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FUEL CYCLE IN JAPANESE FUGEN- HWR

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Working Group 4

Task 9 : Plutonium Recycle - Reactor Alternative

Fuel Cycle in Japanese Fugen-HWR

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Fuel Cycle in Japanese Fugen-HWR

1. Outline of Reactor Characterization

1.1 General Description

Up to the not-distant past, the nuclear power programs have been planned elsewhere on a basis that supply of natural uranium would be guaranteed without much difficulty. However, the recent situations told us that this was quite an optimistic view, and a problem of stable natural uranium supply and its effective utilization is becoming a matter of global concern.

On the other hand, a majority of today's nuclear power comes from light water reactors (LWR), with much more expanding programs being planned worldwide in the short range future. In this situation, supply of enriched uranium is not considered big enough against growing demand. Furthermore, the facilities of enrichment are installed only in a few limited capable countries. Because of the expanding growth in the near future, plutonium stock will also build up in spent fuels whether it is preferred or not.

Under this background, the idea of plutonium fuel recycle in thermal reactors is being proposed elsewhere, to save natural uranium requirement, to reduce SWU demand of uranium enrichment, and also to keep up an optimum balance of Pu storage. Although the undoubted primary idea of Pu utilization is directed to the fast breeder reactors (FBR), a great deal of technical development will still be required before its commercial perfection.

Japan's nuclear energy development program reflects all of these background situations, and the Fugen-Project(1),(2) was started in 1967 as a national project to develop a reactor which is to be operated using natural uranium only, but enriched with plutonium to make its effective utilization. This represents a Japanese attitude to seek for a every possible energy source, since the country is lacking most of the important energy resources.

The purpose of this paper is to describe an outline of plutonium fuel utilization in the Fugen-HWR; a pressure tube type, boiling light water cooled, and heavy water moderated reactor. The use of plutonium fuel in the Fugen-HWR takes an advantage of high neutron economy which is essential to HWR, and it is an optional approach to the LWR (Pu-thermal) program. Some of the important technical problems for using Pu fuel in the Fugen-HWR are also discussed in the later part of this report.

1.2 Outline of Reactors and Reference Design

(1) Prototype Fugen

A 165 MWe prototype Fugen reactor (Fig. 1), located at Cape Tsuruga viewing the Sea of Japan, attained its initial criticality in March, 1978 by using plutonium MOX fuel. The start-up commissioning tests were carried out following this criticality, and its first electrical power was put into line on July 29 at 25% of the rated power.

The follow-up commissioning tests have also been successfully completed, and the reactor went into a first 10 day continual operation at rated power during the month of November. After a scheduled shutdown for inspection, the reactor again went into a long-run full power operation since January 1979, and its performance has been quite steady and reliable up to the present.

This prototype reactor uses plutonium topped natural uranium mixed oxide (Pu-NU MOX) as a primary fuel; i.e., 96 MOX fuel assemblies were initially loaded in the central core, and 128 UO_2 fuel assemblies were loaded surrounding this region.
Although the initial core was started by zone loading with use of MOX and UO_2 fuels, the MOX fuels are to replace all region of the core after the replacement cycle. With success of the first electrical power generation on July 29, the prototype Fugen has initiated the way to a full scale utilization of Pu MOX fuel by thermal neutron power reactors.

To show a general idea of the Fugen-HWR, the brief reference data are first shown in Table 1, a vertical cutaway view of the prototype Fugen reactor is then shown in Fig. 2, and its fuel assembly and a cross section of the bundle in Figs. 3 ∿ 4. As shown in Fig. 4, the fissile Pu enrichment is adjusted between inner and outer pins of the fuel bundle, i.e., 0.8/0.8/0.55 w/o fissile Pu enriched for each ring. With such simple adjustment of Pu enrichment, local power peaking in the bundle can be minimized very easily, and this is considered to be an advantage in designing the Fugen-HWR MOX fuel assembly.

(2) Fugen-HWR Demonstration Reactor

Following the prototype Fugen reactor, development of commercial scale Fugen-HWR has been on progress in a past few years. The reactor is planned in 600 MWe size, and its first unit will be called as a demonstration reactor. For further future program, proposal is made to build these reactors in a multi-unit station system (4 ∿ 8 units). A good example for such a multi-unit system is in the case of CANDU-PHW(3) reactors (Pickering and Bruce), and this is considered to be a system commonly thought for any pressure tube type reactors.

By considering a multi-unit plant system in the Fugen-HWR in the future, rationalization of the plant system is strongly promoted and many plant facilities are planned for common use in such a future proposal. Among these facilities are the control room, spent fuel storage, waste disposal, fuel handling facilities, etc. The exclusive use of Pu MOX fuel is a basic philosophy of the Fugen-HWR development, and the plant facilities would be designed to satisfy this purpose.

As for the schedule of development, the conceptual design of the demonstration plant has been completed by the end of 1978; and the detailed design work will follow in the next 2 years. The long range development schedule of the Fugen-HWR is shown in Fig. 5, including the prototype and demonstration reactors. The design work of Pu MOX fabrication plant (60 T/Year) is also underway, which is expected to supply fuels to the demonstration plant.

The reference design of the Fugen-HWR demonstration reactor, shown in Table 1, is similar to the prototype reactor except its escalated power and dimensions. However, a major change of the demonstration reactor from the prototype Fugen is that it uses 36 pin fuel bundles and employs an off-power refuelling method (compared with 28 pin fuel bundles and an on-power refuelling method in the prototype reactor).

In making decision to go to an "off-power" refuelling, the "simplicity" of fuel handling facility was preferred to a possible gain of fuel burnup which would be achieved if by employing an on-power method. However, to minimize a loss of fuel burnup which results from an off-power refuelling method, a proposal is made to refuel twice a year in 8 ∿ 10 batches, with 4 ∿ 5 years of fuel resident time. This refuelling frequency is twice or more that of LWR, but an additional refuelling shutdown in a year would not give a big penalty to a plant capacity factor, since refuelling procedures are rather simple in the pressure tube type reactors.

As for the MOX fuel of the demonstration reactor, the fissile Pu enrichment would be in the range 1.0 ∿ 1.5 %, about twice that of the prototype reactor. With such fissile Pu enrichment, the target burnup will be around 21,000 ∿ 29,000 MWD/MT. Although the higher burnup is generally preferred from the aspect of fuel cost, an appropriate enrichment will be chosen within the given range by considering mass balance and reactor control problems.

2. Fuel Cycle

2.1 Fuel Cycle Flow in Fugen-HWR

A primary idea of the Fugen fuel cycle is to utilize plutonium fuel as Pu - NU MOX to save uranium and separation work unit (SWU) requirements, meanwhile keeping up an optimum balance of Pu fuel storage. In the present design of the Fugen-HWR, the reactor is characterized as a plutonium burner, i.e., it uses more plutonium than it produces. Accordingly, Pu fuel for the Fugen-HWR comes from used LWR fuels as well as self generating plutonium, and its typical fuel cycle flow diagram is shown in Fig. 6.

Although Pu-NU MOX is considered as a basic fuel for the Fugen-HWR, enriched UO_2 can also be used when supply of Pu-fuel becomes insufficient. For another choice, depleted uranium (DU) recovered from used LWR fuels might be used, to substitute natural uranium in Pu-NU MOX. These alternative choice of fuel flow is shown in the dotted line in Fig. 6.

2.2 Flexibility Nuclear Fuel Utilization

Because of an intrinsic nature of HWR having high neutron economy, the Fugen-HWR has many advantages for effective use of nuclear fuels, and also has a wide range of flexibility for choosing varieties of fuel type. Hence, the fuel cycle characteristics of the Fugen-HWR will here be described when using several fuel types, and their mass balance data of fuel utilization are summarized in Table 2 as compared with LWR. These mass balance data for the Fugen-HWR were evaluated in an equilibrium cycle, based on a core model of the demonstration reactor.

(1) Pu-NU MOX fuel

Pu-NU MOX is a basic fuel considered in the Fugen-HWR, with an average 1.44 w/o fissile Pu enrichment in a bundle. (See Table 2, Pu-NU MOX, Case 1) With use of this fuel, one expects to have 28,700 MWD/MT burnup in an equilibrium cycle, almost equivalent to that of a standard BWR. This burnup value is also compared with a case of LWR (Pu thermal)(4) which gives 29,500 MWD/MT by using 3.35 w/o fissile (Pu + U) MOX fuel (See Table 2, U, Pu recycle). This comparison clearly shows the effectiveness of Pu fuel utilization in the Fugen-HWR.

