MASTER

TANDEM MIRROR HYBRID REACTOR STUDY
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6.4 BALANCE OF PLANT DESIGN AND PRECONCEPTUAL COST ESTIMATE

6.4.1 Introduction

In any nuclear power plant, reactor design and performance are the major determining and driving factors of the plant economic and technical viability. However, the balance-of-plant (BOP) -- which includes heat transport and energy conversion systems, plant auxiliary systems, plant electrical system, and structures and facilities -- has a major effect on the plant economics. In fact, the BOP can account for as much as 70 to 85 percent of the total plant capital cost and therefore will have a significant impact upon the economic viability of the plant. Further, decisions made in the reactor design can have significant impact on the BOP design. A preconceptual BOP design and an order-of-magnitude cost estimate were developed for the helium cooled TMHR and are described in this section.

The main objective of the BOP design study was to develop a preliminary understanding of the requirements of plant design and a preconceptual plant design. Of particular importance are the requirements imposed by the high-temperature reactor coolant (helium) in the heat transport system, and the requirements imposed by the reactor and its auxiliaries on buildings and structures. These requirements have a significant impact on the economic viability of the plant. Thus, the main BOP systems and considerations addressed in this study include the heat transport

system, the energy conversion system, the heat rejection system, and the plant arrangement.

The EOP design developed for the helium cooled system was based on the reactor operating characteristics and design information provided by General Atomic (GA). Bechtel used this information to calculate plant performance and develop a preconceptual reactor mechanical arrangement and an integrated plant design.

There were two important considerations in developing the plant design. The first one was the choice between using a modular and a non-modular solenoid design. In the modular approach, the solenoid region is divided into many identical modules, each comprising first wall, blanket, shield, and magnet. The modules can be periodically removed and taken to a hot shop, where the fuel pins are removed and the modules refurbished. In the non-modular approach, the entire solenoid is essentially a single unit; fuel pin removal and reactor repair are done in place. The modular approach was chosen by GA and LLL primarily based on the ease of maintenance consideration.

The second consideration was the use of a prestressed concrete vessel for piping, circulators, and steam generators versus the use of a standard piping loop. The prestressed concrete reactor vessel (as used for gas-cooled fission reactors) eliminates the possibility of a double-ended piping failure, and it contains the radioactive reactor coolant (helium) circuit in a smaller, space-

efficient package. However, the standard piping layout was chosen because the TMHR linear configuration does not lend itself structurally to a prestressed concrete vessel configuration.

The TMHR design base parameters, developed by GA, are given in Table 6.1. The table shows that the blanket/first wall power varies annually from 3,660 MWt to 4,110 MWt. This is due to a variation in the blanket multiplication factor as a function of time. For a detailed discussion of this, refer to Section 6.2.

Table 6.1

TMHR DESIGN BASE PARAMETERS

Reactor Power	
Blanket/First Wall	3,660 to 4,110 MWt*
Direct Converters	
- Direct conversion	337 MWe
- Thermal exhaust	337 MWt
Solenoid length	51 m
Number of solenoid modules	16
Reactor coolant (helium) temperature	
Inlet to reactor	285°C
Outlet from reactor	585°C

*Annual variation in blanket/first wall power due to variation in the blanket multiplication factor

The solenoid length is shown as 56 meters in Table 6.1. However, at the end of the BOP design study, it was learned that the length was reduced from 56 meters to 39 meters as a result of revised analysis. But there was no time to incorporate this change into the BOP design and in this report. However, the cost estimate was revised to account for this change on the reactor building cost. Since the plant arrangement could not be altered at this late stage, other modifications in the plant cost due to the change in the solenoid length could not be made. These cost modifications are, however, expected to be minor, and would affect the cost estimate for piping, electrical, and other miscellaneous items.

This section (Section 6.4) is divided into nine subsections. The Subsections 6.4.2 through 6.4.7 describe the BCP design and plant arrangement, and the Subsections 6.4.8 and 6.4.9 describe the preconceptual cost estimate.

Before proceeding to these subsections, an overview of the main BCP systems is shown in Figure 6.1. This schematic diagram shows the power flow scheme from the reactor (blanket/first wall and direct converters), through the steam generators and the energy conversion system, and to the cooling towers. The peak thermal output from the reactor is 4,447 MWt--4,110 MWt from the blanket/first wall, and 337 MWt from the direct converters. The BOP is designed to handle the peak reactor thermal output.

Figure 6.1 SCHEMATIC INTEGRATED MAIN BOP SYSTEMS FOR HELIUM COOLED TMHR

6.4.2 Reactor Heat Transport System

A large amount of heat must be removed from the blanket/first wall, the direct converters, shield, neutral beam injectors (NBIs), RF plasma heating system, and magnet cooling system. Helium is used for cooling the blanket/first wall and the direct converters. The other components are cooled by low-pressure, low-temperature water systems. Only the heat from the helium circuits (blanket/first wall and direct converters) is used to generate electricity. The heat in the water systems is of low grade and is rejected by cooling towers.

Figure 6.2 shows the blanket/first wall heat transport system heat balance. Helium is circulated such that the inlet (285°C) helium cools the first wall first, then passes through the blanket, and leaves the blanket at 585°C. The first wall is cooled with the coolest helium in order to maintain low wall temperature and to increase the wall life. The inlet helium pressure is 5.5 MPa.

The helium from the blanket/first wall goes directly to the steam generator; no intermediate loop is used. The assumption is that the concentration of tritium can be kept low enough in the helium coolant so that the amount that will diffuse into the steam and be released in the turbine building is acceptably small.

