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# Prospects for FBR Commercial Plants



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The Japan Atomic Power Company

&

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**ABSTRACT**

FBR development activities in Japan have been performed by the government in cooperation with private enterprises. The prototype reactor "MONJU" is now undergoing functional testing, and the first demonstration plant is in the conceptual design stage. R&D for commercial plants has been conducted for several years.

Commercial plants are required to be superior to LWRs with regard to economy, safety, and reliability. Accordingly, the Power Reactor & Nuclear Fuel Development Corporation and the Japan Atomic Power Company set up specific R&D goals for commercialization, identified plant concepts, and planned the necessary R&D activities.

In order to make the concepts a reality, both government and private enterprises must play a roll in developing and demonstrating FBR technologies through construction and operation of prototype and demonstration plants. In addition, they must perform FBR optimization activities, such as an enhanced safety core and a passive decay heat removal system etc., according to long-range plan.*

* This work is a joint study between the Japan Atomic Power Company & Power Reactor and Nuclear Fuel Development Corporation.

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## Attached Figures and Tables

## 1. Introduction

FBR development activities in Japan have been performed by the government in cooperation with private enterprises as an important part of the national policy toward atomic power. FBR technology has advanced for 20 years or more since it began with basic and fundamental studies. It has now reached the stage where it is very likely to be commercialized, and the prototype reactor "MONJU" has begun trial operation.

For the complete realization of FBRs as commercial power plants, it is necessary to further improve not only the economics but also the safety and reliability of such reactors so that they will be socially accepted by the time of expected commercialization in the early 21st century (around the 2020's through 2030's). This requires a steady continuation of the technical development and demonstration activities with post-"MONJU" experimental reactors to be built for trial operation leading toward technical and experience-based commercialization of reactors.

In commercializing FBRs, reactor development should also include innovative fuel cycle technologies (such as those for fabrication and reprocessing of fuels) in an attempt to improve the economics and safety of an FBR system as a whole including its fuel cycle.

In the early 21st century when commercial operation is likely to be realized with an FBR plant which is more advantageous and attractive than a contemporary LWR;

[1] The goals were set up to improve the reactor economics, safety, reliability, operability, and maintainability/ repairability,

[2] The commercial plant concept was envisaged comprehensively to clarify future prospects, and

[3] The aims of technical development were conceptually summarized so as to achieve their concrete realization.

## 2. Goals Set Up toward the Commercialization of FBRs

Toward the future successful commercialization of those FBRs which are more advantageous and attractive than contemporary LWRs, the goals were set up in terms of economics, safety, and other considerations via the analysis of the advantages possessed by such reactors, the problems to be solved for their performance to approach those of LWRs's, and the future trends in LWRs. The primary R&D goals are as follows: (See Fig.1-1 through Fig.1-5)

(1) Economics

1) With the advantageous characteristics of sodium cooling in mind,

- Simplification through materials minimization, as well as
- Integration of the nuclear reactor equipment/ structure, and
- Simplification of cooling and fuel-handling systemsare targeted to obviate the major causes of higher construction costs relative to LWRs.

2) With the FBR performance advantages in mind,

- Higher fuel burnup, and
- Higher plant temperature and thermal efficiency are targeted to reduce fuel expenses and power generation costs.

For an attempted reduction of fuel cycle costs, it is important to combine a target of higher fuel burnup with an effort to technically improve the methods of fabricating and reprocessing fuel.

(2) Safety

On the assumption that a multitude of commercial FBRs may come into operation,

- Higher core safety (improvement of core properties), and
- Highly reliable safety equipment (utilization of passive equipment/ systems and others) are targeted to improve the safety so that it can be more easily accepted by society in general.

(3) Reliability, operability, and maintainability/ repairability

Improvements in reliability, operability, and maintainability/ repairability are attempted through the adoption of technically innovative developments including those of LWRs while allowing one to reflect on the experience with plant design, construction, and operation involving prototype, demonstration, and other reactors.

From the viewpoint of taking advantage of proper characteristics possessed by FBRs as well as setting up the goals toward their commercialization, it is necessary to target, for desired technical development, an upgraded system to use plutonium throughout the fuel cycle as a whole including utilization of new types of fuel and TRU recycling.

## 3. Conceptual design of an FBR commercial plant

The commercialization of FBRs will probably not be realized unless innovative technologies are developed with a proper perspective of the future especially with regard to plant design and experience accumulated by the construction, operation, maintenance, and repairs of precursor plants.

To identify how economically viable FBRs will become and where technical development activities should be directed in the foreseeable future, a concept of an FBR commercial plant was envisaged on the basis of the above-mentioned R&D goals toward the commercialization of FBRs in terms of economy, safety, and other considerations. (See Fig.2-1 through Fig.2-5)

The FBR commercial plant was envisaged, taking into account the following:

1) As for the level of output, a large reactor was used because it, like in LWRs, is considered as economically advantageous on the assumption that a multitude of FBRs may come to be built when their operation is competitive with large LWRs.
   The economy is affected not only by the scale effect based on the level of output but also by other effects including those of maturity and modularity as well as the level of standardization which depends on the number of reactors built.
2) The fuel type to be used is envisaged as mixed-oxide fuel, which is technically much more mature with incomparably more experience and performance data so far accumulated. As for nitride, metallic, and other new types of fuel, their demonstration work is left as a future assignment and it seems that the decision on whether or not they may be adopted depends upon the results of technical developments to be conducted in the future. If accepted as adaptable, such fuels may then

be introduced into commercial plants so that the fuel cycle should continue to be improved.

3) As for the core safety envisaged, the aims are based on the assumption that commercial FBRs will come to be built and run in a greatly increasing numbers. Based on these improvements the FBR can be more easily accepted by society in general although there may be some adverse impact in terms of reactor economy (such as a larger core diameter due to improved core properties).