The requirement of NU in the Fugen-HWR (1.44 % Pu-NU MOX) is about 40 Tons/GWe·Y at 100% capacity factor, and this is only 20 ∿ 34% of the amount required in LWR (See Table 2). The requirement in LWR varies depending on whether depleted uranium and plutonium from spent fuels are to be reused. Such a small uranium requirement in the Fugen-HWR is resulted from the use of Pu fuel, but also helped by its effective fuel burnup which can be achieved without using enriched uranium.

Plutonium enrichment of the MOX fuel is not necessarily fixed as long as it is within some allowable range considered from the reactor characteristics. To study the effect of enrichment, MOX fuel with 1.0 w/o fissile Pu enrichment was also evaluated (See Table 2, Pu NU MOX, Case 2) In this case, NU requirement increases to about 55 Tons/GWe·Y, while fissile Pu requirement would decrease to about 0.3 Ton/GWe·Y. As a general tendency, in lowering Pu enrichments, NU requirement increases but Pu requirement decreases, and therefore a suitable enrichment might be selected from the overall consideration of mass balance and reactor characteristics.

(2) Pu-DU MOX fuel (DU from used LWR fuels)

Depleted uranium recovered from used LWR fuel still contains about 0.80 ∿ 0.85 w/o fissile part which is still higher than natural uranium, and there is no reason why this recovery uranium can not be used in the Fugen-HWR. In fact, the calculation gives burnup of 28,800 MWD/MT by using Pu-DU MOX (1.3 w/o fissile Pu in 0.85 w/o DU). In this case, NU requirement is substituted by DU while fissile Pu requirement decreases by some amount corresponding to the difference of fissile assay in NU and DU.

It is important to point out that the LWR fuels are often discharged with smaller burnup than design values, and the DU recovered from such discharge fuels might sometimes have a larger fissile part than the nominal value as quoted here. In the Fugen-HWR, 0.1 w/o fissile fuel increment approximately corresponds to 2,000 MWD/MT burnup increase. This means that the use of LWR-DU in the Fugen-HWR will turn out more favorable than the present evaluation shown in the third column of Table 2. Although uranium recycle is generally considered in LWR, the proposed LWR-Fugen uranium cycle is also quite effective and it might be an alternative choice of using LWR-DU.

(3) Pu-DU MOX fuel (DU from enrichment tail)

Depleted uranium discharged as enrichment tail (0.2 ∿ 0.3 w/o fissile assay) is considered to have only a small value, and it is presently abandoned in a big stockpile. No technical difficulties are expected to use this depleted uranium in the Fugen-HWR, as long as the use of Pu-NU MOX fuel is already established as a primary fuel. When the use of such depleted uranium is planned to substitute natural uranium, one needs to increase fissile Pu topping by about 0.5 w/o to attain the same burnup to the case of Pu-NU MOX fuel. This additional requirement of Pu topping corresponds to the depletion of fissile part in DU as compared with NU.

The burnup analysis (not referred in Table 2) gave 22,000 ∿ 30,000 MWD/MT by using 1.5 ∿ 2.0 w/o fissile Pu-DU (0.3 w/o fissile assay) MOX fuel. Natural uranium requirement vanishes in this case. When economies of Pu-NU and Pu-DU MOX fuels are compared, the former requires NU while the latter requires an additional 0.5 w/o of fissile Pu topping to attain the same degree of fuel burnup. If fuel manufacturing costs are not very different between these cases, and assuming very small value of DU, the profit point is determined by a balance of NU price and the additional Pu requirement. This is a trade-off relation between NU and Pu, and it means that future escalation of NU price, or devaluation of Pu price will make the use of such DU more attractive. It is also pointed out that this fuel cycle pattern most effectively controls the excess buildup of Pu fuel, and releives the undesirable plutonium pressure when it really becomes critical.

(4) Enriched UO_2 fuel

No difficulty is expected for using enriched UO_2 fuel in the

Fugen-HWR. In fact, the prototype Fugen uses 1.5 w/o enriched UO_2 fuel in an outer core of the initial load, and the SGHWR(5) also uses enriched UO_2 fuel in the similar reactor system and is showing an excellent operational experience.

Use of enriched UO_2 fuel in the Fugen-HWR might be considered any time if supply of Pu fuel becomes insufficient, and this is a very probable case to take place depending on the future fuel cycle situation. By using UO_2 fuel with enrichment range 1.75 ∿ 2.0 w/o, the equilibrium cycle burnup will be 23,900 ∿ 29,100 MWD/MT in the Fugen-HWR (see Table 2, EU case 1, 2), where in this case the interest is in saving of both NU and SWU requirements without using plutonium fuel.

Note that UO_2 fuel might easily substitute Pu-NU MOX fuel from the replacement core, on the condition that these fuels are in som enrichment range matching each other. The opposite refuelling will be also possible; i.e., MOX fuels to substitute UO_2 fuels in the replacement core. All such flexible fuel loading would be controlled by a fuel management program unique to the Fugen-HWR which is explained in Chapter 2.4 of this paper.

2.3 Material Saving in LWR-Fugen Combined System

In an actual plan of plutonium recycle, a material balance has to be considered. The Fugen-HWR primarily expects to use tail assay of spent LWR fuels to save NU and SWU requirements, and these saving effects are here studied in a LWR-Fugen combined system, and then compared with the cases of LWR only.

(1) Fugen-HWR combined with LWR

The Fugen-HWR, using Pu-NU MOX as a primary fuel, is here taken up as a representative case, and combined with the U recycle LWR. A simplified fuel cycle flow in this case is shown in Fig. 6, wherein enriched uranium is fed to LWR while natural uranium and recovered plutonium are to the Fugen-HWR. As for the depleted uranium from spent

LWR fuel, a general idea is to be reused in LWR, or to be used in the Fugen-HWR as an alternative choice.

As shown in Table 2, an equilibrium cycle fissile Pu requirement in the Fugen-HWR (Pu-NU MOX, case 1) is 0.379 Ton/GWe·Y at 100% plant capacity factor, while fissile Pu discharge from LWR (U-recycle) is 0.229 Ton/GWe·Y. When Pu-balance is taken with this relation, a unit of the Fugen-HWR is deriven by 1.66 units of LWR in equilibrium cycle. If the Fugen-HWR (Pu-NU MOX, case 2) is considered, the Fugen-LWR ratio would be become 1/1.30 by the same arithmetic. With such Fugen/LWR combinations, the overall NU and SWU requirements are calculated by using mass balance values of Table 2, i.e.,

case 1, Fugen-HWR (1.44 w/o fiss. Pu-NU MOX) + LWR (U-recycle)

$$\text{NU requirement} = \frac{(155.6 \times 1.66) + 40.0}{1.66 + 1.0} = 112.1 \text{ Ton/GWe}\cdot\text{Y}$$

$$\text{SWU requirement} = \frac{145.5 \times 1.66}{1.66 + 1.0} = 90.8 \text{ Ton SWU/GWe}\cdot\text{Y}$$

case 2, Fugen-HWR (1.0 w/o fiss. Pu-NU MOX) + LWR (U-recycle)

$$\text{NU requirement} = \frac{(155.6 \times 1.30) + 55.0}{1.30 + 1.0} = 111.9 \text{ Ton/GWe}\cdot\text{Y}$$

$$\text{SWU requirement} = \frac{145.5 \times 1.30}{1.30 + 1.0} = 82.2 \text{ Ton SWU/GWe}\cdot\text{Y}$$

where 100% plant factor and 0.20% enrichment tail are being assumed.

(2) LWR only; with and without U or Pu recycle

The requirements for NU and SWU for this case are directly quoted from Table 2, i.e.,

NU requirement = 116.8 ∿ 197.7 Ton/GWe·Y

SWU requirement = 98.3 ∿ 149.8 Ton SWU/GWe·Y

The numerical span given in the above requirements depends on whether uranium or plutonium are used by recycle.

Comparison of these cases are also graphically shown in Fig. 7, where the advantage of the Fugen-HWR is clearly understood and its combined saving effects are shown predominant over the case of LWR (Pu-thermal).

Although these evaluations are made only in the equilibrium cycle mass balance, they are effective in quick understanding of the Fugen-HWR fuel cycle characters.

2.4 Fuel Management and Control Program

In addition to the effective use of nuclear fuel, the Fugen-HWR has many technical advantages for using MOX fuel; and these are briefly described.

