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USE OF PLUTONIUM IN HEAVY WATER MODERATED BOILING LIGHT WATER COOLED REACTOR

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1. Specific Characteristics of FUGEN Type Reactor*-1

It is now nearly ten years since the development of the heavy water moderated boiling light water cooled reactor began in Japan, and the prototype, which has been named FUGEN (165 MWe), is now under construction at Tsuruga, Fukui-ken, Japan, scheduled to reach criticality in 1975.

FUGEN has several specific characteristics and features, and the aim of this project is to establish and demonstrate these through the development and operation of this reactor.

1.1 Use of Plutonium

"Economy" is considered a most important factor in a reactor to be used commercially for the generation of electric power. Under present conditions, especially considering the cost of enriched uranium and of fuel fabrication (100 $/kg U or above), it can be expected that the operation of this type of the reactor will be more economical with enriched fuel (either slightly enriched uranium or natural uranium enriched with plutonium) than with natural uranium only. This can be readily understood by reference to Fig. -1, which also indicate that the chaper the enriched fuel is, the higher the optimum fuel enrichment will be. However, consideration has also to be given to the peaking factor for fresh fuel in determining its enrichment.

If one care to use only natural uranium, the "Plutonium Self-Sustaining Cycle" can be considered for this type of the reactor, which means the use of natural uranium enriched with plutonium (recovered from the spent fuel itself) as fuel. This effects a reduction of the power cost below that of fueling with natural uranium without the use of the above plutonium.

On the other hand, the void reactivity (the difference between the reactivity of the core filled with liquid coolant and the one of the core without it) is regarded as one of the most important factors in this type of the reactor, especially from the stand point of reactor safety.

In the region of designing this type of the reactor, higher burn-up and also greater positive void reactivity would be expected when the lattice pitch is widened. However, the use of plutonium in the core, either spiked or uniformly mixed, lessens void reactivity, which gives a good effect on reactor safety characteristics. Fig. -2 shows the difference in void reactivity between in the initial core loaded with uranium and in the equilibrium core containing some plutonium; a void reactivity, difference of about ($2\% \Delta k/k/100\%$ void difference) is observed between them. This also means that some consideration has to be given to control and engineering reactor safety systems to meet this difference in void reactivity. This problem, however, can easily be overcome if plutonium is used in the initial core. In FUGEN, about half the initial core will be mixed oxide fuel.

The economic evaluation of this type of the reactor was done in 1969 by an ad hoc committee organized by Japan Atomic Energy Commission, the main points of which may be summarized as follows:

1) The FUGEN type reactor would be competitive with a light water reactor if the construction cost of the former can be kept within about 115 to 120 % of the latter.

2) Efforts should go into the development of mixed oxide fuel fabrication, with emphasis on the reduction of the cost of fabrication.

These could be the most important points to be taken up in the development of the FUGEN Project.

1.2 Flexibility in Using either Uranium or Plutonium

This type of reactor could be operated effectively (and efficiently) either with slightly enriched uranium oxide fuel or with mixed oxide fuel without modification of dimensions of the fuel assembly or core configuration. In this type of reactor, compared with the light water reactor, there would not be much difference in plutonium concentration between in the equilibrium core with feeding enriched uranium oxide fuel and in the one with feeding mixed oxide fuel. This fact provides flexibility in the use of fuels with almost optimum cost of power generation in either case. Thus, the FUGEN type reactor will present a favourable selection of fuels for users in accordance with the economic situation at any particular time.

1.3 Effect of Uranium Price on Power Cost

The cost of power generation is governed largely by the price of uranium, including enrichment, and there could be definite trend for the cost of uranium to increase year by year; and the demand for uranium will sharply increase over the next fifteen to twenty years. The same tendency is seen in the cost of the unit separative work for uranium enrichment, directly affecting power costs.

The effect on power generating costs for the FUGEN type reactor was evaluated by the same ad hoc committee of Japan AEC, in comparison with the light water reactor, as summarized in Table -1. As the FUGEN type reactor has the merit of neutron economy, the average conversion ratio can be expected to be about 0.7 to 0.8 as against 0.6 or so for light water reactors. This means that natural uranium consumption per unit of power generated in light water reactors can be expected to be 1.5 to 2 times as much as in the FUGEN type reactor. If the "Plutonium Self-Sustaining Cycle" is adopted in the FUGEN type reactor, enriched uranium will not be used for running the reactor.

This trend for the price of uranium to increase will continue over the coming years, which would favour the FUGEN type reactor.

1.4 Effect of Using FUGEN Type Reactor on Demand of Uranium Enrichment Facility*-2

It is estimated that total electric power generating capacity from nuclear power plants in Japan will be as high as 60 GWe by 1985, for which most reactors will be light water type. This means that large uranium enrichment facilities will be necessary to feed the light water reactors.

It is therefore essential that Japan have perspective on enriched uranium demand to meet the need. A quantitative evaluation was also made of Japan's demand for enriched uranium, varying the combination ratio of the light water reactor, the FUGEN type reactor and the fast breeder reactor. The result is shown in Fig. -3 and the following conclusions can be drawn:

1) something near the present production capacity of the ORNL uranium enrichment facility will be needed by 1990, even if commercial fast breeder reactors are brought into operation by 1985.

2) the capacity of the uranium enrichment facility will be reduced by nearly 45 % if the FUGEN type reactor is utilized from 1978 (comparison is with (LWR + FBR) and with (FUGEN Type + LWR + FBR)).

These conclusions can be appreciated if the cost of enriched uranium is much higher than the present figures or the currently expected figures.

2. FUGEN[*-3, *-4]

2.1 General

The prototype reactor, FUGEN (Fig. -4), is designed to generate 165 MWe, and the main design data is listed in Table -2. The plant comprises five main buildings; reactor building, reactor auxiliary building, fuel building, turbine hall and administrative building.

2.2 Reactor

General arrangements around the reactor are shown in Fig. -5. Refueling is to be done from the bottom of the reactor, and control rods are driven into the core from the top of the reactor. The fuel handling system of FUGEN is so designed that either on-power refueling or off-power can be achieved, and the computer controlled refueling machine is situated below the reactor.