Figure 6.2 BLANKET/FIRST WALL HEAT TRANSPORT SYSTEM HEAT BALANCE

There are eight 515 MWt steam generators and eight helium circulator/steam turbine drive sets in the blanket/first wall cooling circuit. The 16 modules of the solenoid are divided into two eight-module groups. The helium inlets and outlets of each group are connected to a hot and a cold leg mixing plenum. The eight steam generators are connected to these plena. This arrangement provides reliability and flexibility of plant operation. The arrangement is shown schematically in Figure 6.3.

The heat transport system heat balance for the direct converters is shown in Figure 6.4. The heat transport system used for the direct converter is similar to that for the blanket/first wall except for thermal rating. The steam conditions from both the systems are the same, and the steam from the two system is combined before entering the turbine. The steam conditions at the turbine inlet are 496°C and 8.27 MPa.

The steam cycle used is similar to that used for the gas-cooled fast reactor (GCFR) systems. Each steam generator has three sections: evaporator, superheater, and resuperheater. The incoming helium heats the resuperheater section first, then the superheater section, and finally the evaporator section.

The feedwater enters the tube side of the steam generator, where it is heated, and steam is generated in the evaporator section. The steam is then superheated in the superheater section. The superheated steam is expanded through a turbine which drives the

Figure 6.3 MODULE TO STEAM GENERATOR PIPING CONNECTION SCHEMATIC

Figure 6.4 DIRECT CONVERTER HEAT TRANSPORT SYSTEM HEAT BALANCE

helium circulator. The exhausted steam is then resuperheated and expanded in the turbines.

6.4.3 Energy Conversion System

A schematic diagram of the energy conversion system is shown in Figure 6.5. The energy balance shown on this diagram is for the total reactor (4,447 MWt).

The turbine generators selected are two identical tandem compound 1,800 rpm units operating with a superheat cycle. Each unit consists of one high-pressure (HP) cylinder, two low-pressure (LP) cylinders, and one generator. Turbine inlet steam conditions are 8.27 MPa, 496°C and the steam is exhausted at 9.5 kPa.

The conversion system also includes a condensate system and a feedwater heating system. The function of the condensate system is to condense the steam exhausted from the low-pressure cylinders of the turbine generator units. The condensate system consists of steam condensers and condensate pumps which deliver the condensate to the feedwater heating system.

6.4.4 Heat Rejection System

A large amount of heat is rejected from the energy conversion system while the turbine exhaust steam is condensed in the steam

Figure 6.5 ENERGY CONVERSION SYSTEM HEAT BALANCE

condensers. This rejected heat amounts to approximately 64 percent (2,872 MJ/s) of the total heat generated in the reactor. This is due to the thermodynamic inefficiency of the Rankine Cycle used in the conversion system.

The heat rejection system, shown in Figure 6.6, rejects this waste heat by transporting the heat rejected in the condensers to cooling towers, where it is transferred to the atmosphere. This system consists of circulating water pumps and cooling towers. The circulating water pumps draw cooled water from the cooling towers and deliver it to the condensers to cool the condensing steam. The effluent hot water from the condenser then flows back to the cooling towers and transfers the heat to air.

6.4.5 Plant Performance

The overall plant performance was calculated using the information presented in Table 6.1 and Figures 6.2 through 6.6. The plant performance is shown in the power flow diagram in Figure 6.7 and is summarized in the following table:

Turbine Generator output	=	1,615 MWe
Direct converter output	=	337 MWe
Gross electric output	=	1,952 MWe

Plant loads

Neutral beam injector	=	172 MWe
RF heating	=	605 MWe
Miscellaneous reactor loads	=	10 MWe
Other plant loads	=	81 MWe
Total plant loads	=	868 MWe

Net plant output	=	1,084 MWe
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Figure 6.6 PLANT HEAT REJECTION SYSTEM

Figure 6.7 POWER FLOW DIAGRAM - HELIUM COOLED TMHR

6.4.6 Integrated Plant Design

The integrated plant design effort consisted of two parts: developing a reactor mechanical arrangement, and developing an overall plant arrangement. These are discussed below.

6.4.6.1 Reactor Mechanical Arrangement. The reactor mechanical arrangement was developed on the basis of the information (physical dimensions) obtained from LLL and GA on the following:

- Solenoid (central cell)
- End cells
- Direct converters
- Neutral beam injectors
- Solenoid modules
- Magnets

An isometric view of this arrangement is shown in Drawing P-000.

6.4.6.2 Overall Plant Arrangement. A preconceptual plant arrangement was developed for the helium-cooled TMHR. A primary objective of this effort was to develop a containment concept which would allow remote maintenance of the reactor in addition to providing the normal functions of services and support to the reactor systems and equipment. Another major objective was to develop a concept for the arrangement of the heat transport

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systems, equipment, and the piping to establish the requirements for the building design. Because of the high temperature (585°C) and large pipe sizes (up to 150 centimeter diameter) required for the helium coolant, the thermal expansion and support requirements for the coolant pipes affect the building size and its cost significantly. Thus, primary emphasis was placed on developing a plant arrangement concept for the reactor and the heat transport system equipment containment.

Several considerations influenced the development of the preconceptual plant arrangement. These are described below.

The reactor solenoid region is divided into 16 identical modules. The reactor is maintained by removing one or more of these modules at a time, and performing the module maintenance work in a hot shop area. To accomplish this, the design must permit the isolation, movement, and reinstallation of the modules, besides providing the normal functions of services and reactor support. The design should limit the placement of equipment in areas where personnel cannot enter, and should permit hands-on maintenance to the maximum extent possible.

The plasma must be placed in a high vacuum (10^{-6} torr). Establishing the vacuum boundary is another major consideration. The boundary can be established at the following places:

- o First wall

- Shield
- Reactor chamber (part of the containment building enclosing the reactor solenoid region)

For this design, the reactor chamber was designed as the vacuum boundary. This greatly simplifies the problems of making and breaking intermodule vacuum seals. This approach increases the volume that must be evacuated, but the increase is not very significant.