4) From the viewpoint of economy and safety, innovative technologies, as highly hopeful contributors to the overall improvement of the system, are incorporated into the envisaged plant design, with proper qualifications on the feasibility and the period required for their commercialization.

   Specifically toward improved reactor economy, aims are placed on the reduction in physical weight of reactors and cooling systems to about 70% of LWRs.

In envisaging the plant design as above,

- Integration of equipment such as the adoption of large-capacity submerged-type electromagnetic pumps,
- Simplification and standardization of equipment/structure through the adoption of seismic isolation technology, and
- Deletion of secondary sodium systems (intermediate heat transfer systems),

are considered as important points for improved economy.

The economy of the plant envisaged is roughly evaluated to produce the following results: (See Fig. 3)

1) It has been considered that plant construction for an FBR economically viable enough to be competitive with LWRs requires the former's costs

to be equivalent to 110% or less of the latter's. An FBR plant has larger scale merits with increasing output. This, combined with the prospective reduction of about 20% in construction costs after multiple reactors are introduced (NOAK costs) from those for an initial unit (FOAK costs) such as due to the effects of maturity, and estimates of the costs for the current No.1 demonstration reactor, lead to costs at somewhere around 110% of those for LWRs due to an expected increase in output to 1300 MWe and the maturity effect of commercial introduction.

2) When the higher goals set up toward the commercialization of FBRs were reviewed for possible achievement at an earlier initial-unit stage, of economies viable with that of LWRs, the following results were obtained:

[1] The costs of plants with secondary sodium systems are currently estimated to be almost the same, independent of the method of equipment integration, despite a conceivable gap between envisaged plant designs due to the differing states of equipment design technologies in progress. The results are about 70% of an LWR in terms of physical weight of the reactors and cooling systems and 97-104% in construction costs, which are estimated to be lowered to 80% after multitudes of reactors are introduced. For the FBR commercial plant designs envisaged new technologies were adopted including improved core properties, equipment integration using large-capacity submerged-type electromagnetic pumps, seismic isolation technology, and simplified upper core parts in addition to those technologies incorporated into the design of an No.1 demonstration unit so far developed. At home and abroad, efforts have already been initiated toward the realization

of these innovative technologies for likely implementation of their development in the foreseeable future.

Further consideration is possible of the reduction in construction costs such as by taking advantage of FBR scale merits due to an increase in output to 1500 MW or adopting the twin-plant system with common spent fuel handling equipment, which plays a major part of an FBR.

[2] For a plant without a secondary sodium system, the physical weight of reactors and cooling systems were assumed to be about 60% of that of an LWR plant and construction costs, 90% or so. Construction costs are likely to be around 70% after multiple units have been introduced.

It is, therefore, considered, at least, for the time being that the goals toward the commercialization of FBRs may possibly be achieved with only the limited development in the foreseeable future of innovation technologies (such as equipment integration through the utilization of large-capacity submerged-type electromagnetic pumps), even if three-dimensional seismic isolation, secondary sodium system deletion technologies and the like are not incorporated.

## 4. Technical development of FBRs

Successful development of necessary technologies toward the commercialization of FBRs as intended within a reasonable time limit requires that systematic long-term R&D activities and the demonstration of plant operations be continued.

The specific goals for important technical developments are mentioned below.

### 4.1 Cores

Toward the achievement of safety characteristics more easily accepted by the society in general, it is necessary to exercise combined efforts toward the diversification and improved reliability of core-protective reactor shutdown systems and at the same time, to implement more drastic measures to improve core properties.

- Development of a core design, taking advantage of passive factors, leading to more negative reactivities even when including swelling and bending.
- Creative development and embodiment of a new core concept of coordination for metastable state maintenance in an anomaly.
- Upgrading of analytical technology to evaluate core behavior in an anomaly.
- Diversification of reactor shutdown systems to improve their functional reliability.

### 4.2 Removal of decay heat

Reliable removal of decay heat as well as reliable core properties and reactor shutdown systems greatly contributes to improved safety of a reactor. An FBR has a number of merits for successful development of a highly reliable decay heat removal system including a possible low-pressure design favored by the high boiling point of sodium as a coolant, high-temperature operation for capable functioning of the final heat sink that discharges heat into the atmosphere, and easy utilization of natural and physical phenomena such as density difference-induced circulation.

The aims of technical development include efficient application of these merits to the improvement of reliability through system simplification and diversification.

- Development of analytical methods for the evaluation of natural/physical phenomena such as spontaneous circulation.
- Development of system/plant design technologies making use of natural and physical phenomena.
- Development of passive/static equipment and control methods.

### 4.3 Consolidation/integration as well as simplification of equipment

The economy will hopefully be improved to a higher extent if consolidation/integration as well as simplification is implemented on reactor and cooling system equipment as its installation produces a large share of plant construction costs.

#### 4.3.1 Development of electromagnetic pumps and consolidation/integration of cooling equipment

An electromagnetic pump has a number of merits for the consolidation/integration of circulation pumps and heat exchangers including the high reliability achieved in the absence of movable parts such as rotary sections and the flexibility of an arrangement that can be easily built into cooling system equipment.

The aims of technical development include efficient application of these merits to the ongoing improvements in reliability and economics through implemented rational consolidation/integration of cooling equipment.

- Development of large-capacity immersed electromagnetic pumps.
- Demonstration of the reliability of large-capacity cooling system-integrated equipment.

### 4.3.2 Simplification of reactor upper structure/fuel replacement equipment

The economics of an FBR using sodium coolant is improved, if the reactor upper structure is simplified, because a reactor cannot be opened to the atmosphere during fuel replacement and has a complex structure with rotary plugs. The requirement for the reactor upper structure to be very rigid to maintain the proper positioning of the control rod driving mechanism magnifies the effect of its drastic simplification in combination with seismic isolation technology.

Conceivable methods of simplifying the reactor upper structure include a variety of concepts to vertically evacuate the core upper structure for fuel replacement instead of using rotary plugs. Among these concepts, the most economically advantageous collapsible up-down reactor upper structure is targeted.