In the calandria tank there are 224 pressure tubes, each of which contains 28 rods cluster fuel assembly. A rather wide gap, 12 mm, is taken between the pressure tube and the calandria tube with the consideration of lessening the heavy water inventory and thermal insulation between the primary coolant and the moderator. A supporting plate is to be horizontally set in the middle of the calandria tank, as shown in Fig. -5, to support the pressure tubes in the event of an earthquake.

As the pressure tube is a key component for this type of the reactor, its in-service inspection is highly desirable, with emphasis on inspections for creep of the pressure tube and scratches or cracks on its inner surface, which might be expected to occur during reactor operation. A pressure tube monitoring system and equipment are under development, one of which is shown in Fig. -6.

2.3 Reactor Safety*-5

Much attention has been paid to reactor safety, as set out below:

1) The emergency reactor shut-down system and emergency core cooling system are so designed that no melting of fuel is to be expected in the event of a loss-of-coolant accident, even without control rods inserted in the core.

2) No other pressure tubes would be ruptured by a jet flow ejected from a ruptured pressure tube. This has been demonstrated by full-scale safety experiments carried out in our O'arai Engineering Center.

3) The inlet headers in the primary cooling system are set at the level of the reactor top, so that the coolant can always be expected to remain in the core, even if a reactor inlet pipe is accidentally ruptured. On the other hand, steam-water mixture (used for heat removal of the fuel assemblies in all other unruptured channels) can flow into the ruptured channel (through the steam drum) and cool the fuel assembly.

4) The emergency core cooling system consists of quick injection, high pressure injection and low pressure injection systems. In case of a major rupture in the primary circuit, the quick injection system supplies water (from

the accumulator) to cool the fuel assemblies at the initial stage of an accident. The low pressure injection system would then be activated and water supplied to the inlet header to provide adequate cooling of the core. If a rupture port is small, the high pressure injection system initiated by a signal from the low water level in the steam drum would spray water into the steam drum and depressurize the primary cooling system, so activating the low pressure injection system.

3. Development

In order to obtain the data necessary for the reactor design, manufacture, construction and operation, many development works are now going on in various fields; such as design, reactor physics, heat transfer and hydraulics, reactor structure and components, fuel and materials and reactor safety.

The following are typical developments in connection with the FUGEN Project.

3.1 Large Testing Facilities

Large testing facilities, such as a 14 MW heat transfer rig (HTL), full-scale component test loop (CTL), full-scale safety experimental facility and critical assembly (DCA) have been built at the O'arai Engineering Center of Power Reactor and Nuclear Fuel Development Corporation. This was done nearly three years ago, and many experiments are being carried out.

1) HTL (Fig. -7)

HTL has been in operation since March 1970 with a capacity of 14 MW. Since the reactor performance is much affected by heat removal characteristics in the core, experiments are being made in a full-scale fuel assembly test section. Data is being accumulated on the heat transfer and hydraulic characteristics of the reactor core, especially for burn-out limits and pressure drop in the fuel region.

2) CTL (Fig. -8)

CTL is the facility used for endurance testing of fuel assemblies and pressure tube assemblies. This work started at the beginning of 1970, and tests are being done under conditions simulated to the reactor.

3) Full Scale Safety Experimental Facility (Fig. -9)

This facility was built for the purpose of demonstrating the safety of this type of the reactor against blow-down accidents, as well as to solve other safety problems.

Full scale experiments have been carried out on accidents caused by rupture of the pressure tube, down-comer, reactor inlet pipe and so on. Typical results were reported at the Geneva Conference (71),[*-3] Nuclex (72)[*-5] and the recent CREST Meeting.[*-6]

Further study and experiments are now going on, especially on emergency core cooling systems.

4) DCA (Fig.-10)

DCA reached criticality in Dec. 1969. Experiments with uranium fuel have been completed and experiments with mixed oxide fuel are now being done. The data, including void reactivity, control rod worth, neutron flux distribution, micro-parameters, have been obtained and some of the results were reported at the international reactor physics meeting held in Paris in Sept. 1972.[*-7]

3.2 Reactor Components

1) Refueling Machine

The final target of this development is to achieve on-power refueling in FUGEN. Along this line, development work was firstly done on important components of the refueling machine, such as the grab, the seal mechanism, the ball valve, etc. Based on the results of these experiments, a full-scale refueling machine was designed and manufactured; and functional testing is to be made from early next year.

2) Others

The development of fuel, reactor equipments such as the pressure tube assembly, including mechanical rolled joints with stainless steel pipe, control rod drive mechanism, reactor structure, and so on is also being done, with emphasis of demonstrating their integrity and endurance.

4. Conclusion

As we have shown, the FUGEN Project is now going on. In the FUGEN type reactor (heavy water reactor), various kinds of fuels, such as uranium, either enriched or natural, plutonium and maybe thorium, could be efficiently and effectively used, as has been stated in references.[*-8, *-9, *-10, *-11]

On the other hand, the most important point is always in the technology associated with the primary coolant (in developing a reactor), including reactor physics, core heat removal, fuel, safety system, etc. The FUGEN type reactor uses light water as its primary coolant, which has now been in use for many years; and it may be said that the technology won from light water reactors can be utilized fully in this type of reactor, and or vice versa.

In view of the special characteristics and features we have mentioned, this type of the reactor appears to be very feasible for any conditions that can be expected over the coming years.