Brief descriptions of the arrangements of the major systems and equipment are given in the following paragraphs. However, due to budgetary limits, it was not possible to indicate all of these systems and equipment on the plant arrangement drawings. The preconceptual plant arrangement is shown on Drawings P-001, P-002, P-003, and P-004.

Drawing P-001 is a plan view of the TMHR plant. It shows the layout of the reactor containment building, the reactor service building, the steam generator building, and the two direct converter buildings. It also shows the location of the control building and the two plant auxiliary buildings.

The reactor solenoid is enclosed in a long chamber, called the reactor chamber. The solenoid is 56 meters long and is divided

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into sixteen 3.5-meter-long, removable sections. Each section is referred to as a module.

Each module consists of one blanket, one shield, one magnet, one base foundation, one square main frame, and associated distribution piping and instrumentation. The blanket contains the fuel pins, and lithium for tritium breeding.

The square main frame encases the magnet and restrains it during operation. The magnet can be freed for removal by disassembling the frame. The frame also contains four lifting pads for the module.

The base foundation supports the module, accurately locates its position, and contains locking devices for securely fastening the module in position. The base also supports the isolation valves and operating mechanisms for the two inlet and two outlet helium pipes. Seals are provided around the inlet and outlet piping and around the electrical cable penetrations to provide a vacuum-tight seal with the base foundation.

The module is free-standing and is not connected to the adjoining modules. The intermodule magnet forces are transferred into the square main frame and the base, which are securely attached to the floor and the adjacent wall.

The hot and cold helium mixing plena are shown in the Drawings P-002 and P-003. These pipes are about 180 centimeters in diameter. There are two hot mixing plena and two cold mixing plena. The hot plena are cross-connected to each other, and the cold plena are cross-connected to each other, to provide interconnection between all the modules.

The reactor auxiliary systems water/water heat exchangers shown in Drawing P-001 are for the waste heat rejected from the NBIs, RF heaters, magnet power cables, and any other low-grade heat from reactor support systems.

The drawing P-004 shows the general plant plot plan. It shows the relationship of the major plant buildings with the plant facilities such as cooling towers, electrical transformers, switchyard, etc. Major plant buildings shown on the plot plan include:

- Reactor containment building
- Steam generator building
- Reactor service building
- Control building
- Auxiliary buildings
- Turbine building
- Direct converter buildings

The reactor containment building and the steam generator building are on a common base mat. This reduces the potential for a helium pipe break due to differential base mat movement during a seismic event. The base mats for the direct converters are separated to avert potential thermal expansion problems.

Brief descriptions of the major buildings are given in the following paragraphs.

Reactor Containment Building. The reactor containment building contains the following major equipment:

- Solenoid (central cell)
- NEIs
- RF heaters
- Helium piping and valves
- Fuel processing
- Vacuum pumping
- Cryogenics
- Helium purification

The chamber is a vacuum chamber that contains the solenoid region. The walls are two meters thick and are of reinforced concrete lined with stainless steel. Drawing P-003 shows a cross-sectional view of the chamber. The width of the chamber was established by the space needed to remove a blanket module from the solenoid.

The modules sit on a foundation made of high-density, heavily reinforced concrete. This foundation furnishes the required shielding and strength. Heavy shielding is required to limit activation of material below and possibly permit personnel access to the piping gallery when the reactor is in operation.

The mechanical vacuum pumping equipment, HVAC, and cryogenic equipment are located in the reactor support equipment bay (Drawing P-003). This location was chosen because it reduces the length of ducting for vacuum systems and length of pipes for cryogenics. Since the functions of these ducts and pipes are interrelated, it is beneficial to place them relatively close together. During operation, the reactor support equipment bay has limited access.

The main piping gallery contains the large mixing plena, the module connection piping, the magnet power cables, and the flow control valves (Drawing P-002 and P-003). This arrangement facilitates plant operation and maintenance. A platform is provided for workers, plus rigging fixtures for disconnecting the module piping and electrical cables. This area has limited accessibility during operation. Access is not permitted if a module is removed, because of radiation streaming from above.

Helium purification equipment, magnet power dump tanks, the fuel processing system, etc., are located such as to reduce the

distance from the reactor solenoid and efficiently use the adjacent spaces.

Steam Generator Building. The steam generator building (Drawing P-003) contains the following major equipment:

- Eight blanket/first wall steam generators, eight helium circulator and steam turbine drive sets, and associated piping
- Two reactor system water/water heat exchangers, motor-driven pumps for circulating water, and associated piping
- Two direct converter steam generators, two helium circulators and steam turbine drive sets, and associated piping

The building also contains a maintenance bay where the steam generators, heat exchangers, and circulators can be repaired.

Reactor Service Building. The reactor service building (Drawing P-002) contains the following major equipment and facilities:

- Fission fuel storage and handling
- Fusion fuel storage and handling
- Hot shop
 - Module disassembly
 - Blanket disassembly
 - Remote maintenance
- Radwaste storage and handling

One of the major functions of the reactor service building is blanket replacement. A description of blanket replacement is given below.

A bridge-type device is used in the reactor chamber for lifting and transporting modules in and out. The lifting device has four arms which can be locked in the raised position. Four-point positive lift prevents sway during movement and eliminates the alignment problem with a standard overhead crane.

The module is disconnected, carried to the door of the centrally located hot shop, and placed on a transporter which transports the module through the hot shop work and storage stations. The hot shop has enough space to store two modules and work on two more.

The blanket sections (from the modules) are removed by equipment which is remotely controlled from consoles outside the hot shop, and are then transferred to the blanket disassembly area in the hot shop. New blanket sections are installed, and the module is tested and placed in storage.