- Development of collapsible up-down reactor upper structures.

## 4.4 Fuel

The aim of fuel development is placed on the upgrading of fuels toward reduced power generation costs, increased safety allowances, or enhanced core compactness.

- Development of cladding materials with excellent creep strength and swelling resistance
- Development of annular pellets.

## 4.5 Secondary sodium (intermediate heat transfer) system elimination

Aside from an effective means of equipment integration and simplification as mentioned in the preceding paragraph, a conceivably more drastic measure to improve the economy of FBRs is the elimination of the secondary sodium (intermediate heat transfer) system unique to an FBR.

Toward the implemented elimination of secondary sodium systems, it is necessary to develop the technology to detect leaks, a system to control accidents, and a process to evaluate the safety so that assumed leaks may be coped with as well as to prevent accidents due to sodium-water reactions using a highly reliable double-wall tube steam generator and burst detecting system. One must also improve the theory and data so as to avoid an assumed simultaneous inner and outer double-wall tube burst mode.

- Development of highly reliable double-wall tube steam generators and demonstration of their reliability.
- Development of a quickly responding and highly reliable burst detecting systems.
- Development of the technology to control accidents due to sodium-water reactions as well as an evaluation process.

4.6 Seismic isolation

The seismic isolation design, if adopted, greatly contributes to improved economy due to its superiority over the seismic isolation design in the reduction in weight/ simplification of reactor structures and cooling system equipment and standardization of plant designs. At present, a horizontal seismic isolation technology is likely to be realized in the foreseeable future but, toward the time of the commercialization of FBRs, it is hoped to develop a three-dimensional seismic isolation technology.

The aims of technical development include combined efforts to develop seismic isolation factoring and other equipment and equalize seismic isolation criteria.

- Establishment of horizontal seismic isolation technology and development of three-dimensional seismic isolation technology.
- Establishment of seismic isolation design criteria.

4.7 Technologies to inspect and repair structures/ equipment in the sodium environment

An FBR has a problem of more difficult inspection and repair of structures/equipment under the sodium environment than an LWR as the former involves hot, opaque, and active sodium during the inspection or repair of reactor system structures/equipment.

From the viewpoints of improved reliability and plant operation rates, it is necessary to exercise further efforts toward upgraded inspection and repair technologies.

4.8 Upgrading and diversification

4.8.1 New types of fuels

In the future, new types of fuels, such as nitride and metallic fuels, are likely to surpass oxide fuels in terms of economy, safety, and the like. It is, therefore, necessary to promote the accumulation of information about their feasibility and actual performance during irradiation. As for nitride fuels, the commercialization in the foreseeable future seems more likely as the existing technologies to fabricate and reprocess mixed-oxide fuels are extensively applicable to the nitride counterparts.

4.8.2 Medium-size/small reactors

Passive core safety characteristics and decay heat removal reliability may be easily secured if an appropriately low level of core output is employed.

In parallel with the technical development toward the commercialization of large power reactors, the trend of medium-size/small reactor development should be identified and reviewed to establish the basis on which a diversity of needs may be fully responded to in the future.

- Review of medium-size/small reactor core properties.
- Review of medium-size/small reactor plant safety.
- Review of medium-size/small reactor plant concepts.

### 4.8.3 Fuel cycle

In the technical development related to FBR fuel cycles, an attempt is made to upgrade and commercialize the technologies to fabricate, process, and reprocess technically much more mature mixed-oxide fuels. From a viewpoint of the upgraded and well-balanced fuel cycle system as a whole, efforts are also concentrated on promoting TRU burnup and general recycling technology. It is, therefore, necessary to coordinate core and fuel development activities with the trends of technical developments related to these fuel cycles.

## 5. Conclusion

It has been proven that FBRs are likely and destined to become major power generation facilities competitive with LWRs toward the early 21st century by which time the commercialization of FBRs will become a reality.

Toward the commercialization of FBRs, it is necessary not only to promote the development and prevalence of FBR technologies through the construction/operation of prototype and demonstration reactors but also to exercise systematic long-term efforts for technical developments including:

- Improved core properties,
- Highly reliable safety equipment including decay heat removal systems,
- Equipment integration by means of large-capacity immersed electromagnetic pumps, etc.,
- High-performance fuels,
- Secondary sodium system elimination, and
- Seismic isolation.

The above importantly requires future well-maintained efforts of the government and private enterprises to cooperate through coordinated performance of the roles of each body under a unified comprehensive program to promote the nationwide development, and it is vital to continue such efforts.

# Fig.1-1 Targets For Commercial FBR (For Economy)

## ① Advantages Over LWR

- Higher Fuel burn-up is easier to achieve
- Plant efficiency is higher and plant capacities smaller
- The low-pressure system does not cause an increase in mass quantities even when capacity is increased

## ② Disadvantages Compared to LWR

- More stainless steel is used in both the primary & secondary system & structure is more complicated
- Equipment, such as the fuel handling system, is more complicated
- Requires a safety system to prevent sodium leakage
- Requires special electric instrumentation, such as sodium anti-freeze system and core instrumentation
- Measures to improve economic performance of fuel reprocessing must be taken

## ③ Future Course for ALWR & Next-Generation LWR

- To generate 1300MWe without increasing mass quantity(ALWR)
- To reduce costs of mid-size reactor by simplifying the system and reducing active components(Next-generation LWR)

## Stance for Target Setting

### ① Efficient Application of FBR Advantages

- Reduction of fuel cost by increasing burn-up
- Reduction of costs per KWe by making reactor capacity large
- Improvement of plant efficiency

### ② Resolution of Additional FBR Problems

- Reduction of fabrication cost of reactor structure & the cooling system
- Reduction of component quantity of other systems
- Reduction of engineering cost by standardization of the plant
- Reduction of fuel cost (including fuel reprocessing cost)

### ③ Mapping Out the Future Course for Next-generation LWR

- Simplification of the equipment
- Reduction of active components

## Individual Targets for the Commercial FBR

- Simplification of the reactor structures( ②,③)
- Reduction of operation cost(①,②) (Reduction of fuel cost including reprocessing cost)
- Elimination & integration of cooling systems( ②)
- Reduction of component quality of other item(②)
- Reduction of engineering cost by standardization of the plant(②)

# *Fig. 1-2 Targets for Commercial FBRs (for safety)*

### (1) Advantages over LWR

- Passive safety can be secured down to the final heat sink at the time of decay heat removal (spontaneous circulation/natural draft).
- The low-pressure system is free from blowdown even if the primary system bursts so that an appropriate level of liquid surface can be secured by static equipment (guard vessel).
- Nuclear safety is high in normal operation.
- The thermal margin is high up to the boiling process and an anomaly can be moderately responded to.