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*-10 ENEA, "Illustrative Power Reactor Programmes", May, 1968

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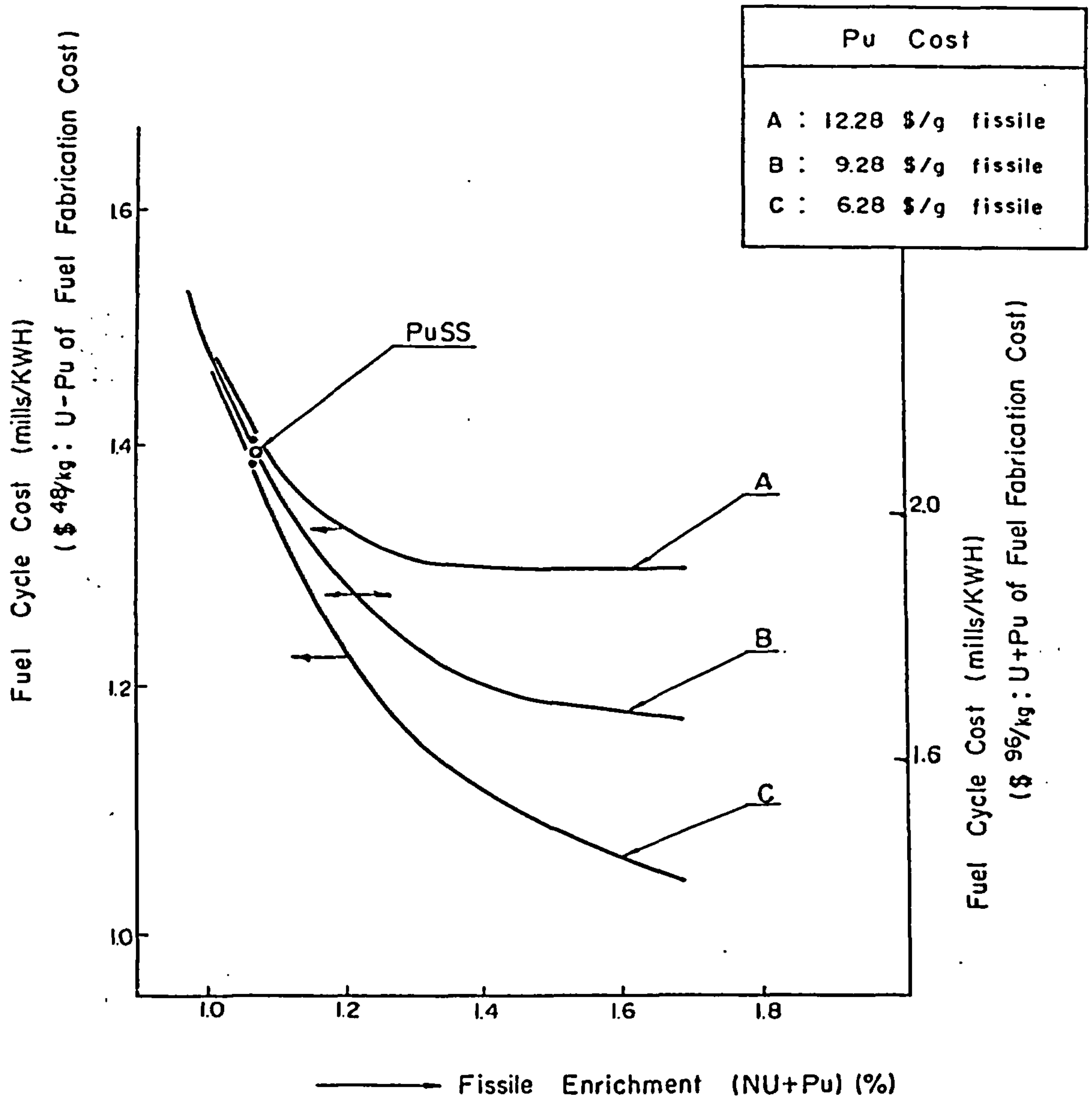