The fuel pins and lithium are removed from the blanket and transferred to the radwaste area for further processing. Other material that is to be disposed of is processed in this area.

In the level below, the lithium is processed by removing tritium and impurities. The fuel pins are processed and placed in spent fuel storage pools. These pools are used for cooling and storing the spent fuel pins, and storing the new fuel pins.

Control Building. The control building (Drawing P-001) contains the following:

- Central control room
- Cable spreading room
- Switchgear
- Auxiliary panels
- M-G sets
- HVAC

Auxiliary Building. The auxiliary building (Drawing P-001) contains the following:

- Diesel generators
- Batteries
- Gas engine generators
- Switchgear

Turbine Building. The turbine building contains the following major equipment:

- Two 900,000 kVA generators

- Two steam turbine generator sets, each consisting of one high-pressure and two low-pressure turbines, and one generator.
- Condensers
- Feedwater heating system consisting of
 - Condensate pumps
 - Feedwater heaters
 - Steam-turbine-driven feedwater pumps

6.4.7 Conclusions, Potential Problems, and Recommendations

The present design allows an initial assessment to be made of the problems associated with fusion reactor plant design in general and the helium cooled TMHR plant design in particular. The design and analyses are preconceptual. Many of the systems and associated equipment are not defined in detail, and some of them probably have not yet been identified. Allowances have been made to accommodate these unknowns and uncertainties; but until further design and analysis are done, many uncertainties must remain.

6.4.7.1 Conclusions. On the basis of the present study, the following conclusions can be drawn:

The plant layout, including equipment and piping arrangement is preconceptual. Further study is needed to spell out the arrangements in detail and improve them. The primary piping arrangement is a critical aspect of the plant layout and can have

a large impact on building costs. The layout assumes the use of expansion joints in the primary piping. This will require development and testing to gain ASME Code acceptance.

The design and layout of high-temperature piping is critical. No stress analysis has been performed to substantiate the piping arrangement. The stress analysis will probably rely heavily on inelastic analysis and other sophisticated techniques leading to high design costs. Special design configurations, such as internally insulated or concentric and externally cooled pipe, might be required.

The structures in this plant are significantly larger than those in fission power plants. All the structures are very massive because of shielding and other safety requirements. The preconceptual design is considered to be a feasible design consistent with current technology and industry practice. However, some aspects of the design/analysis of the structures have to be investigated further before a method for their design can be established. For example, in the containment building, special vehicles, possibly running on tracks, have to be built for removing blankets, which will subject the floor slab to moving dynamic loads. A thorough analysis of the floor slab, subjected to moving loads, is needed.

6.4.7.2 Potential Problems and Recommendations. Potential problems associated with the helium-cooled TMHR systems and some possible recommendations are discussed below.

Helium piping is very large and presents seismic restraining, fabrication, and thermal expansion problems. The use of flexible joints could reduce the thermal expansion problems, but may significantly increase in-service inspection requirements to assure coolant system integrity. Methods of connecting the helium piping to the modules have to be examined.

Many large valves are required in the helium piping. Fabrication, reliability, and leaktightness have to be examined. The accurate control of the helium flow rate may be a problem, and a large penalty may have to be paid for the pressure drop across such a control valve.

The ability to adequately cool the fuel pins in case of a double-ended piping failure should be examined further.

A detailed study should be made of all the potential ramifications of using a vacuum chamber (e.g., seals).

Tritium removal and handling equipment should be defined so it can be integrated into the plant design. The systems could significantly affect the design because of size and service requirements.

Thermal transients should be examined in detail. Reduced lifetime or damage to the reactor module piping and blanket may result from these transients.

7.2 MOLTEN SALT CHEMICAL PROCESSING

7.2.1 Introduction

The evaluation of molten salt (M-S) processing requirements for removal of bred tritium, fissile material, and impurities is described below. Because of the preliminary scoping nature of the study, only the major processes required were identified, and simplified process diagrams were developed on the basis of proposed systems and technology for the M-S breeder reactor (MSBR).

The main objectives of the molten salt (M-S) processing are the isolation of protactinium-233 (Pa-233) from the region of high neutron flux during its decay to uranium-233 (U-233) and the removal of fission products from the M-S. The system also recovers the bred U-233 and tritium (T) from the M-S and removes corrosion product impurities (e.g., nickel). The M-S is processed to keep the neutron losses (by absorption to Pa-233 and fission products) to a very low level, thus enhancing the breeding of the fissile U-233 from the fertile Thorium-232 (Th-232) contained in the M-S. Continuous processing of a small M-S stream in an on-site processing system keeps the concentrations

of Pa-233 and fission products within reasonable limits (about 1% of their generation rates).

The approach taken in this study to evaluate the TMHR M-S processing requirements included the following steps:

- Review the chemical processes proposed in the MSBR design for removal of gaseous products, U-233, Pa-233, fission products, and impurities
- Determine if these processes are applicable to the TMHR M-S and satisfy the TMHR objectives
- Determine the adequacy of these processes and identify any additional processing needs

As a result of this evaluation, it was found that the proposed MSBR M-S processing scheme is generally applicable to the TMHR M-S. However, because of the need for tritium as a TMHR fusion fuel, additional processing requirements were identified to isolate tritium from the mixture of gaseous products. As suggested by the MSBR design group at the Oak Ridge National Laboratory (ORNL) (at a meeting held at ORNL on 8/15/79), some simplification of these processing requirements is feasible. This is discussed at the end of the Subsection 7.2.2.