(1) Fuel Loading and Burnup Management

Burnup management of the Fugen-HWR is carried out by using an on-line computer system, with which the important operating parameters are recorded for every fuel channel. Shown in Fig. 8 is an example of core mapping(16) for the prototype Fugen reactor; wherein the power, exposure, MCHFR and fractional flow are shown in the core of quadrant symmetry. The example mapping of Fig. 8 is an off-line simulation, but this sort of core mapping is actually produced by an on-line system by utilizing readings of nuclear and process instrumentations. With such a core management system, varieties of fuel type can be used in a mixed bed loading, and one is able to follow the safety of each fuel performance. This management system is also a big help for the flexible use of fuels discussed in the previous section.

As for the refuelling system, the prototype FUGEN employs an "on-load" method, while the Fugen-HWR demonstration reactor expects to employ an "off-load" method for purpose of simplifying the mechanical system of fuel handling. In either case, refuelling in the Fugen-HWR is performed rather easily, since not accompanied by a big task as to open the top of a pressure vessel in the case of LWR. In the Fugen-HWR, refuelling 1/8 ∿ 1/10 of the core by an "off-load" system requires about a week, and this might happen twice a year. However, one of these refuelling works takes place during the regular maintenance shutdown, so that a penalty to plant factor by refuelling shutdown would become very small. On the other hand, easy refuelling of the Fugen-HWR will give an advantage to the fuel management; i.e., refuelling interval, location, number and type of fuels, etc., are occasionally selected and refuelling is performed for convenience of core performance.

(2) Control of the Pu-fuelled Reactor

(i) Control rod effect:

The control rods of the Fugen-HWR are inserted in the D_2O space in between the pressure tube lattice, and its absorber surface are generally 5 ∿ 10 cm apart from the nearest fuel rods. Hence, the control rod effect is only slightly influenced by the fuel types, and it does not give restrictions to the flexible use and free loading of fuels in the Fugen-HWR. In an actual case, the control rod worths decrease only about a few percent by fully replacing UO_2 fuel to Pu MOX fuel, and such a small change is easily absorbed by the control margin. The total maneuvering control worth is relatively small in the Fugen-HWR, and it is about 6 % Δk in the demonstration reactor design including shutdown margin. This means that the total control rod worth is affected by only 0.2 ∿ 0.3 % Δk depending on the type of fuels.

(ii) Local power peaking:

The fuel assembly of Fugen-HWR is of a structure in which fuel pins are arranged in ring-arrays from the center. Shown as an example in Fig. 4 is a cutaway view of the prototype FUGEN fuel assembly which consists of 28 fuel pins in three rings. For the Fugen-HWR demonstration reactor, a number of fuel pins might increases to 36 but arranged similarly.

To avoid local power peaking (LPF) in a fuel channel, fissile plutonium topping is adjusted for each ring of the MOX fuel assembly. Generally, the hottest spot occurs in the outer pins of the assembly, so that LPF can be avoided simply by lowering Pu topping of the outer pins. Also, one dimensional design analysis is good enough for the evaluation and its accuracy has been easily checked by experiments. Such a simplicity in evaluating thermal behavior of MOX fuel assembly is to be compared to the case of LWR (Pu-thermal) which employs UO_2 and MOX fuels in mixed bed and with several enrichments as well.

(iii) Void effect:

Plutonium fuel in the Fugen-HWR has a dominant effect to make coolant void reactivity more negative(7), and this gives a very favorable contribution to the stable reactor character. Any fuel might contain plutonium isotopes after some irradiation, and its operational character changes during the transition core. With use of Pu-NU MOX fuel, the operational character is kept reasonably unchanged during this transition and this helps a lot in reactor control system design.

2.5 Non Proliferation Consideration

To carry out a full scale program of Pu fuel utilization, the physical protection of Pu against robbery and detailed preventive measures for its proliferation have to be considered, in addition to the safety and health control of Pu fuel as a radioactive material.

Generally, in the long range fuel cycle evaluation, plutonium storage tends to buildup during the period prior to commercial introduction of FBR, and such an excess buildup would last for some uncertain period.

Exclusive use of Pu fuel in the Fugen-HWR is a basic philosophy of its development, and the reactor is expected to use about 2 tons of fissile plutonium for each GWe initial inventory. After the equilibrium cycle, it consumes 0.38 ∿ 0.30 Tons (net) of fissile plutonium for each GWe·Year of reactor operation (See Table 2, Pu-NU MOX, Case 1 ∿ 2). The rate of plutonium fuel consumption would become larger if natural uranium is substituted by depleted uranium obtained from the enrichment tail.

Such a flexible character of plutonium utilization is considered to be an advantage to keep up an optimum balance of plutonium buildup in the overall fuel cycle program. In other words, the Fugen-HWR is able to control the excess buildup of Pu fuel meanwhile making its effective utilization. At a time of plutonium shortage, on the other hands, it might also use slightly enriched uranium fuel to become a plutonium producer. All such flexible positions of the Fugen-HWR therefore indirectly contribute to the non-proliferation of plutonium fuel.

3. Reactor Safety

Safety design and its design criteria are the important items to be reported in this paper, and the unique features of the Fugen-HWR safety consideration are here described.

3.1 Reactor Physics

(1) Based on the experiences of the prototype Fugen development, the important safety items of the demonstration reactor such as pressure tube dimensions, steam quality, two phase flow velocity, MCHFR, etc., shall be kept approximately equal to the prototype reactor, and the reasonable margins be also provided.

(2) Coolant void reactivity coefficient and LOCA reactivity worth shall be made slightly negative, or approximately equal to zero; so that the undesirable transient effects to the reactor might be minimized. For this purpose, plutonium fuel will give a favorable effect, i.e., the coolant void reactivity would be shifted to

negative side with existence of Pu fuel.(7)

3.2 Reactor Control and Instrumentations

(1) Other than the shutdown system by control rods, the liquid poison injection system is provided as a backup safety device, which directly injects poison into the D_2O moderator. Since the D_2O moderator exists outside of the pressure boundary, this injection system has a quick response, and is reliable, too. Furthermore, its facility design is rather simple.

(2) To detect failures of inlet and outlet feeders at the earliest possible occasion, an acoustic emission leak detector system, an independent channel flow monitoring system, a hot box pressure monitoring system, etc. are to be provided.

(3) Taking an advantage of the zero void reactivity coefficient (or slightly negative), the load following reactor control will be planned in the Fugen-HWR in the future. It is noted that fuel failures resulting from power transients have not occurred in most of the other pressure tube type HWRs. However, this must be confirmed before actually employing the load following control system.

(4) Failed fuel detection system (FFD) shall be provided at each fuel channel, so that any minor fuel failures and their channel locations might be detected in early time; and refuelling is performed immediately when it is judged necessary from safety consideration. Note that this becomes possible in any pressure tube type reactors, and the Fugen-HWR takes an advantage of it.

3.3 Radioactive Waste Management

The basic philosophy of radioactive waste management is to minimize metallic impurities from corrosion-erosion products in the heat transport system, and also to minimize radioactive release from the failed fuels. The following measures are to be taken for this purpose.

(1) Failed fuels can be immediately detected by the FFD system, and they will be refuelled anytime by shutting off the reactor 1 or 2 days. This then contributes to lower the contamination level of the primary coolant system.

(2) Primary coolant demineralizer and condensate demineralizer systems both employ powdex filters to clean heat transport coolant. The capacity of these demineralizer system shall be made large enough to satisfy the purpose.

3.4 ECCS System

Emergency core cooling system (ECCS) of the prototype Fugen(8) consists of three types of water injection system. One is an accumulator type, named accumulated pressure core injection (APCI). The other two are pump injection type; one is high pressure core injection (HPCI) and the other is low pressure core injection (LPCI). The APCI is intended for use in case of a large rupture accident of the primary cooling system, and provides effective core cooling for the initial period of an accident. In case of small or intermediate size rupture accidents, the HPCI acts to spray water into the steam phase of the steam drum, to quickly reduce the pressure in the loop. The LPCI provides long term cooling after the APCI water in the accumulator is injected.

In the safety design evaluations of the prototype Fugen reactor, the following break type accidents;

(1) ruptures of pressure tube, and of inlet feeder tube,

(2) ruptures of the downcomer, and of the main steam pipe,

were evaluated by simulation. These break points are referred in Fig. 9.

Experiments have also been carried out to study the characteristics of blow-down in the primary cooling system, and to confirm the core cooling effect of ECCS, by using a full scale safety experiment facility. The ruptures in the experiments were considered in pressure tube, inlet feeder pipe, down-comer, and main steam pipe.