### (2) Disadvantages Compared to LWR

- The sodium density coefficient and void reactivity may become positive and positive reactivity may be inserted under accident conditions.
- Care must be taken as the core may return to criticality after melting.
- It is necessary to prevent a fire due to sodium leaks.
- Sodium-water reaction takes place due to a burst steam generator heat transmission tube.

### (3) Future Course for ALWR & Next-Generation LWR

- Pursued enhancement of safety equipment passivity.
- Attempted improvement of thermal margin by the low output density core technology.
- Review of walk-away characteristics under accident conditions.

### Stance for Target Setting

(1) Efficient application of FBR advantages
- Passive decay heat removal taking advantage of spontaneous circulation.
- Possible taking of static measures to secure an appropriate level of liquid surface.

(2) Resolution of Additional FBR Problems
- Reduction of the reactivity loaded under accident conditions.
- Minimization of the possibilities to return to criticality.
- Confinement of sodium fire influences.

(3) Mapping Out the Future Course for Next-Generation LWR
- Simplification of equipment/systems.
- Further improvement of safety equipment reliability.
- Further secured storage function.
- Expansion of thermal margin, if necessary.

### Targets for Commercial Reactor Safety

- **Appropriate measures against a possible positive reactivity loading phenomenon** (2) (including prevented development of void (boiling), diversified reactor shutdown mechanisms, CDA cessation in the reactor and passive core safety).
- **Decay heat removal using an appropriate combination of passive and active equipment** (1).
- Establishment of appropriate storage facilities (3).
- Control of a sodium-caused fire (2). Measured against sodium-water reaction (2).

Written in bold letters are major R&D targets.

# Fig. 1-3 Targets for Commercial FBRs (for Reliability)

### (1) Advantages over LWR

- Corrosion resistance of member materials can be easily secured under the sodium environment.
- Sodium can be directly driven using an induced magnetic field.

### (2) Disadvantages Compared to LWR

- Liable to thermal loads.
- Complex dynamic equipment is required to secure sealing characteristics of sodium and cover gas.
- Less accessibility to the reactor internals.

### (3) Future Course for ALWR & Next-Generation LWR

- Longer plant life is based on actual performance of operating reactors.
- The scope of static equipment is widened in an attempt to reduce the number of dynamic equipment units and relax the dependence upon auxiliary systems.

### Stance for Target Setting

(1) Efficient Application of FBR Advantages

- Longer plant life.
- Utilization of electromagnetic pumps

(2) Resolution of Additional FBR Problems

- Development of highly thermal load-resistant structures and materials.
- Simplification of dynamic equipment under the cover gas environment.
- Improvement of accessibility to the reactor internals.

(3) Mapping Out the Future Course for Next-Generation LWR

- Relaxation of dependence upon auxiliary and cover gas systems.

### Targets for Commercial Reactor Reliability

- **Simplification of dynamic equipment including reactor cooling systems (1).**
- Simplification of equipment/ facilities (2)(3).

Written in bold letters are major R&D targets.

# *Fig. 1-4 Targets for Commercial FBRs (for Operability)*

### (1) Advantages over LWR

- The scarcity of operational limits due to secured integrity of xenon oscillation and fuels or any other purposes makes easier the operation conforming to loads.
- Fuel replacement intervals and operation cycles can be extended on the strength of a large core interval coefficient.
- No LOCA takes place and operability is favorable at the time of decay heat removal.
- Unchangeable phases make simpler thermo- and hydro-dynamic behavior in the core and cooling system.

### (2) Disadvantages Compared to LWR

- Burst fuels have not yet been demonstrated for their justifiable continual operation characteristics.
- Severe transient thermal stresses require the operation with temperature fluctuations in mind.

### (3) Future course for ALWR & Next-Generation LWR

- Suspension of operator work for 3 days subsequent to any accident is planned.
- Operation for 24 months is intended.

### Stance for Target Setting

(1) Efficient application of FBR advantages

- Pursuit of easy load conformance.
- Extension of fuel replacement intervals.
- Resort to the flexibility of core operation (variable breeding rates, long-life cores, and TRU cores).

(2) Resolution of Additional FBR Problems

- More highly secured burst fuel continual operation characteristics.
- Appropriate limitation on temperature and upgrading of operation.

(3) Mapping Out the Future Course for Next-Generation LWR

- Further reduction of operator workload.

### Targets for Commercial Reactor Operability

- Extension of fuel replacement intervals (1).
- Resort to the flexibility of core operation (1).
- Improved capability to handle burst fuels (2).
- Upgraded method of operation to relax transient thermal stresses (2).

# *Fig. 1-5 Targets for Commercial FBRs (for Maintainability Repairability)*

### (1) Advantages over LWR

- Easy narrowing of the inspectorate facilitates exposure dose reduction during checkup and regular examination.
- Scarce liquid radioactive wastes make wastes control easier.

### (2) Disadvantages Compared to LWR

- Difficult repair of reactor internal structures. (Repairability of sodium drains, places to which cores are evacuated, and reactor internal structures).
- Lack of experience with large sodium leaks fails to clarify accessibility and the workload to re-startup.
- Difficult visualization of equipment and other conditions under the sodium environment.