7.2.2 Evaluation of the M-S Processing System

It is believed that an M-S chemical processing system similar to that proposed for the MSBR satisfies the chemical processing

objectives of the TMHR for the following reasons:

- The two reactor systems (MSBR and TMHR) use approximately the same M-S composition -- LiF 71.7 mole %, BeF₂ 16 mole %, ThF₄ 12%, and UF₆ 0.3 mole % (the latter for the MSBR only)
- The same processes take place in the two reactors -- fissioning of U-233 and Th-232, breeding of T and U-233, generation of Pa-233, and fission products, and corrosion products.

Since fission is suppressed in the TMHR and enhanced in the MSBR, and since there is a difference in neutron flux and energy spectra between the two reactors, the generation rates of the different materials to be handled by the chemical processing systems for the two reactor systems are different. For the most part, this affects the sizing of the components of the system and not the applicability of the MSBR M-S processing technology to the TMHR M-S. The generation rates of tritium, Pa-233 and fission products are as shown below (information furnished by GE):

Tritium	175.7 kg/year
Pa-233	8,044 kg/year
Fission products	96.45 kg/year

The chemical processing of the TMHR M-S consists of a gaseous processing system and a non-gaseous processing system. A brief description of each system is given in the following paragraphs.

A simplified flow diagram for processing the TMHR M-S is shown in Figure 7.1.

7.2.2.1 Processing of Gaseous Products. A small percentage of the discharge flow of the M-S circulation pumps is bypassed back to the pump (see Figure 7.2). This bypass loop contains a gas bubble injection section, where a sparging gas (principally helium) is introduced as small bubbles. These bubbles, generated by a bubble generator, have diameters of about 0.5 mm. The bypass loop also contains a gas separator, upstream of the bubble generator, which removes the inert gas and its burden of fission product gases and tritium with nearly 100 percent stripping efficiency. The stripped gases consist principally of xenon, krypton, tritium, and exceedingly small amounts of noble metals. The removed gas, along with a small amount of entrained M-S, is taken to a small tank, where the off-gas is combined with the gas purged from the pump bowls and from the exit annulus at the top of the blanket module.

A two-hour holdup of the off-gases in the M-S drain tank permits a portion of the noble metals to be deposited on the internal surfaces. The off-gases are then passed through particle traps, where the remaining particulates are removed before the gases are introduced into the charcoal beds for absorption and 47-hour holdup of the xenon, permitting decay of 97 percent of the xenon. A small portion of the gas leaving the 47-hour charcoal bed enters the long-delay charcoal bed (about 90-day xenon holdup),

Figure 7.1 SIMPLIFIED FLOW DIAGRAM FOR MOLTEN SALT PROCESSING

Figure 7.2 SCHEMATIC FLOW DIAGRAM-OFF-GAS TREATMENT SYSTEM

and the gas flowing out of this bed passes through tritium and krypton traps before entering a gas storage tank. The gas entering this tank is augmented by makeup helium and used wherever clean helium is needed. Tritium, krypton, and the remaining xenon is then purged off the traps and stored in bottles for future disposal. Most of the gas leaving the long delay charcoal bed is compressed for reintroduction into the M-S circulation system at the bubble generators.

Owing to its use as a TMHR fusion fuel, the tritium needs to be separated from the krypton-xenon-tritium mixture. Two tritium isolation processes are shown in Figures 7.3 and 7.4. The first process (see Figure 7.3) utilizes a palladium (Pd) diffusion separation process to isolate tritium and hydrogen from the gaseous stream. This process had been applied successfully to hydrogen isolation and should theoretically be applicable to tritium isolation as well. In this process, hydrogen (and tritium) are first absorbed by palladium and then diffused through the palladium medium, where it is collected at high hydrogen (and tritium) purity. The remainder of the krypton-xenon isolation train follows the same process described above.

Although the tritium generation rate of the TMHR is about 2,000 times greater than the tritium generation rate of the MSBR, the amount of gases to be removed from the helium gas increases only by a factor of 6 compared to MSBR, which represents no process applicability problems from the MSBR to the TMHR.

Figure 7.3 GAS RECOVERY IF T&H PASS THROUGH Pd SEPARATOR

Figure 7.4-TRITIUM RECOVERY WITHOUT Pd SEPARATOR

The proposed palladium separation process assumes that tritium diffuses through palladium in a manner similar to the way hydrogen diffuses. A second tritium isolation process, shown in Figure 7.4, may also be used. In this process, tritium is first oxidized to tritiated water, absorbed in zeolite beds, desorbed from the beds, and then recovered by electrolysis.

Any hydrogen present in the tritium stream then needs to be removed before tritium is used as TMHR fuel. This process was not addressed in the present study.

7.2.2.7 Processing of Nongaseous Products. A small side-stream of the M-S is continuously processed in a fluorination reductive-extraction metal-transfer process (Figure 7.5). This process consists of two parts: 1) removal of U-233 and Pa-233 from the M-S stream leaving the reactor, and 2) removal of rare-earth fission products from the same M-S stream. This side stream of M-S, taken from the reactor drain tank, flows through a fluorinator, where about 95 percent of the U-233 is removed as gaseous UF_6 . The M-S then flows to a reductive extraction column, where Pa-233 and the remaining U-233 are chemically reduced and extracted into liquid bismuth flowing countercurrent to the M-S stream. The reducing agent, lithium and thorium dissolved in bismuth, is introduced at the top of the extraction column. The bismuth stream leaving the column contains the extracted U-233 and Pa-233 as well as lithium, thorium, and fission product zirconium. The extracted materials are removed

Figure 7.5 CONTINUOUS PROCESSING SYSTEM FOR TMHR M-S

from the bismuth stream by contacting the stream with an HF-H mixture in the presence of a waste M-S which is circulated through the hydrofluorinator from the Pa-233 decay tank. The M-S stream leaving the hydrofluorinator, which contains UF_6 and PaF_5 , passes through a fluorinator, where about 95 percent of the U-233 is removed. The resulting M-S stream then flows through a tank, where most of the Pa-233 decay heat is removed. Uranium produced in the tank by Pa-233 decay is removed by circulation of the M-S through a fluorinator.