Although the ECCS of the prototype Fugen completely satisfy the safety design criteria, a further safety measure is in pursuit for the ECCS design of the demonstration reactor. The proposal for this is to utilize the feed water and condensate pumps for the duplicated purpose also for the ECCS. These pumps are to be driven by the highly reliable on-site station power source even during the normal plant operation, and they move in to function as ECCS pumps without interruption, only accompanied by valve control. The following advantages are expected in this new proposal, i.e.,

(1) In case of the loss of coolant accident (LOCA), the dryout-reflooding thermal transients to the fuel surface can be avoided more easily. This prevents the fuel failures and minimize the release of the radioactive materials.

(2) The pumps are in continuous operation prior to functioning as the ECCS pumps, and this drastically increases the reliability of its function at a time of necessity.

4. Conclusions

A general concept of the Fugen-HWR; a pressure tube type, heavy water moderated, boiling light water cooled, and plutonium fuelled reactor is first described; and its characterizations from the fuel cycle aspect are briefly discussed herewith.

Because of the intrinsic nature of heavy water moderated reactor, the Fugen has many advantages for effective use of nuclear fuels, and also has a wide range of flexibility for using various fuel types.

It expects to use Pu-NU MOX as a standard fuel, and to save NU and SWU requirements in the overall fuel utilization program combined with the other type of reactors. With using Pu-NU MOX fuel (1.0 ∿ 1.44 w/o fissile Pu enriched) in the Fugen-HWR combined with LWR (U recycle) as Pu fuel suppliers, the overall saving of NU and SWU requirements in equilibrium cycle will be 4 ∿ 5 %, and 8 ∿ 16 %, respectively, beyond the case of LWR uranium-plutonium recycle. If plutonium recycle is not considered in LWR, this gap of saving effect widens much more.

Although Pu-NU MOX is primarily expected as a fuel of the Fugen-HWR, it is also possible to use Pu-DU MOX and enriched UO_2 as alternative fuels depending on the future fuel cycle situation, and such a flexibility is considered to be an advantage in the Fugen-HWR fuel cycle.

Apart from the fuel cycle aspects, the Fugen-HWR has many technical advantages for using Pu MOX fuel. One of these is the operational fuel management program. The Fugen refuelling system allows to load different type of fuels in a mixed bed method, and fuel burnup is channelwise managed by an on-line computer. Another point to mention is the use of FFD system, which detects minor fuel failures and their channel locations, hence greatly contributes to the safety of the reactor.

It is also pointed out that the Fugen-HWR is suitably designed for the exclusive use of Pu MOX fuel, and it effectively controls the excess buildup of plutonium fuel in the long range fuel cycle program.

As an overall conclusions, the position of the Fugen-HWR is strongly recommended as one of the choice for making Pu utilization in thermal reactors.

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Table 1. Reference Data of Prototype FUGEN and Demonstration Reactor

	Prototype FUGEN	Demo. Plant Conceptual design (step 4)
Electric Power (MW)	165	600
Thermal Power (MW)	557	2000
No. of Channels	224	720
Core Height (mm)	3700	3700
Diam. of Calandria (mm)	4900	9200
Pressure Tube		
Material	Zr-Nb	Zr-Nb
Inside Diam. (mm)	118	118
Fuel		
No. of Rods/Ass.	28	36
Pellet Diam. (mm)	14.4	12.5
Pu-NU MOX, Enrich. Fiss.Pu (% average)	0.67	1.44
UO_2, Enrichment (%)	1.5	—
Refuelling	On-power (demonstration)	Off-power

Table 2 Reactor Characteristics and Fuel Utilization (at 100 % Capacity Factor)

Reactor Type	Fugen-HWR					LWR(1)		
Fuel Type	Pu-NU MOX (Case 1)	Pu-NU MOX (Case 2)	Pu-DU MOX Use of DU from LWR	UO_2 (Case 1)	UO_2 (Case 2)	Once-through	U-recycle	U, Pu recycle
Equilibrium Cycle								
Burnup (MWD/MT)	28,700	21,000	28,800	29,100	23,900	29,500	29,500	29,500
Fissile enrichment:								
Loading U-235 (w/o)	0.71	0.71	0.85	2.0	1.75	2.87	2.87	3.35(U+Pu) fissile
Fissile Pu (w/o)	1.44	1.00	1.30	-		-	-	
Discharge U-235 (w/o)	0.13	0.16	0.15	0.17	0.22	0.80	0.80	0.67
Fissile Pu (w/o)	0.54	0.49	0.52	0.39	0.37	0.65	0.65	1.36
NU requirement:								
Loading (MT/GWe·Y)	39.96	54.95	40.30 (Du)	143.1	150.0	197.7		
Discharge (")	-	-	-	-	-	-		
Net use (")	39.96	54.95	40.30 (Du)	143.1	150.0	197.7	155.6	116.8
Fissile Pu requirement:								
Loading (MT/GWe·Y)	0.588	0.557	0.528	0	0	0	0	0.457
Discharge (")	0.209	0.259	0.200	0.147	0.174	0.229	0.229	0.457
Net use (")	0.379	0.298	0.328	-0.147	-0.174	-0.229	-0.229	0
SWU Req.(MT SWU/GWe·Y)	0	0	0	89.1	84.1	149.8	145.5	98.3

(1) LWR data are taken from Ref. (4) for the case of PWR/BWR = 2/1, but being adjusted for the following losses.

(2) Allowances are made for losses during fabrications and reprocessing; 1 % for NU and Pu, 2 % for EU.

(3) Enrichment tail of 0.20 % is considered for all cases.

(4) The negative sign indicates production of Pu.

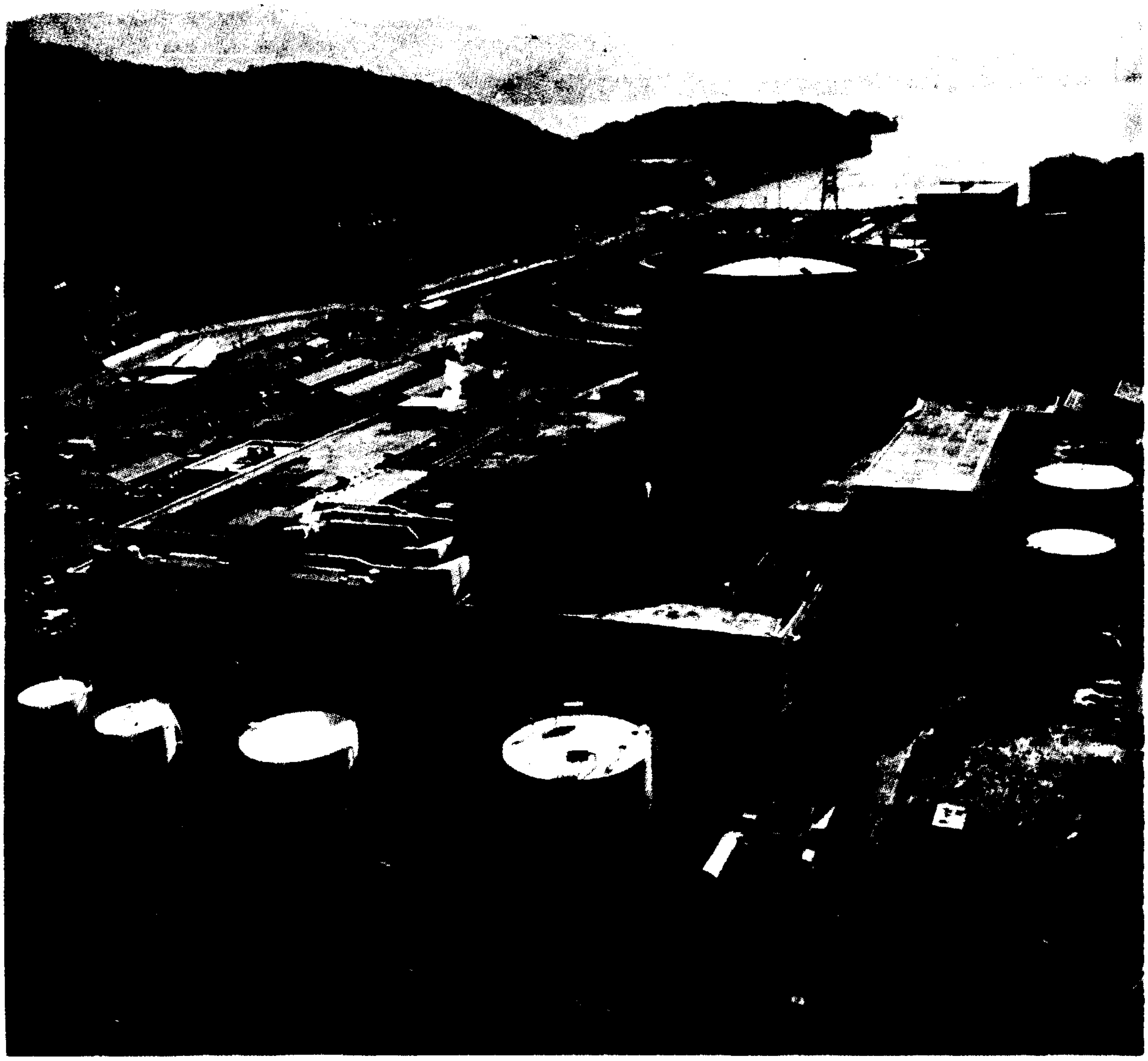

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Fig. 1 A bird-Eye View of the Prototype Fugen Reactor