### (3) Future Course for ALWR & Next-Generation LWR

- Regular examination period contraction.
- Reduction of exposure dose during regular examination.
- Improved response to examination through boundary simplification and reduction.
- Stringent control of loose parts.
- Improved cooling system equipment maintainability.

### Stance for Target Setting

(1) Efficient Application of FBR Advantages

- Exposure dose reduction during regular examination.

(2) Resolution of Additional FBR Problems

- Improved repairability of reactor internal structures.
- Improved repairability of sodium leaks.
- Improved repairability of secondary system equipment.

(3) Mapping Out the Future Course for Next-Generation LWR

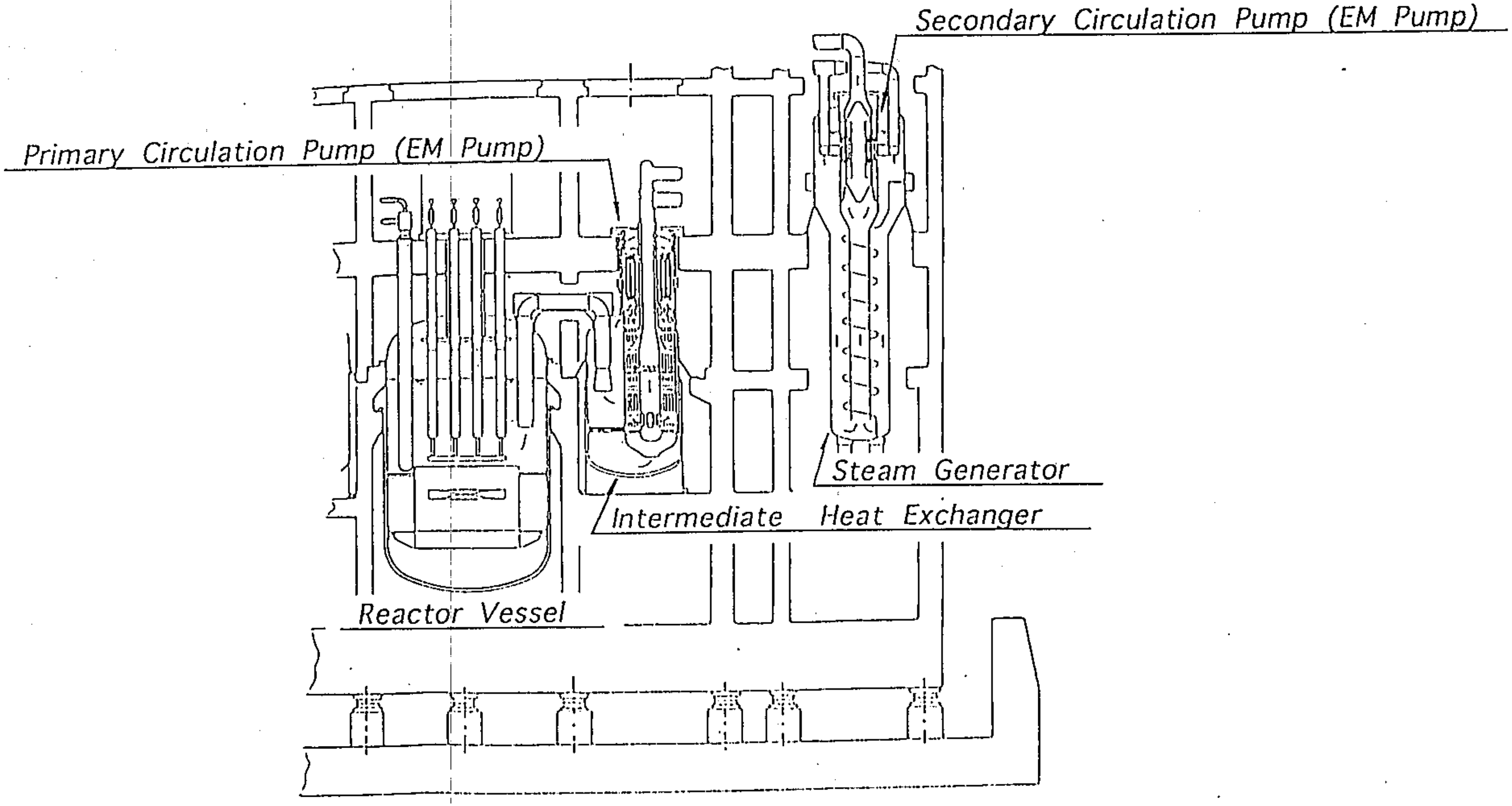
- Regular examination period contraction/ exposure dose reduction.
- Improved response to examination.
- Minimized sources for loose parts and improved recoverability.
- Elimination of frequently replaced parts.

### Targets for Commercial Reactor Maintainability/Repairability

- Regular examination period contraction (1).
- Secured accessibility to reactor internal (2).
- Improved response to examination and repairability (2)(3).