Materials that do not form volatile fluorides during fluorination (e.g., fission product zirconium and corrosion product nickel) accumulate in the decay tank. These materials are subsequently removed from the tank by periodic discard of M-S. Hence, the effluent M-S from the extraction column carries fission products, but no U-233 or Pa-233.

The rare earths are removed from the M-S stream leaving the top of the Pa-233 extractor by contacting the M-S stream with a stream of bismuth that is practically saturated with thorium metal. This bismuth stream, with the extracted rare earths, is contacted with an "acceptor M-S," lithium chloride ($LiCl$). Because the distribution coefficient (metal/M-S) is several orders of magnitude higher for thorium than for the rare earths, a large fraction of the rare earths transfers to the $LiCl$ in this contactor, while the thorium remains with the bismuth. Finally, the rare earths are removed from the recirculating $LiCl$ by

contacting it with bismuth streams containing high concentrations of lithium (5 and 50 mole percent). These materials, which contain the rare earths, are removed from the process. The fully processed M-S is returned to the reactor. Based on data generated by GE (see Section 7.1), the M-S chemical processing loop flow rate was set at 60 l/min. This flow rate keeps the rate of fission product generation due to U-233 fission less than 1 percent of the total fission product generation rate due to all fissions.

Discussions with some of the MSBR team members at ORNL indicated that potential criticality of U-233 in the M-S chemical processing system was not considered, since it was not viewed as a potential physics or engineering problem. However, in the TMHR, U-233 concentration in the M-S is very low, and it would be an easy task to prevent criticality by proper choice of equipment size and configurations.

7.2.3 Comments and Recommendations

The preliminary findings of the study team as described above (LLL, GE, and Bechtel) were discussed with the ORNL-MSBR team. The ORNL staff had the following comments and recommendations:

- A complete MSBR-type processing system is not needed. Only generated U-233 should be isolated by a fluorination process. Buildup of fission and corrosion products in the lifetime of the plant will not be

significant; hence, there is no need to remove them via a processing system

- The gaseous treatment part of the M-S processing system, as shown in Figures 7.3 and 7.4, is adequate
- M-S processing can be accomplished on a continuous or batch basis

Bechtel believes that Pa-233, as well as U-233, should be isolated in order to avoid its return to the blanket, where, through neutron absorption, it will form Pa-234 and reduce the breeding potential of the reactor. Corrosion products should also be removed to reduce the potential of depositing activated corrosion products on the different components in the M-S loop.

The impact that the buildup of fission products in the M-S has on the blanket's breeding potential needs to be evaluated in more detail. The effect that a batch chemical processing system for the M-S would have on the size of the processing components also needs to be evaluated further. Batch processing may require larger components because of the need for handling a larger flow in a shorter time.

7.2.4 Evaluation of R&D Needs

A preliminary assessment was made of the present status of development and further R&D needs. This is outlined in the following paragraphs.

A complete full-scale M-S chemical processing loop has not to date been operated to demonstrate the technical feasibility of the total system. The chemical processes proposed for the MSER fuel M-S processing system include fluorination, hydrofluorination, and various exchange reactions between fuel M-S and liquid bismuth and between bismuth and other M-Ss, such as lithium chloride. There is sufficient information at hand to assure that these processes are chemically sound. Most of the operations involved in the continuous processing system described in Subsection 7.2.2 have to date been carried out only in small-scale laboratory experiments.

Tritium fluoride (TF) is produced in the TMHR blanket according to the following reaction with neutrons:

Because of its corrosive nature, the TF should be almost completely reduced to T to avoid its corrosive effect on components and piping. This can be accomplished in the following chemical reaction:

Hence, enough UF_3 should be supplied in the M-S mixture to transform all of the TF to T. Work done by the MSER team (Ref. 1) indicates that the TF content of the M-S can be almost

completely reduced to T_2 if a UF_3/UF_4 fraction of 0.01 is maintained, and can be reduced even further at a UF_3/UF_4 fraction of 0.1. If this valence adjustment of UF_3/UF_4 is performed in a separate bypass loop, the loop transformation efficiency of UF_4 to UF_3 is 100 percent, and if the overall equilibrium UF_3/UF_4 ratio in the main M-S loop is to be 0.01, preliminary calculations show a bypass loop flow of about 1017 l/min. The feasibility of such valence adjustment in the M-S main loop should be considered. If adequate U-233 is not present in the M-S, the Ce_3+/Ce_4+ couple may suffice to reduce TF to T_2 . If cerium is added to the M-S to adjust the Ce_3+/Ce_4+ ratio, the TF content of the M-S could be reduced to T_2 . More investigation and experimental work will be necessary to verify the applicability of cerium as a redox buffer for the TMHR M-S coolant.

The M-S reactor experiment (MSRE) experience indicates that the presence of tellurium fission product in the M-S caused embrittling and cracking of Hastelloy-N used to contain the M-S in the system. Further testing by the CRNL MSBR team (Ref. 1) indicated that at UF_4/UF_3 ratios of 60 or less, tellurium bearing M-S caused very little cracking of even standard Hastelloy-N. It was also observed that for ratios of UF_4/UF_3 above 80, the cracking was very extensive. It is important to note that because U-233 concentrations in the MSBR were expected to be much higher than that in the TMHR, the optimum equilibrium of UF_4/UF_3 in the TMHR M-S needs to be further investigated.

One basic engineering problem facing the chemical processing system is the use of material that can contain bismuth and bismuth-M-S mixtures. Iron- and nickel-based alloys are susceptible to dissolution and mass transfer in bismuth. Although fluorination of a flowing M-S stream has been demonstrated, the ability to establish and maintain a protective layer of frozen M-S on the fluorinator walls has not been demonstrated except in a fluorination simulation. Complete removal of entrained bismuth from M-S and satisfactory high-temperature instrumentation for process control are yet to be developed and demonstrated.