Fig-1 Fuel Cycle Cost vs Pu Concentration

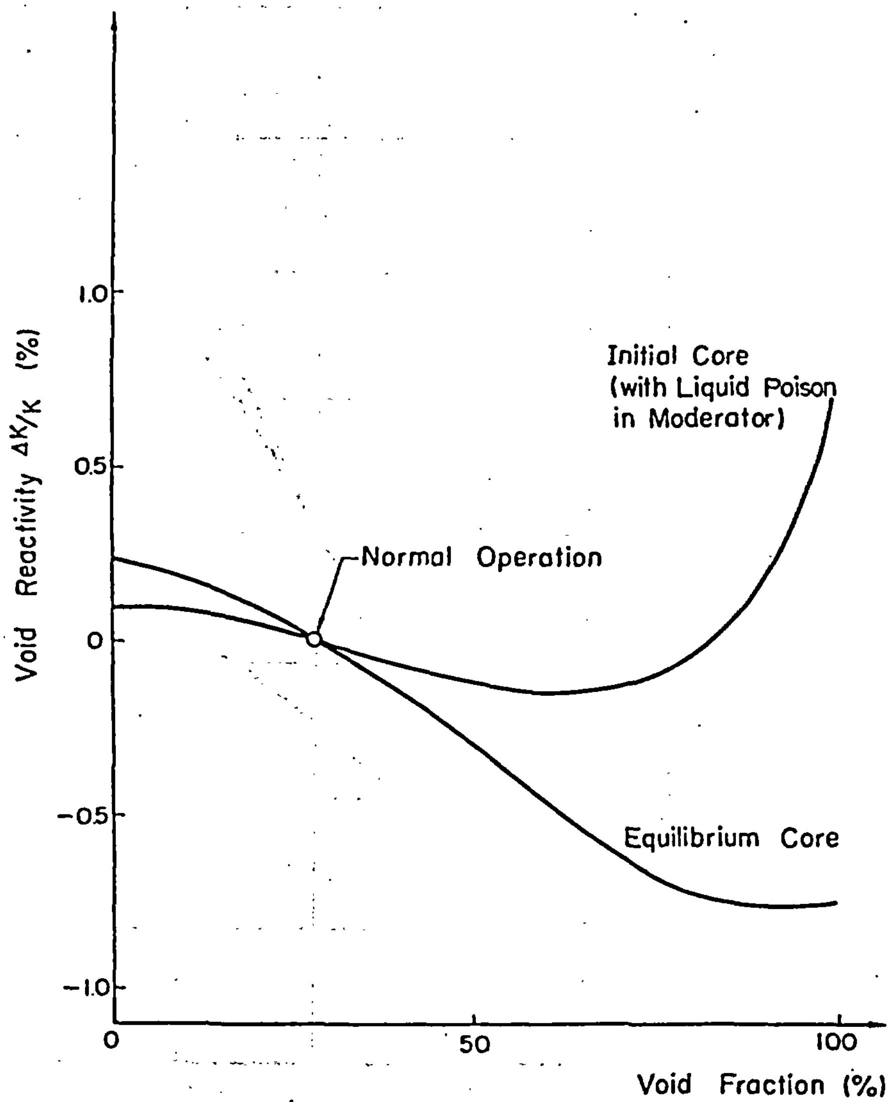


Fig-2 Void Reactivity vs Void Fraction

with 1.5w/o E.U. Fuel

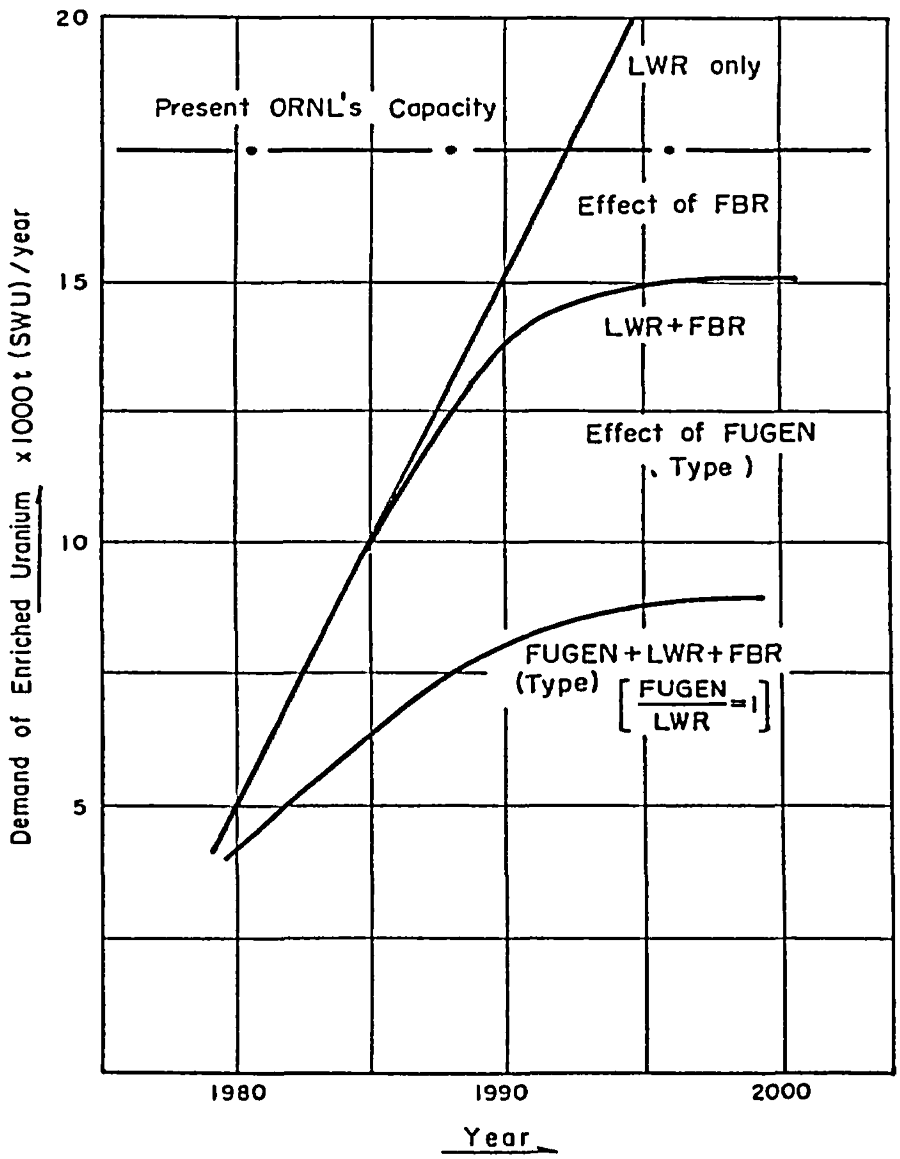