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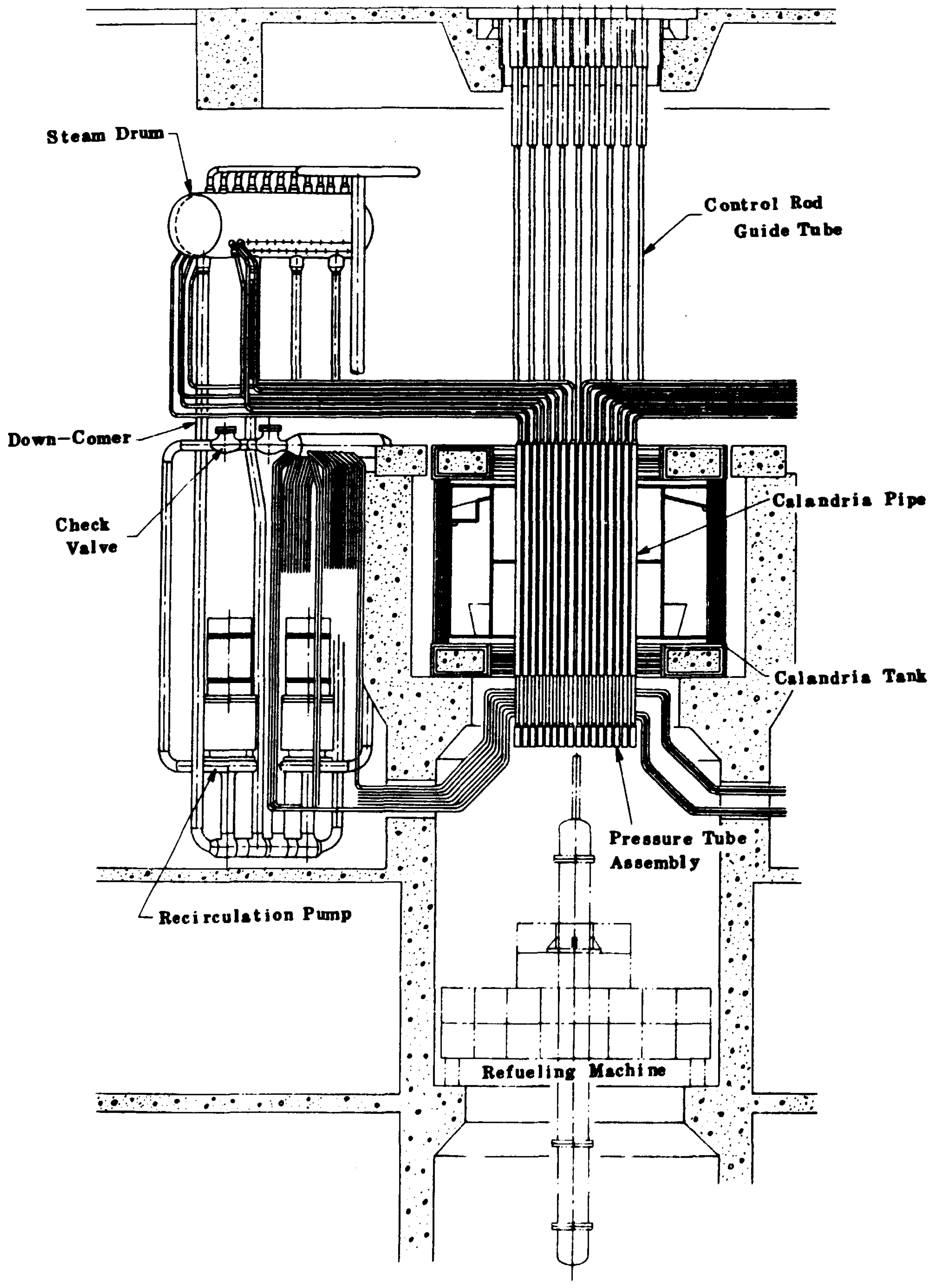