7.3 BALANCE OF PLANT DESIGN AND PRECONCEPTUAL COST ESTIMATE

7.3.1 Introduction

A preconceptual balance-of-plant (BCP) design and an order-of-magnitude cost estimate were developed for the M-S cooled TMHR and are described in this section.

The primary BOP systems and considerations addressed in this study include the heat transport system, the energy conversion system, the heat rejection system, and the plant arrangement.

The BOP design and cost estimate developed for the M-S cooled TMHR were based on the parameters listed in the Table 7.1. The information on these parameters was developed by LLL and GE. It

Table 7.1

BOP DESIGN PARAMETERS OF THE M-S COOLED TMHR

Reactor Power	
Blanket	3,247 MWt
First wall	169 MWt
Direct Converters	
Direct conversion	975 MWe
Thermal exhaust	976 MWe
Solenoid Length	88 m
Number of modules	22
Blanket coolant (M-S) temperature	
Hot Leg	650°C
Cold Leg	550°C
First Wall Coolant (He) temperature	
Hot leg	343°C
Cold leg	288°C
Direct converters coolant (He) temperature	
Hot leg	550°C
Cold leg	350°C

may be noted here that the coolant for the first wall is separate from that of the blanket. The first wall is cooled with helium, while the blanket is cooled with M-S.

An overview of the reactor energy recovery system is given in Figure 7.6.

Figure 7.6 SCHEMATIC REACTOR ENERGY RECOVERY SYSTEMS

7.3.2

Reactor Heat Transport System

The purpose of the reactor heat transport system is to transport the heat generated in the reactor to the energy conversion system. The M-S cooled TMHR thermal heat is produced in three components of the reactor: 3,247 MWt in the M-S cooled blanket, 169 MWt in the helium cooled first wall, and 976 MWt in the helium cooled direct converters. The heat is removed from the blanket by the M-S having the following composition:

LiF	72 mole %
BeF	16 mole %
ThF	12 mole %

Because of the high tritium and corrosion products concentrations in the M-S, an intermediate loop is used to isolate the M-S loop from the steam system. Helium coolant was chosen for this intermediate loop because of its chemical and neutronic inactivity in the case of its leaking into the M-S. Tritium permeating from the M-S into the helium coolant can be combined with oxygen and/or water added to the helium loop for that purpose to form tritiated water, which can be removed in the cleanup system.

The schematic diagram of the heat transport system is shown in Figure 7.7. The M-S leaving the blanket has a temperature of 650°C, a pressure of 1.5 Mpa, and a flow rate of

Figure 7.7 REACTOR HEAT TRANSPORT SYSTEM
SCHEMATIC

23.5×10^3 kg/sec. The M-S then transfers its heat to the helium coolant loops through the intermediate heat exchangers (IHx) and is pumped back to the blanket at 550°C. The M-S pressure drop in the blanket is 0.69 MPa.

In the intermediate loops, hot helium leaves the IHx at 550°C and 5.5 MPa, and flows at a rate of 3.12×10^3 kg/sec to the steam generators. Helium discharged from the steam generators is circulated back to the IHx at 350°C by steam turbine driven helium circulators.

The direct converters are cooled by helium. Helium, leaving the direct converters at 550°C and 5.5 MPa, flows to the steam generators and is circulated back to the direct converters at 350°C by steam turbine driven helium circulators.

The energy from the TMHR first wall is carried by helium. Helium leaves the first wall at 343°C and 6.87 MPa. This energy is used for feedwater heating. The helium flow is 590 kg/sec. The helium circulator for the first wall is electric motor driven. The electric motor driver was selected because of its small capacity.

The heat generated in the shield, neutral beam injectors, and the RF heating system is removed by low-pressure, low-temperature water systems and is rejected to the atmosphere by cooling towers.

A schematic diagram of the conversion system is shown in Figure 7.8. The steam cycle selected for energy conversion is similar to that considered in the GCFR designs. Steam conditions at the turbine inlet are 8.27 MPa and 496°C.

The turbine generators selected are two identical tandem compound 1,800 rpm units operating with a superheat cycle. Each unit consists of one high-pressure (HP) cylinder, two low-pressure (LP) cylinders, and one generator.

The conversion system also includes a condensate system and a feedwater heating system. The function of the condensate system is to condense the steam exhausted from the low-pressure cylinders of the turbine generators. The condensate system consists of steam condensers and condensate pumps which deliver the condensate to the feedwater heating system. The function of the feedwater heating system is to preheat and pressurize the condensate and deliver it to the steam generator at the required temperature and pressure conditions. The system consists of feedwater pumps, L.P. feedwater heaters, and helium feedwater heaters. Feedwater is heated in two stages: in the L.P. feedwater heater by extracting steam from the turbines, and in the helium feedwater heater by the first wall helium coolant. A schematic diagram of the condensate system and the feedwater heating system is shown in Figure 7.8.

Figure 7.8 ENERGY CONVERSION SYSTEM
SCHEMATIC

7.3.4

Heat Rejection System

A large amount of heat is rejected from the energy conversion system while the turbine exhaust steam is being condensed in the steam condenser. This rejected heat (2792 MJ/sec) amounts to approximately 64 percent of the total heat generated in the reactor.

The heat rejection system consists of circulating water pumps and cooling towers. The circulating water pumps draw cold water from the cooling towers and deliver it to the condensers to condense the steam. The effluent hot water from the condensers then flows back to the cooling towers.

A schematic diagram of the heat rejection system is shown in Figure 7.9.

