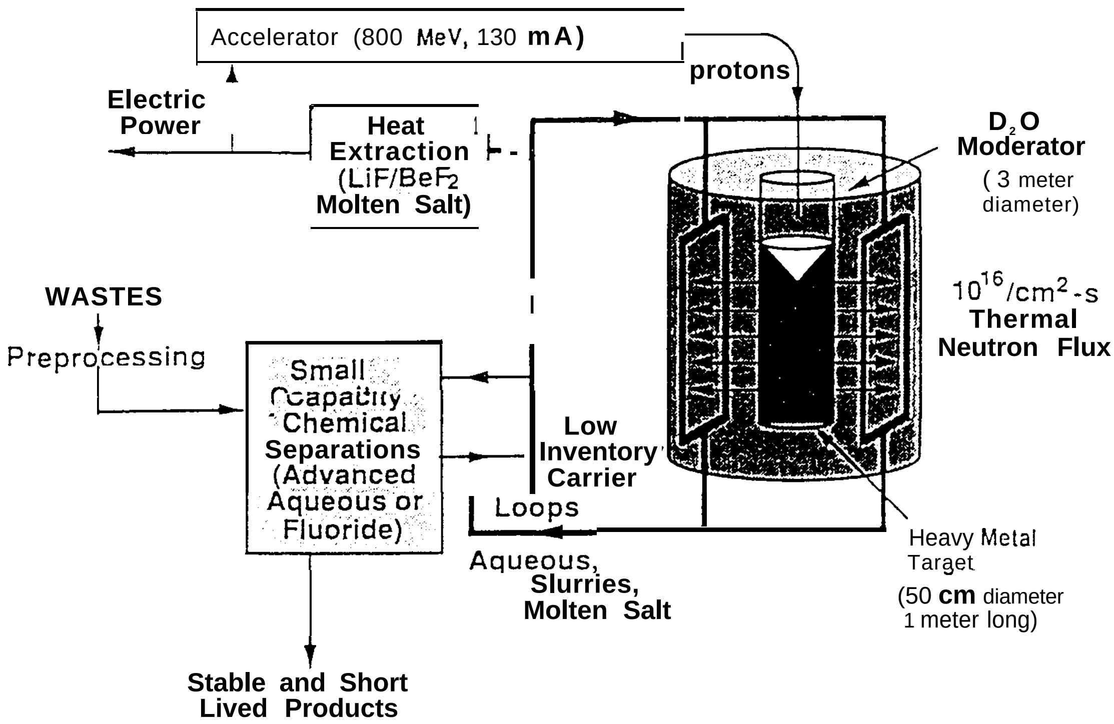

Fig. 11 LANL ATW concept

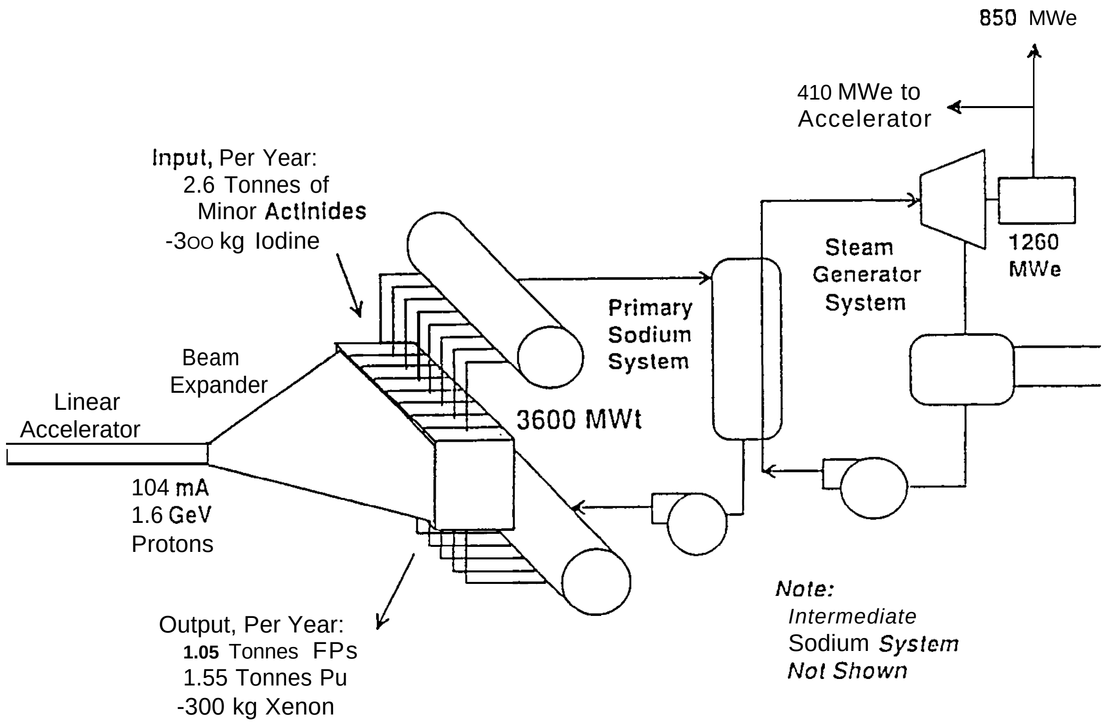

Fig. 12 BNL PHOENIX concept