Fig. 2 General Reactor Arrangement

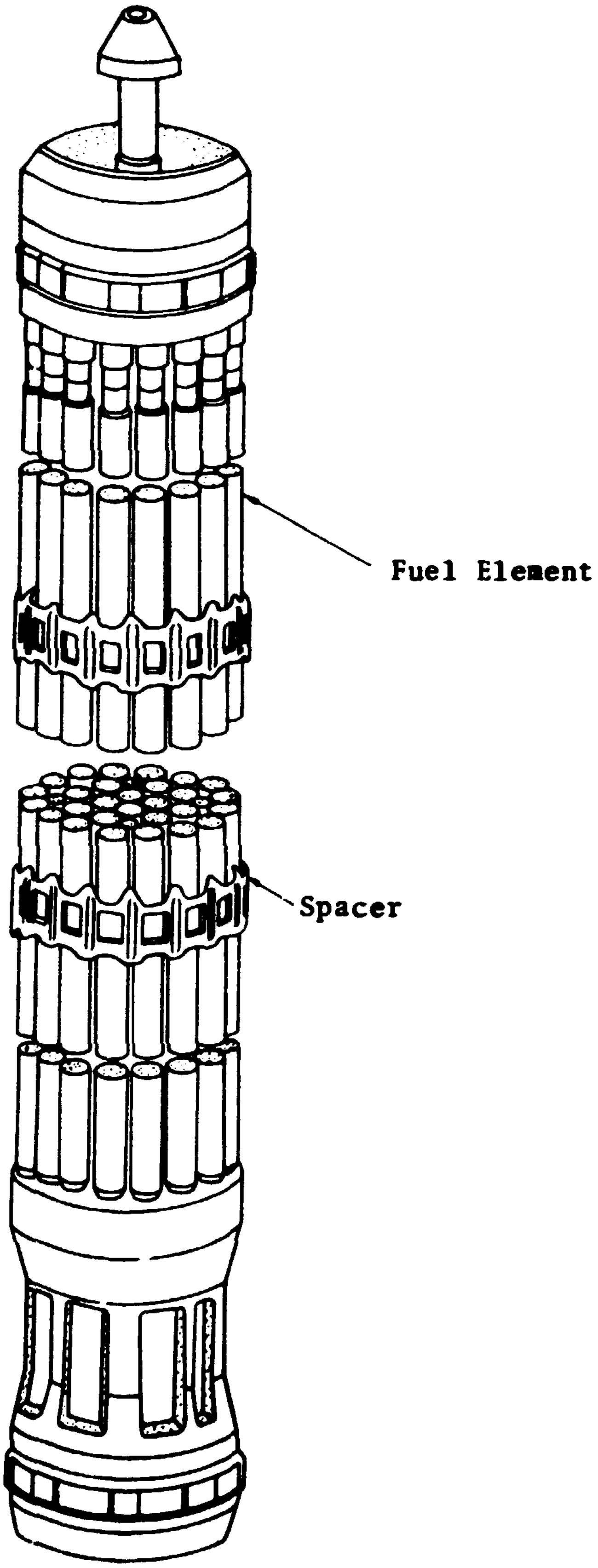


Fig. 3 Outlook of Prototype Fugen Fuel Assembly

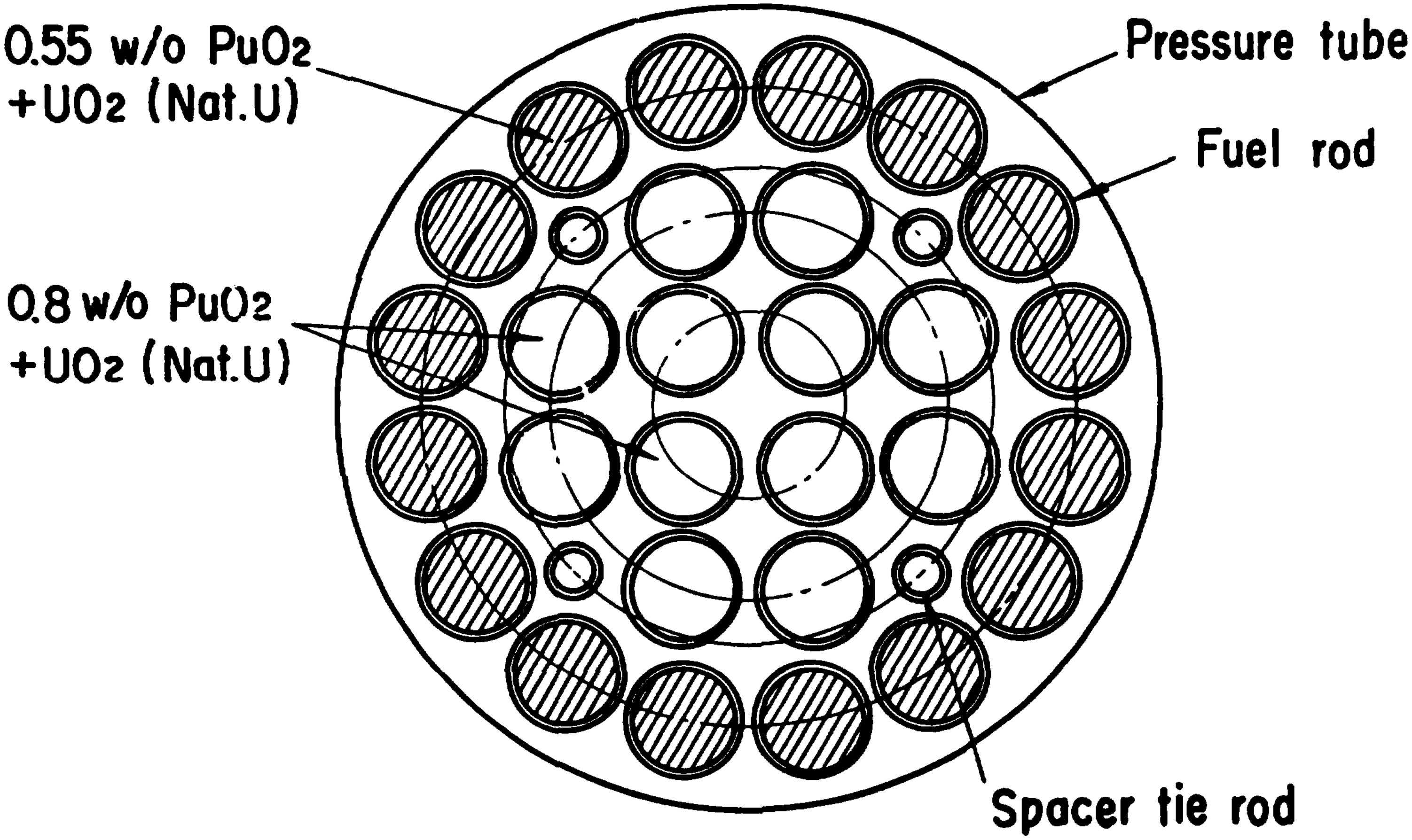
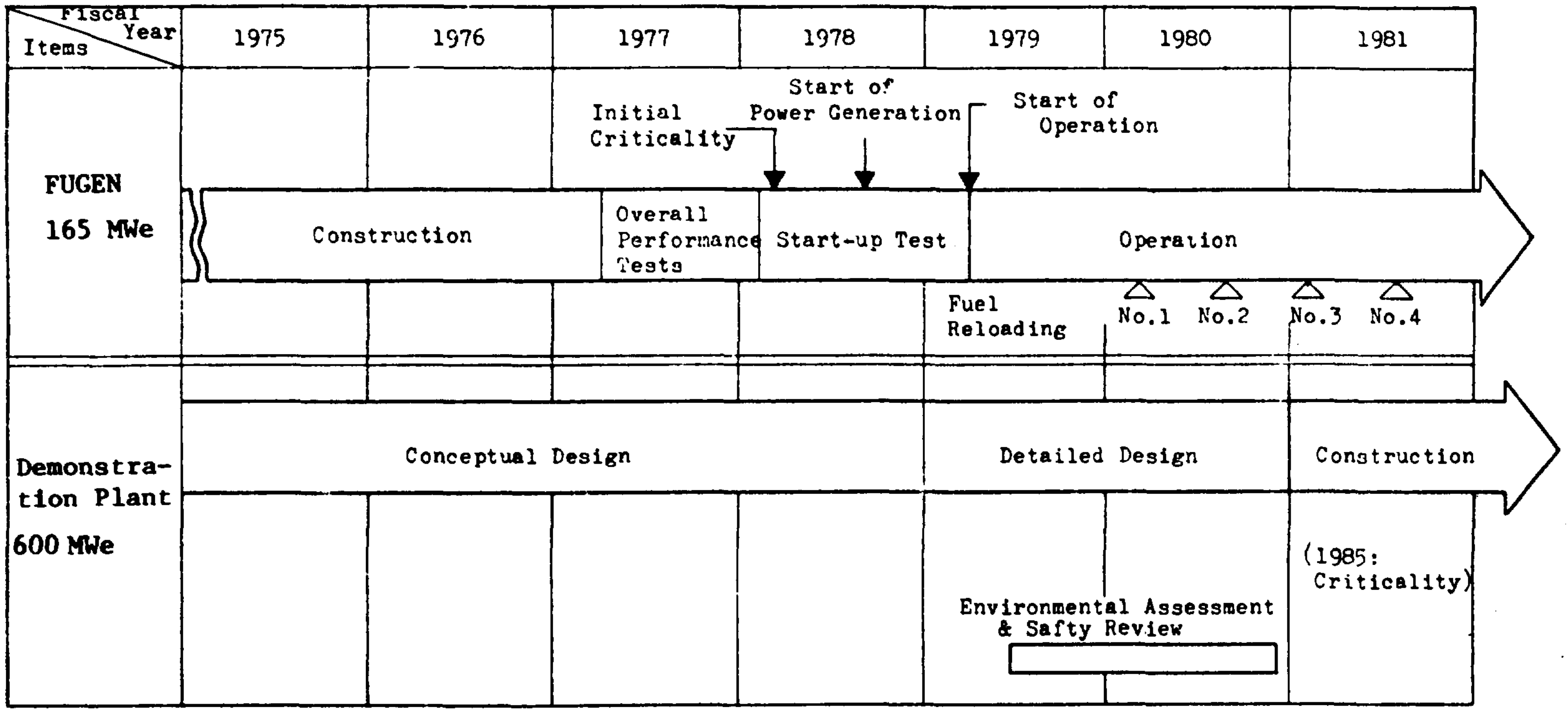
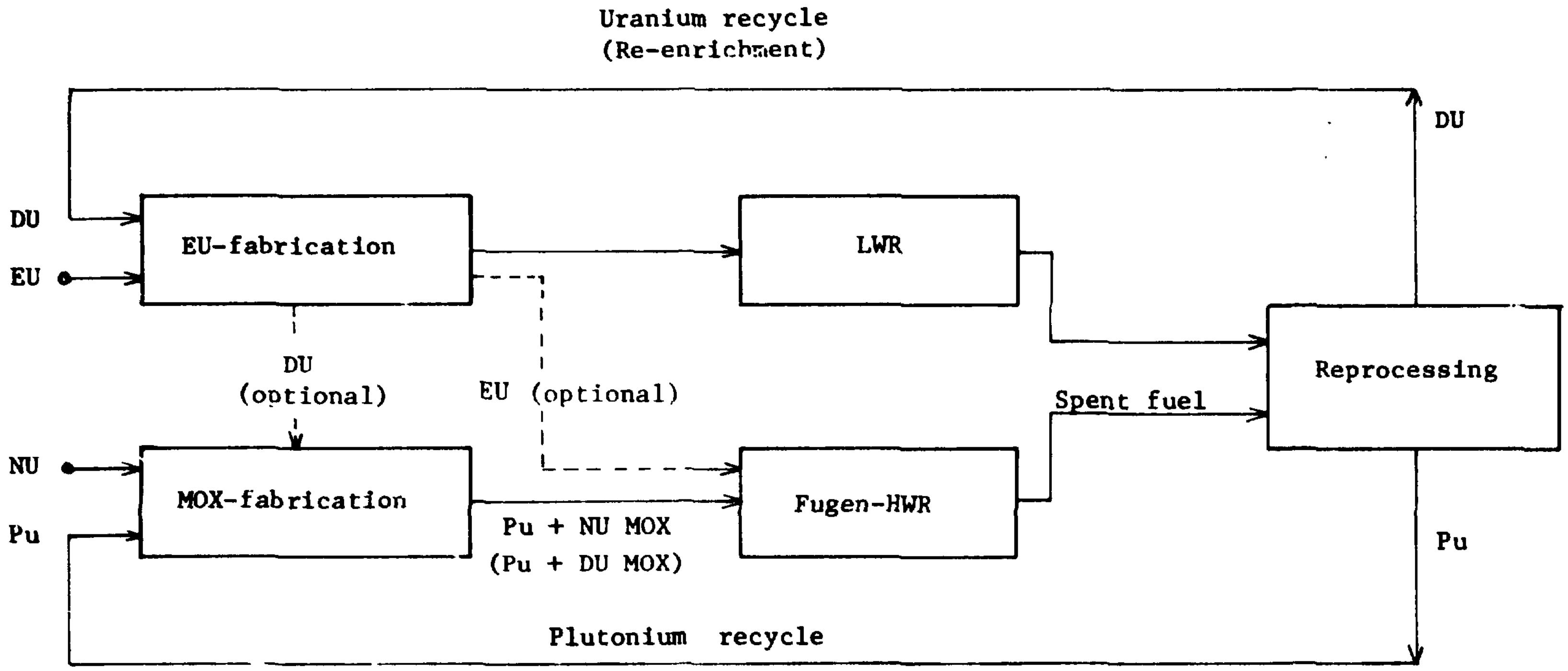