Fig-3 Demand of Enriched Uranium

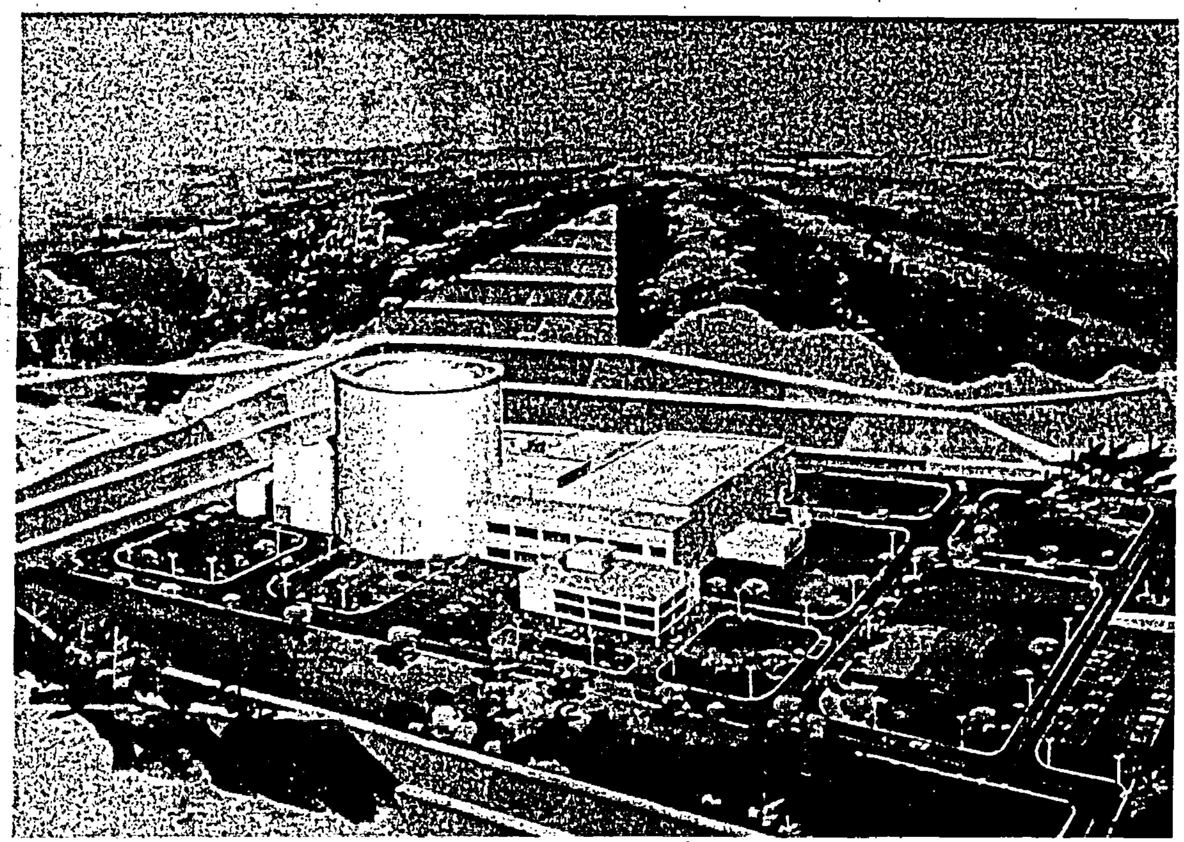


Fig-4 FUGEN Layout

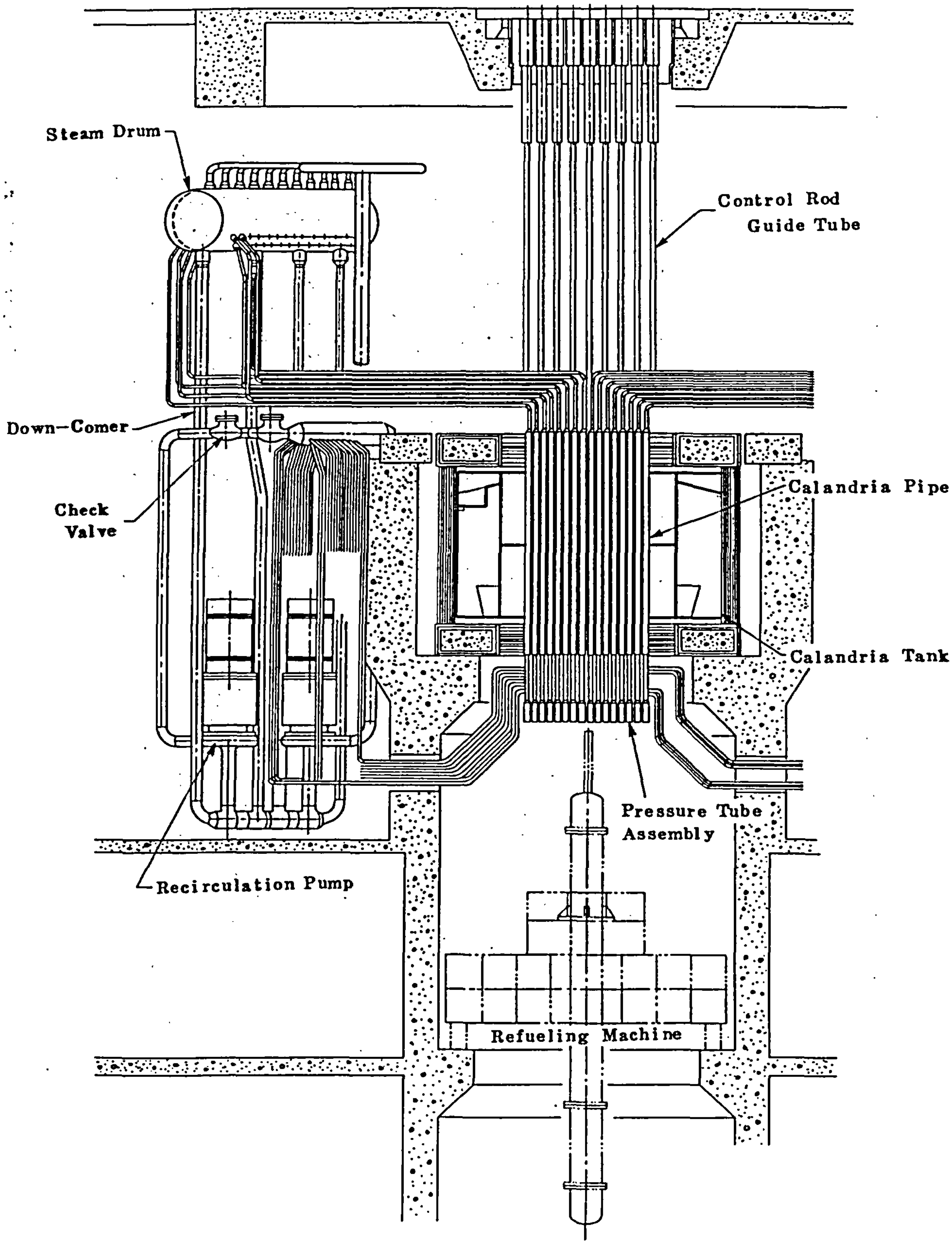
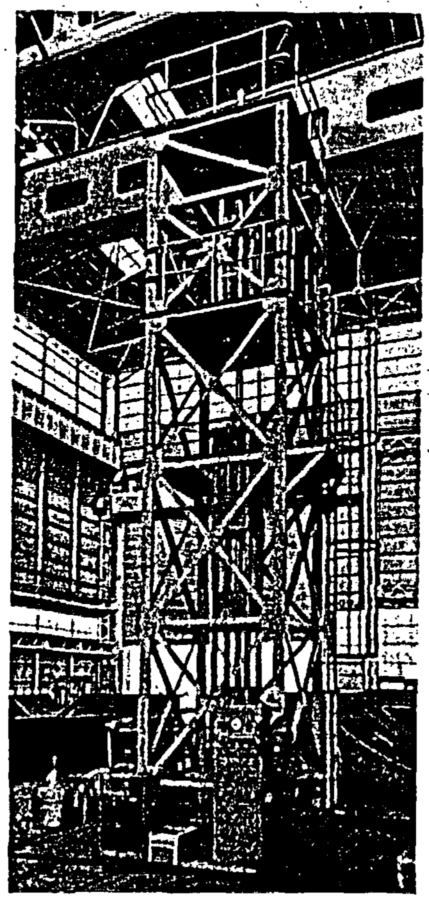
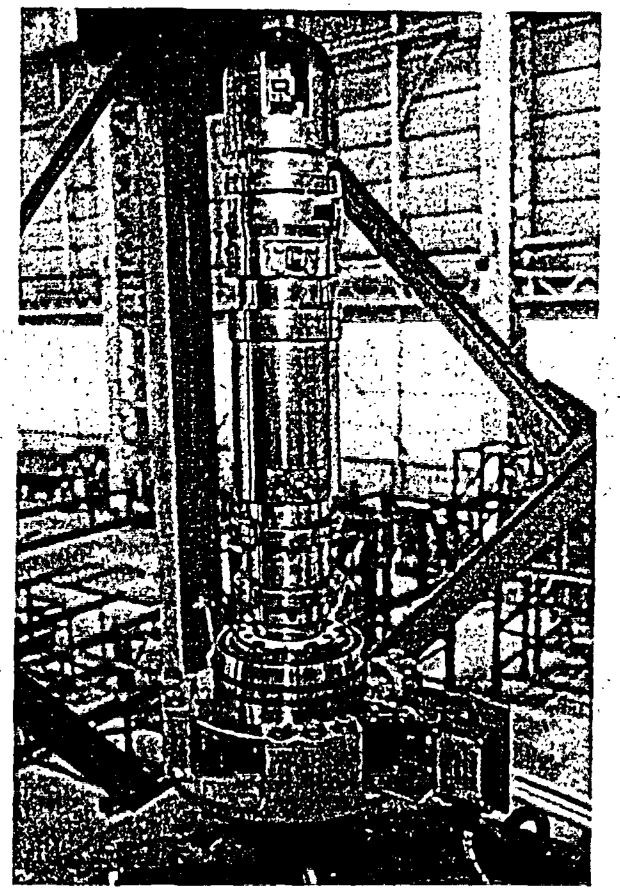