# Concept for a Commercial FBR Plant Reactor & Cooling System

## Fig.2-1 Concept 1



# Concept for a Commercial FBR Plant Reactor & Cooling System

Fig.2-2 Concept 2

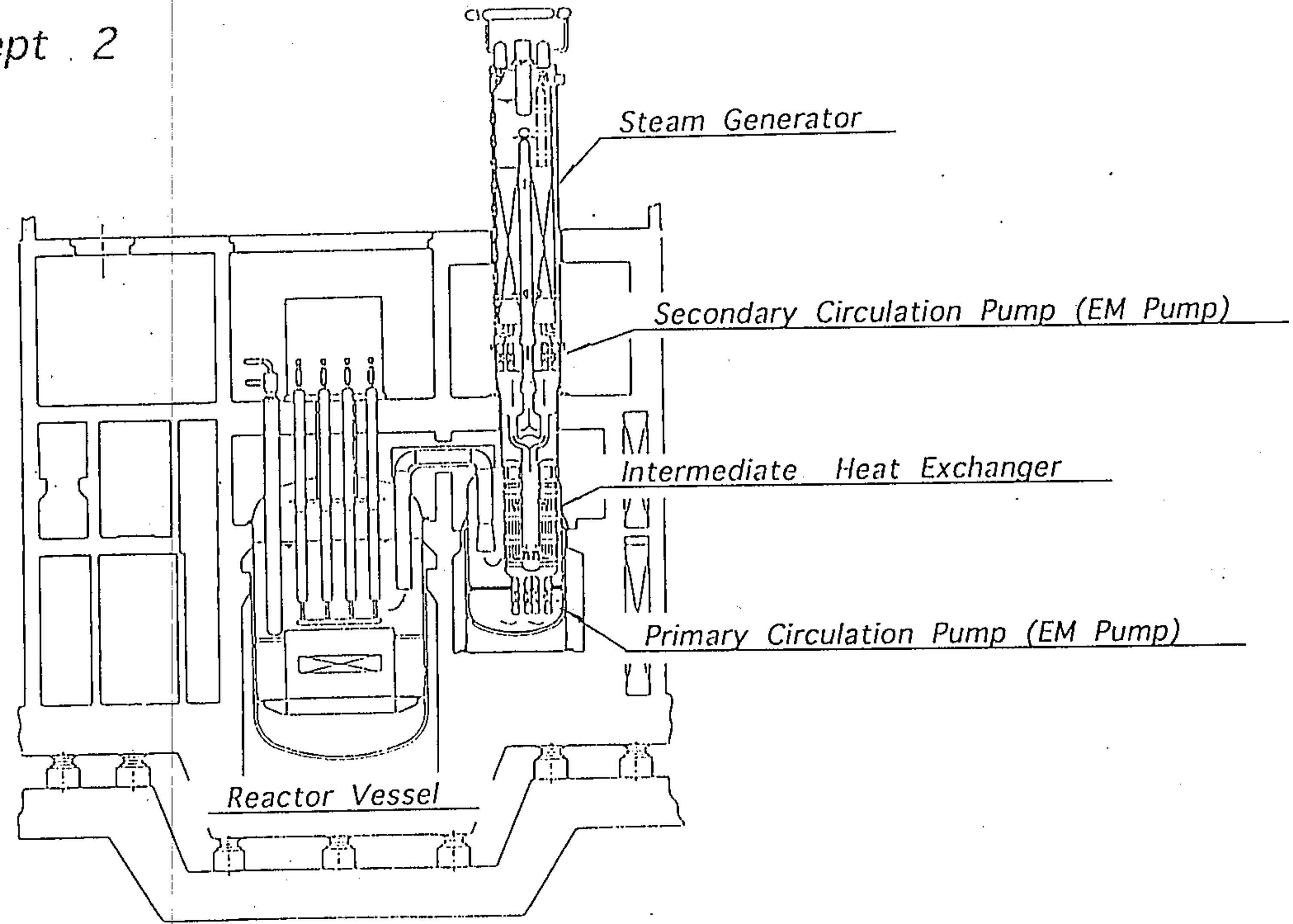
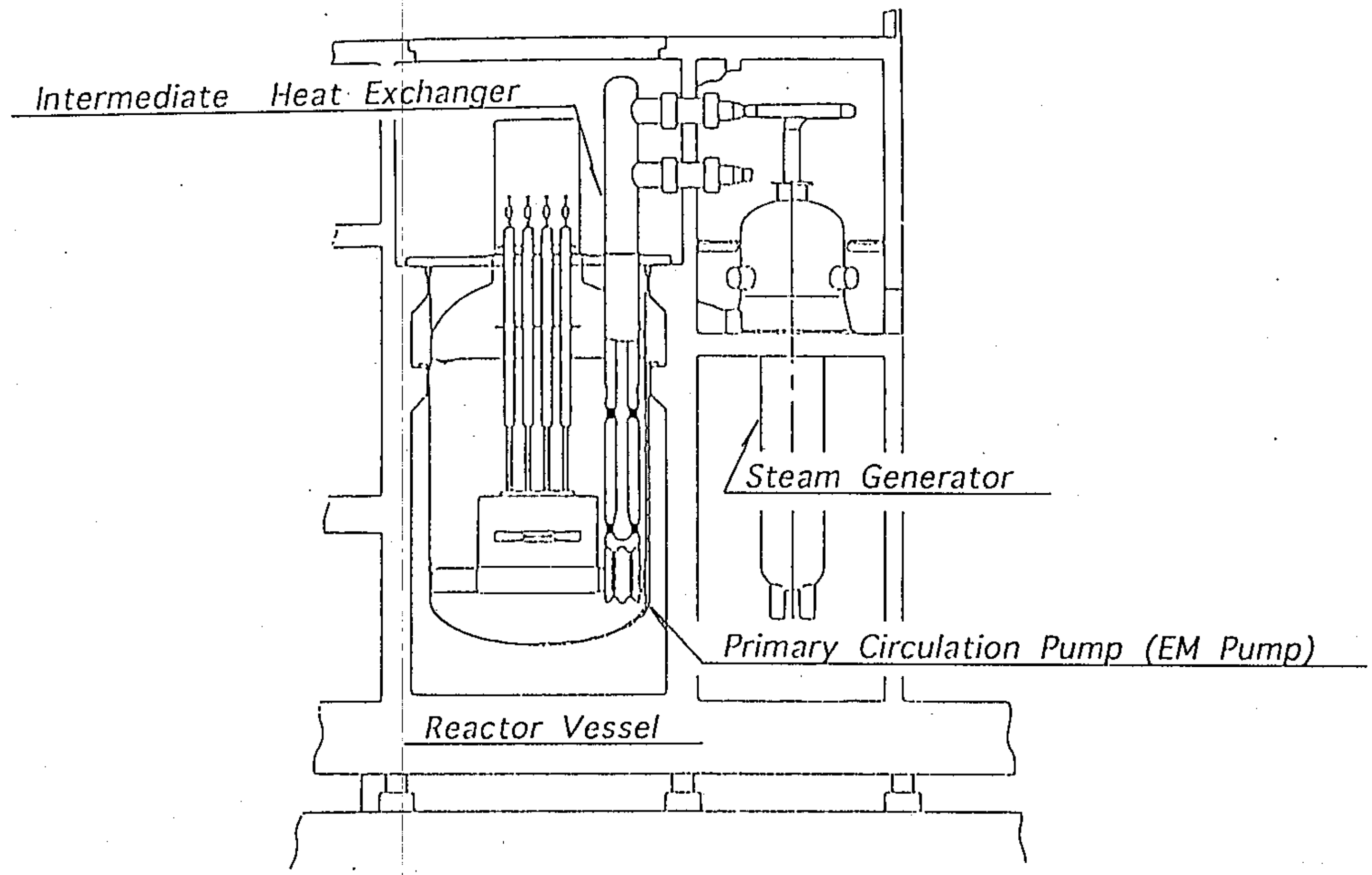