Fig. 4 Cross Sectional View of Prototype Fugen Fuel Assembly

Fig. 5 Development Schedule of Fugen-HWR





EU : Enriched uranium
NU : Natural uranium
DU : Depleted uranium recovered from LWR spent fuel

Fig. 6 Fuel Cycle Flow of Fugen-HWR Combined with LWR

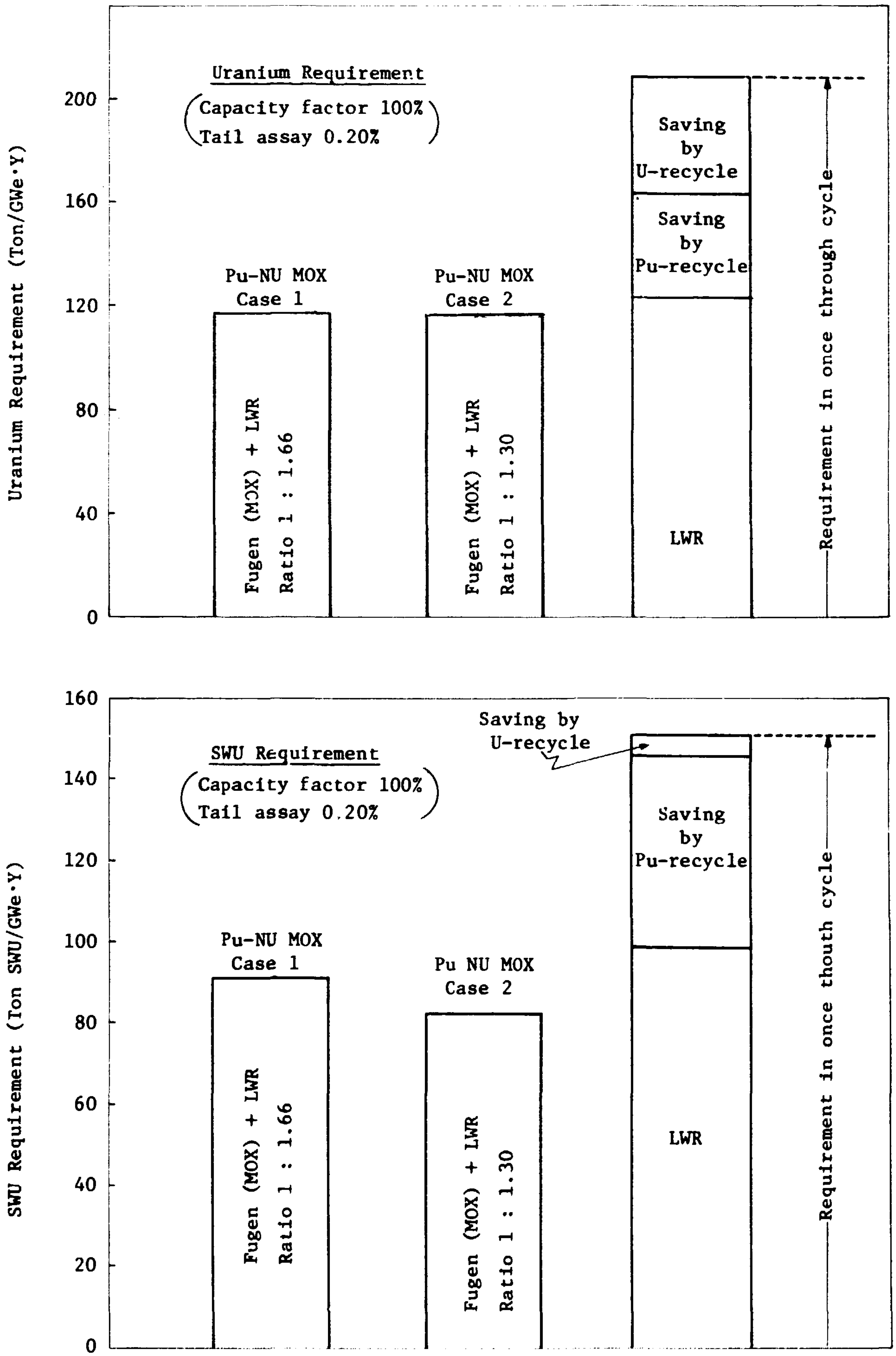
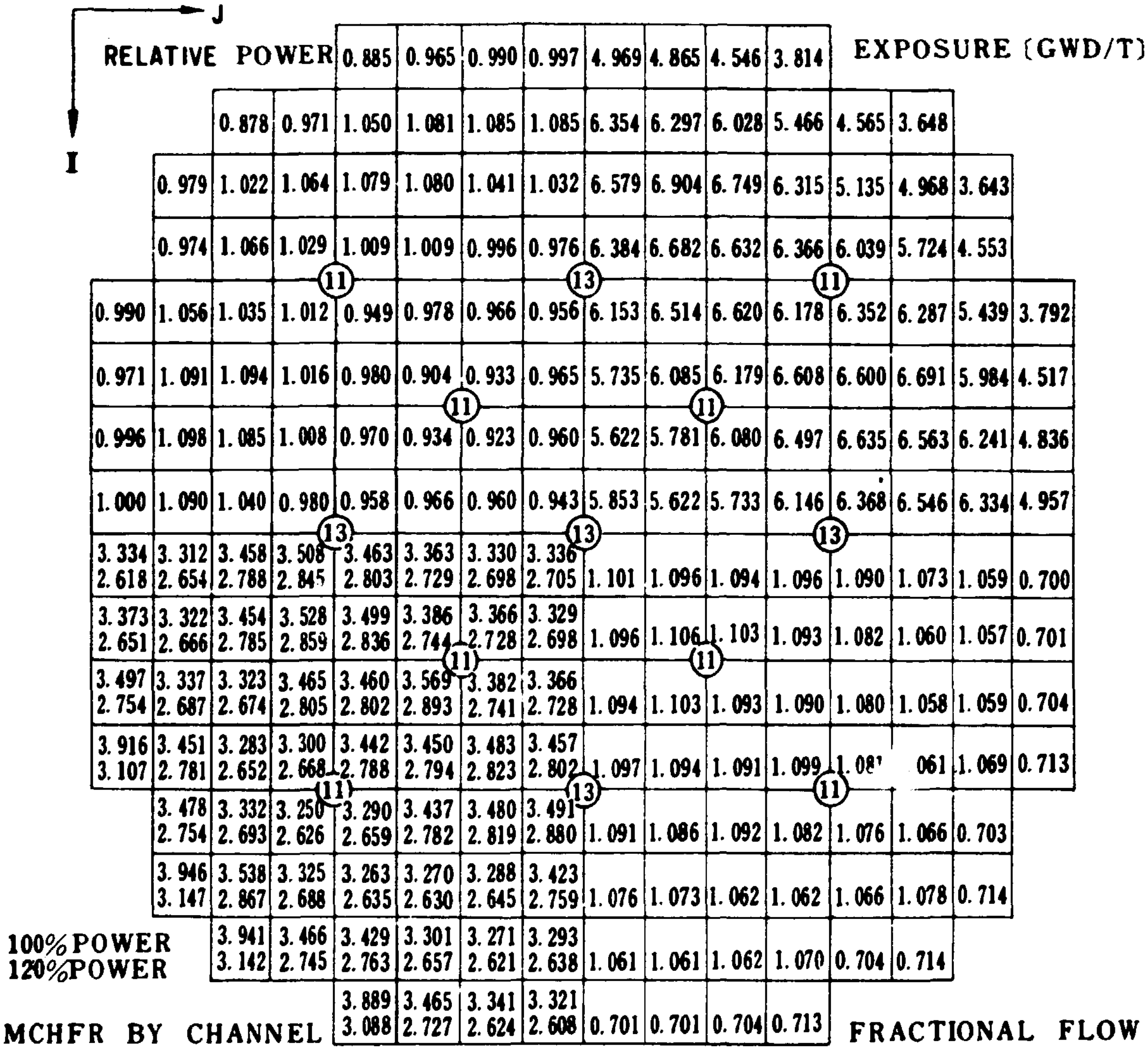