Fig-5 General Reactor Arrangement



(A) General View of Experiment



(B) Detector Head for Pressure Tube Monitoring

Fig-6 Development of Pressure Tube Monitoring Equipment

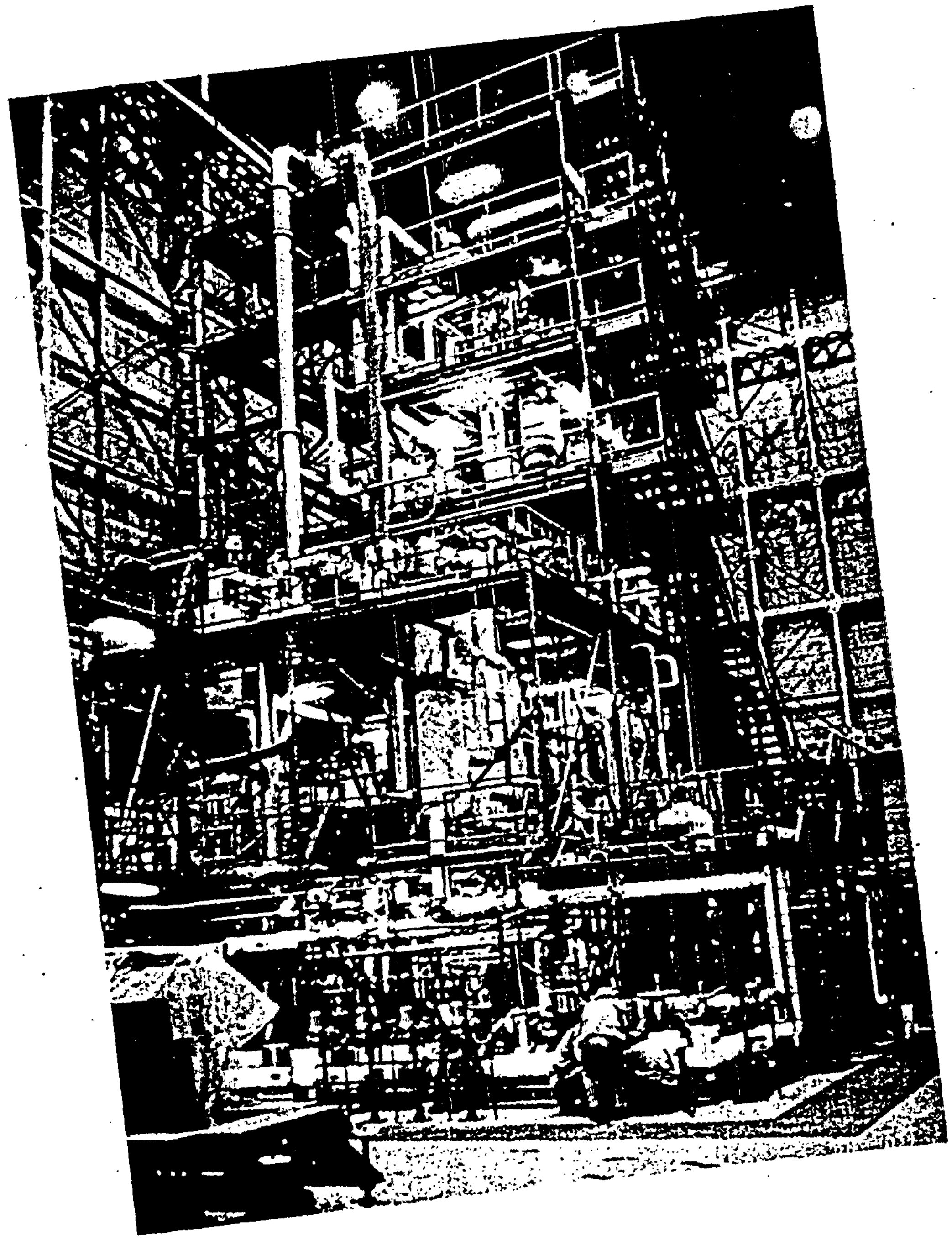


Fig-7 Heat Transfer Rig(HTL)