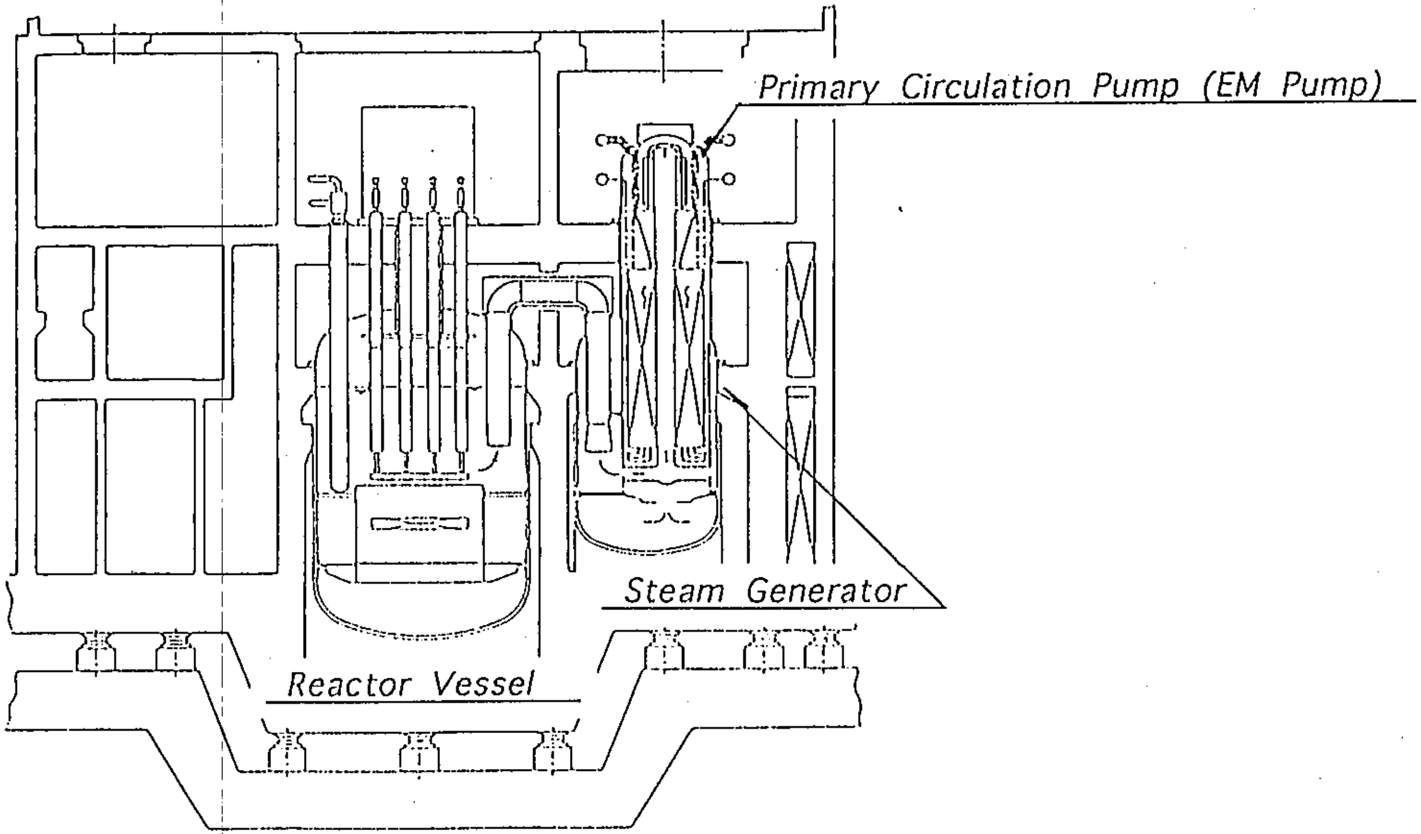
Fig.2-3 Concept 3



## Concept for a Commercial FBR Plant Reactor & Cooling System

### Plant with Secondary System Eliminated

Fig.2-4 Concept 4