Fig. 7 Comparison of Uranium and SWU Requirements



				0.885	0.965	0.990	0.997	4.969	4.865	4.546	3.814				
		0.878	0.971	1.050	1.081	1.085	1.085	6.354	6.297	6.028	5.466	4.565	3.648		
	0.979	1.022	1.064	1.079	1.080	1.041	1.032	6.579	6.904	6.749	6.315	5.135	4.968	3.643	
	0.974	1.066	1.029	1.009	1.009	0.996	0.976	6.384	6.682	6.632	6.366	6.039	5.724	4.553	
0.990	1.056	1.035	1.012	0.949	0.978	0.966	0.956	6.153	6.514	6.620	6.178	6.352	6.287	5.439	3.792
0.971	1.091	1.094	1.016	0.980	0.904	0.933	0.965	5.735	6.085	6.179	6.608	6.600	6.691	5.984	4.517
0.996	1.098	1.085	1.008	0.970	0.934	0.923	0.960	5.622	5.781	6.080	6.497	6.635	6.563	6.241	4.836
1.000	1.090	1.040	0.980	0.958	0.966	0.960	0.943	5.853	5.622	5.733	6.146	6.368	6.546	6.334	4.957
3.334 2.618	3.312 2.654	3.458 2.788	3.508 2.845	3.463 2.803	3.363 2.729	3.330 2.698	3.336 2.705	1.101	1.096	1.094	1.096	1.090	1.073	1.059	0.700
3.373 2.651	3.322 2.666	3.454 2.785	3.528 2.859	3.499 2.836	3.386 2.744	3.366 2.728	3.329 2.698	1.096	1.106	1.103	1.093	1.082	1.060	1.057	0.701
3.497 2.754	3.337 2.687	3.323 2.674	3.465 2.805	3.460 2.802	3.569 2.893	3.382 2.741	3.366 2.728	1.094	1.103	1.093	1.090	1.080	1.058	1.059	0.704
3.916 3.107	3.451 2.781	3.283 2.652	3.300 2.668	3.442 2.788	3.450 2.794	3.483 2.823	3.457 2.802	1.097	1.094	1.091	1.099	1.08	061	1.069	0.713
	3.478 2.754	3.332 2.693	3.250 2.626	3.290 2.659	3.437 2.782	3.480 2.819	3.491 2.880	1.091	1.086	1.092	1.082	1.076	1.066	0.703	
	3.946 3.147	3.538 2.867	3.325 2.688	3.263 2.635	3.270 2.630	3.288 2.645	3.423 2.759	1.076	1.073	1.062	1.062	1.066	1.078	0.714	
		3.941 3.142	3.466 2.745	3.429 2.763	3.301 2.657	3.271 2.621	3.293 2.638	1.061	1.061	1.062	1.070	0.704	0.714		
				3.889 3.088	3.465 2.727	3.341 2.624	3.321 2.608	0.701	0.701	0.704	0.713				

Ⓝ : Control rod insertion (16 = Full out, 0 = Full in)

Fig. 8 An Example of Core Mapping for Prototype Fugen Reactor
(Power, Exposure, MCHFR, Fractional Flow)

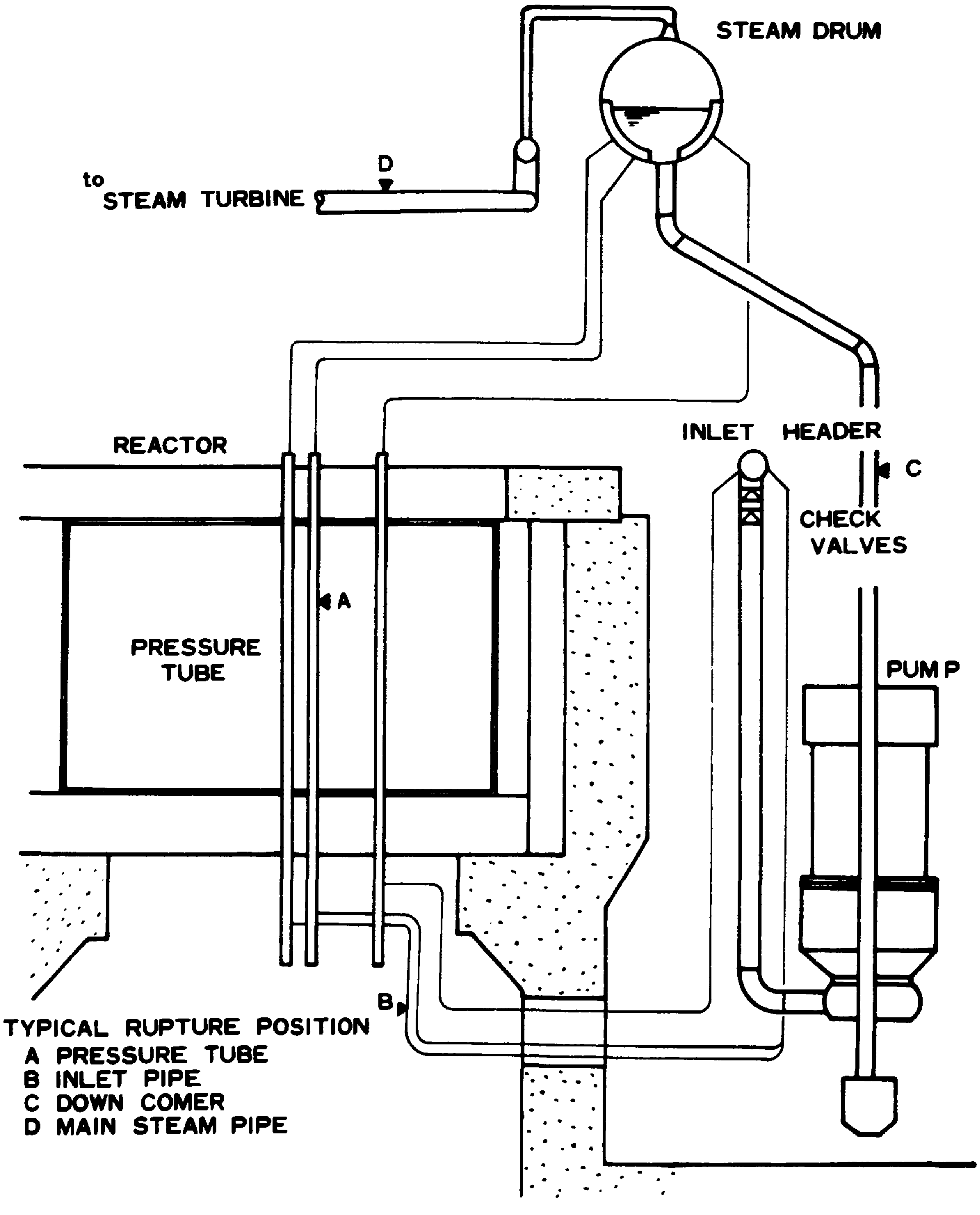


Fig. 9 Prototype Fugen Primary Cooling System