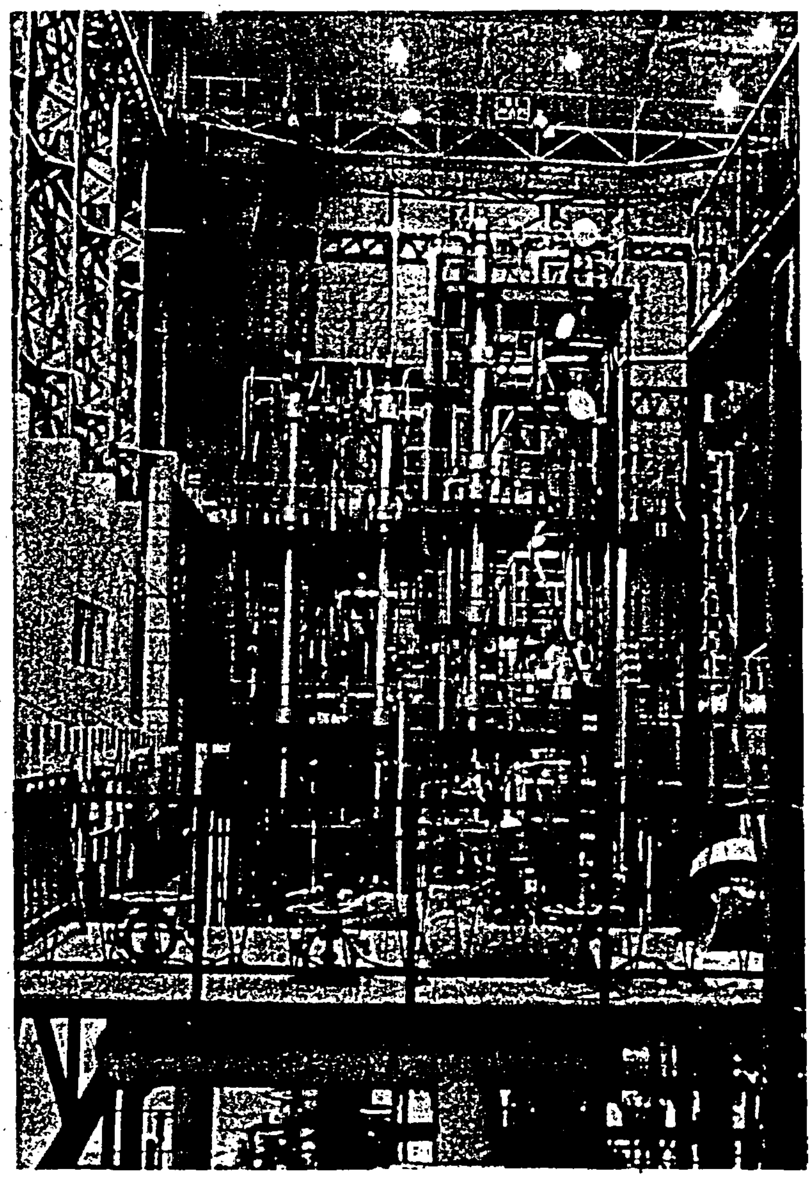


Fig-8 Component Test Loop(CTL)