## Plant with Secondary System Eliminated

Fig.2-5 Concept 5

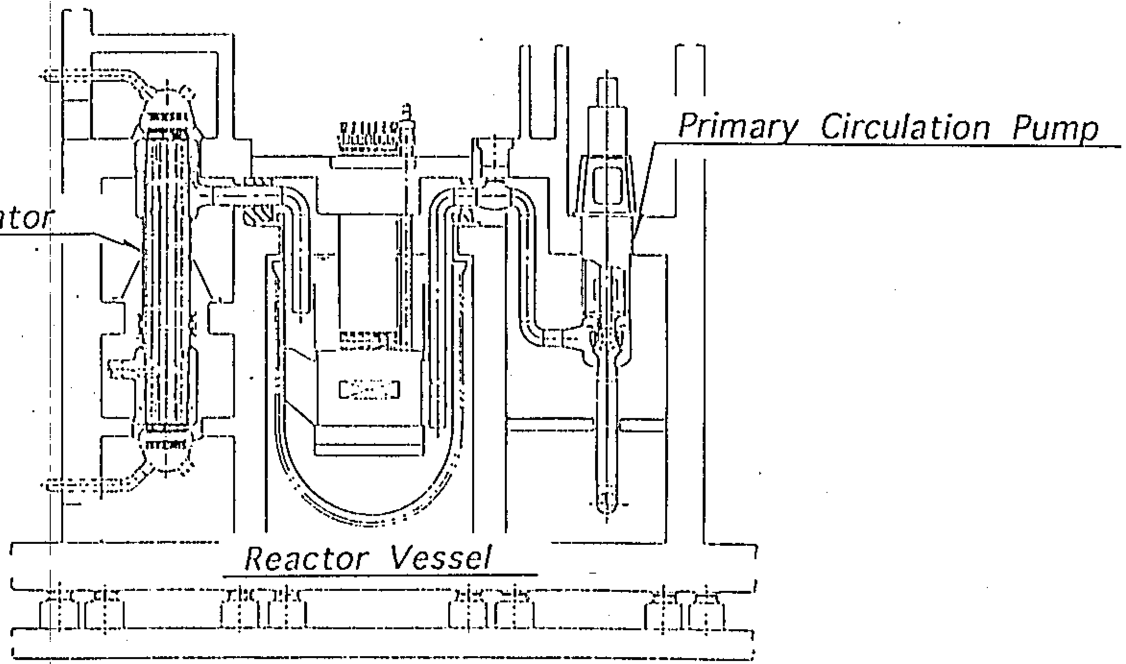
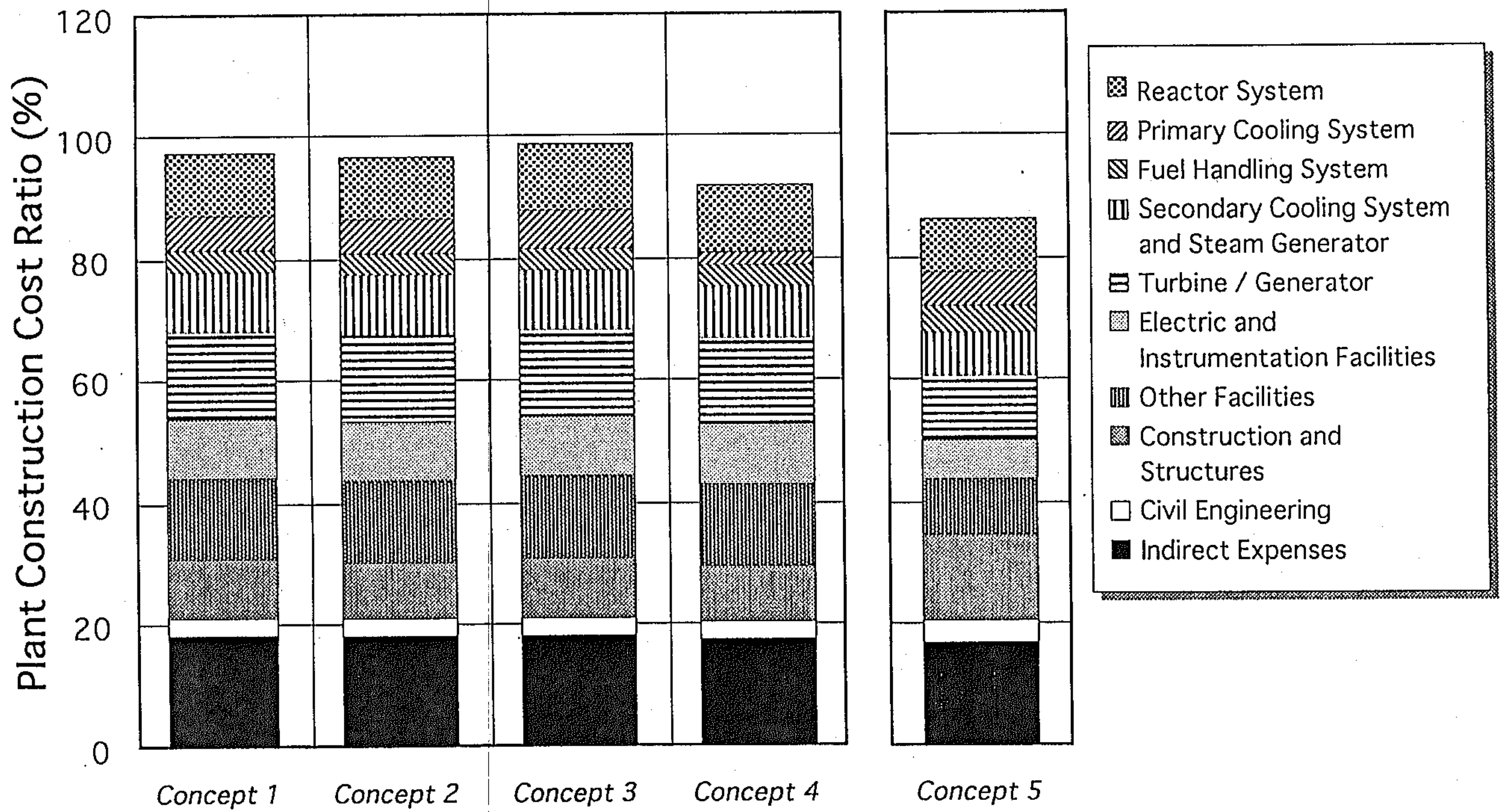


*Fig.3 Estimation of Commercial FBR Plant Construction Costs*



# Projected FBR Plant Construction Costs