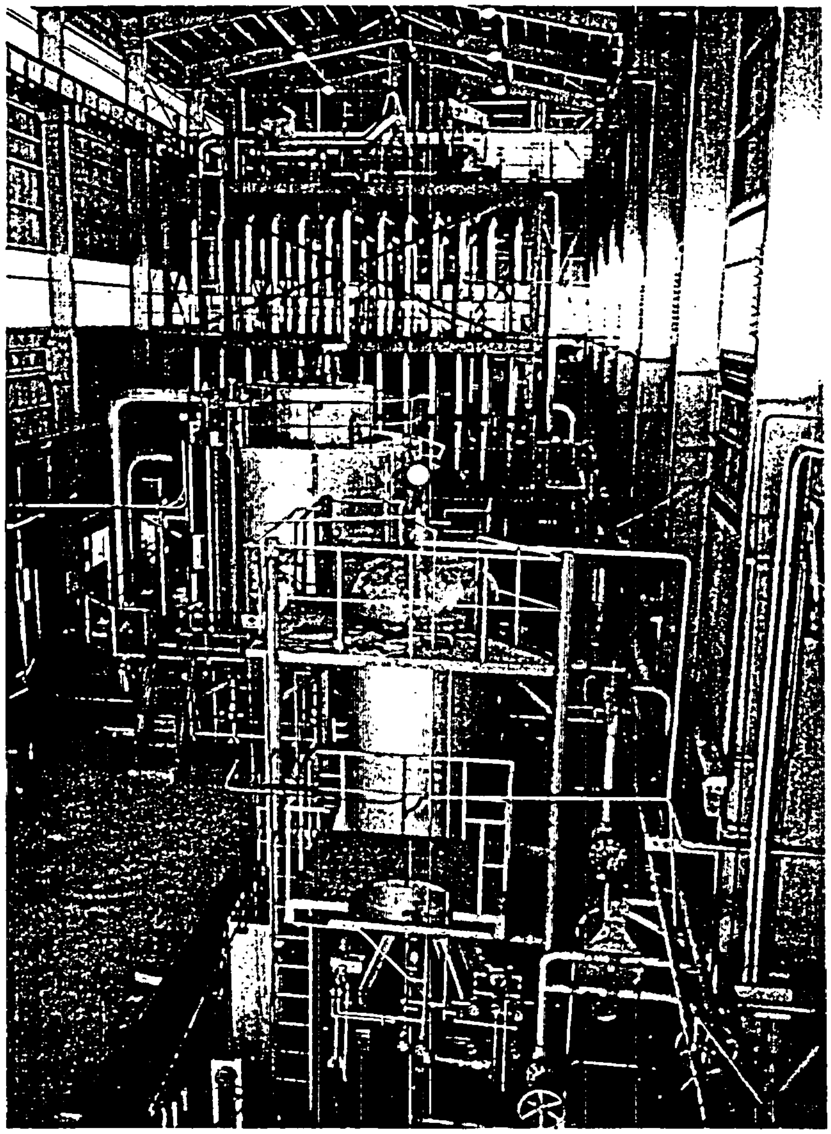


Fig-9 Full Scale Safety
Experimental Facility

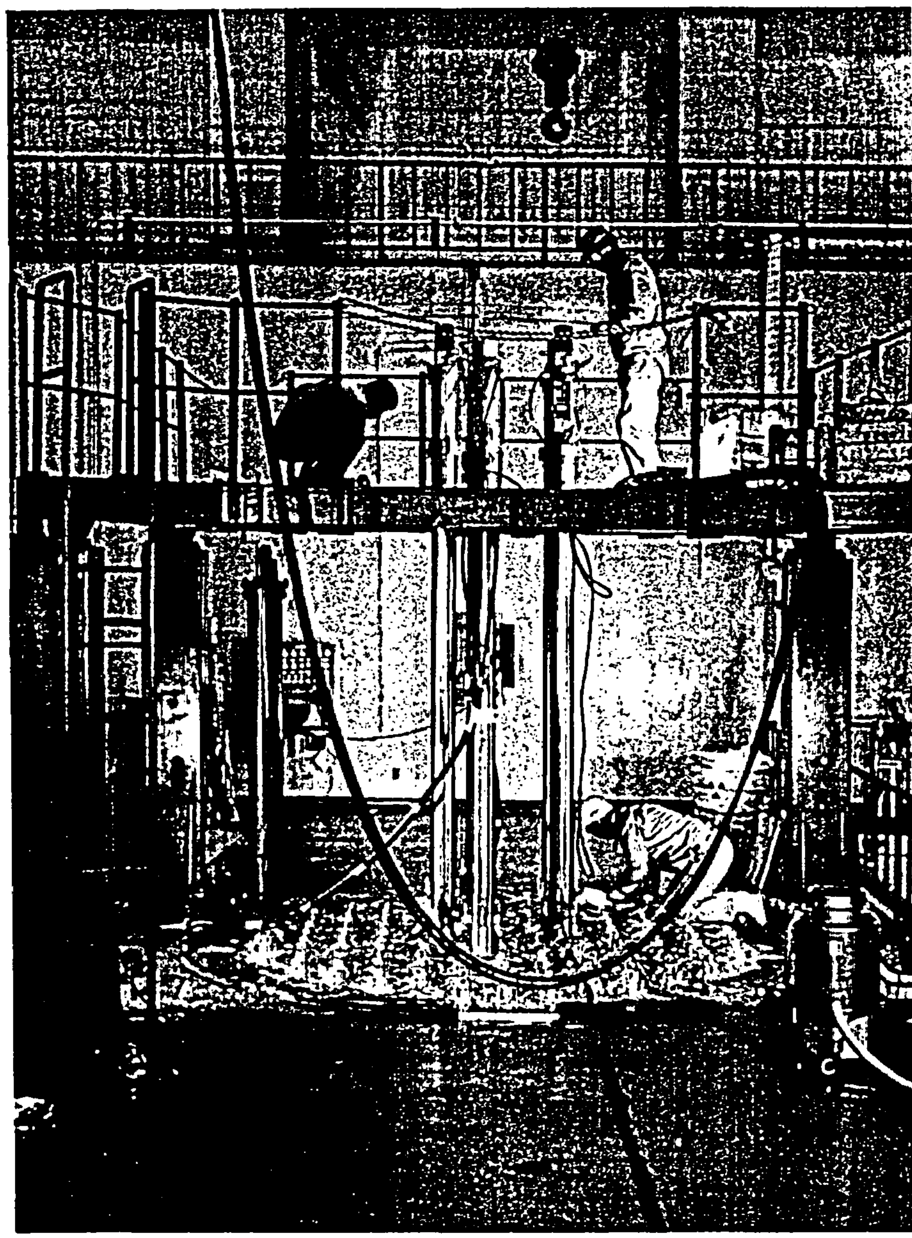


Fig-10 Critical Assembly(DCA)

T a b l e - 1

Effect of Uranium Cost on Power Cost

I t e m s	Cost or Price Changed	FUGEN Type Reactor		Light Water Reactor	Basic Cost or Price
		Pu SS	1.5% U^{235}		
Uranium Price	1 $/$U_3O_8$lb	0.01 ¥/kwh	0.018 ¥/kwh	0.034 ¥/kwh	8 $/$U_3O_8$lb
Cost of Unit Separation Work	10 $/$SWU_{kg}$	0	0.033 ¥/kwh	0.073 ¥/kwh	26 $/$SWU_{kg}$
Fuel Fabrication Cost	10 $/kg U	0.04 ¥/kwh	0.032 ¥/kwh	0.025 ¥/kwh	100 $/kg U

Table - 2

Design Data of FUGEN

Output	
Reactor thermal output	557 MW
Gross electrical output	165 MW
Core	
Core height	3,700 mm
Core diameter	4,060 mm
Lattice pitch	240 mm
Number of fuel channels	224
Fuel inventory	36 t
Heavy water inventory	86 t
Fuel	
Fuel material	UO_2 and PuO_2-UO_2
Pellet diameter	14.5 mm
Cladding material	Zircaloy-2
Cladding thickness	0.84 mm
Number of elements in cluster	28
Nominal element spacing	2.1 mm
Total length of fuel assembly	4.4 m
Pressure tube	
Material	Zr-2.5 % Nb
Inside diameter	117.8 mm
Thickness	4.3 mm
Calandria tube	
Material	Zircaloy-2
Inside diameter	150 mm
Thickness	1.5 mm
Primary cooling system	
Coolant pressure at steam drum	68 kg/cm^2
Coolant temperature at steam drum	284 °C
Coolant flow rate	7600 t/h
Steam exit quality (mean)	14 %
Number of cooling loops	2
Number of recirculating pumps	2
Turbine system	
Steam pressure at TSV	63.5 kg/cm^2
Steam temperature at TSV	279 °C
Steam flow rate to turbine	910 t/h
Condenser vacuum	722 mmHg
Feed water temperature	182 °C