7.3.5

Emergency Cooling and Afterheat Removal Systems

In the M-S cooled TMHR concept, the M-S is the medium in which heat is generated within the blanket, and is the medium that transports heat to the intermediate heat exchangers.

Figure 7.9 HEAT REJECTION SYSTEM

In the following paragraph, only a possible approach is outlined for developing emergency cooling and afterheat removal systems for the M-S cooled TMHR concept. No design work was undertaken in this study.

Because the heat source is in the coolant and not in a solid-fueled core requiring continuous cooling to avoid melting, the safety philosophy is very different from what it would be for the solid-fueled reactors. In the event of any credible accident conditions involving loss of flow or loss of coolant in the blanket coolant loop, the M-S can be drained to the drain tank (see Section 7.3.7). In the drain tank, the decay heat (17.5 MWt at $t=0$) can be removed through redundant cooling systems. The drain tank and its cooling represent the systems emergency core cooling system (ECCS) for the M-S cooled TMHR.

7.3.6 Plant Performance

The overall plant performance was calculated using the parameters listed in Table 7.1, and the information developed in Figures 7.6 through 7.9. The plant performance is presented in the power flow diagram in Figure 7.10 and is summarized below:

Turbine generator output	=	1,600 MWe
Direct converter output	=	975 MWe
Gross electric output	=	2,575 MWe
Plant loads		
Neutral beam injector	=	505 MWe*
RF heating	=	1,778 MWe

Figure 7.10 POWER FLOW DIAGRAM - M-S COOLED TMHR

Misc. reactor loads	=	10 MWe*
Other plant loads	=	128 MWe
Total plant loads	=	2,421 MWe
Net plant output	=	(+) 154 MWe

*These values were developed by ILL

7.3.7 Plant Arrangement

A preconceptual plant arrangement was developed for the M-S cooled TMHR. A primary objective of this effort was to develop a containment concept that would allow remote maintenance of the reactor, in addition to providing services and support to the reactor systems and equipment. Another major objective was to develop a concept for the heat transport systems equipment and piping arrangement to establish the requirements for the building design. Because of the high temperature (650°C) of the M-S, and the large pipe sizes (150-centimeter diameter) required for the intermediate helium coolant, the thermal expansion and support requirements for the coolant pipes significantly affect building size and cost. Thus, primary emphasis was placed on developing a plant arrangement concept for the reactor and the heat transport systems equipment containment.

Drawings P-010 and P-011 show plan and cross section views of the major plant buildings. The M-S system comprises four loops; each includes one M-S pump and two intermediate heat exchangers (IHxs). The M-S header pipe size is 75 centimeters in diameter.

ALL DIMENSIONS ARE IN METERS

1	2	3	4	5
BECHTEL ENGINEERING POWER STUDY (NO. TEL. 541-777-1111) GENERAL DESIGN REACTOR & AUXILIARY BUILDINGS PLAN NO. 100-100-100-100 12073 P-010 0

SECTION A-A

ALL DIMENSIONS ARE IN METERS

1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

BECHTEL
SAN FRANCISCO

INVR STUDY
(MOLTEN SALT REACTOR)

GENERAL ARRANGEMENT OF
REACTOR AND BUILDING

SECTION A-A

12873 9-011

This limitation in pipe size was based on the assumption that it is not practical to fabricate and weld larger pipe sizes. Each IHX is connected to a steam generator via the helium cooling lines of 150-centimeter diameter. There is a total of eight helium intermediate loops.

A general discussion on the various aspects of plant arrangement is given under helium cooled TMHR in Section 6.4.6. This section (Section 7.3.7) addresses only those aspects which differ from those of the helium cooled TMHR.

Some of the considerations that affected the equipment locations in the M-S system are:

- The M-S pumps are located in the hot legs in order to reduce the pressure on the blanket
- Upward flow of the M-S through the blanket is chosen in order to facilitate the collection of gases at the pump free surface
- M-S pumps are located at highest level in the loop in order to have only one M-S/gas interface in the M-S system at the top of the pump bowls

The layout of the solenoid modules, blanket, and related equipment shown is preliminary. More in-depth study needs to be done in order to investigate the removal and replacement of such components and possible interferences uncovered.

As a result of this preconceptual study, several problem areas and areas of uncertainty were identified. Preliminary conclusions and recommendations regarding the major areas are given below.

The present preconceptual design allows only an initial assessment to be made of the problems associated with fusion reactor plant design in general and the TMHR plant in particular. Many of the systems and associated equipment are not defined in detail, and some of them probably have not yet been identified. Allowances have been made to accommodate these unknowns and uncertainties; but until further design and analysis are done, many uncertainties will remain.

7.3.8.1 Conclusions. On the basis of the present study, the following conclusions can be made:

The plant layout, including equipment and piping arrangement, is preconceptual. Further study is needed to spell out the arrangements in detail and improve them. The primary piping arrangement is a critical aspect of the plant layout and can have a large impact on the plant cost.

The design and layout of high-temperature piping are critical. No stress analysis was performed to determine the correctness of

the piping arrangement. The stress analysis will probably rely heavily on inelastic analysis and other sophisticated techniques leading to high design costs. Special design configurations, such as internally insulated or concentric and externally cooled pipe, might be required.

The operating temperatures of the M-S heat transport systems are beyond the present state of the art, and there is no experience in designing and operating large systems at these temperatures. The following are some factors that must be considered in developing the system design:

- Section III of the ASME Boiler and Pressure Vessel Code and other applicable codes will probably require modification to provide a basis for determining the structural adequacy of piping and components
- Basic data are needed on the behavior of materials and structures at the anticipated operating conditions. These should include evaluation of long-term behavior and properties, interaction with coolant and other system materials, corrosion, compatibility, mass transfer, creep, ratcheting, and creep-fatigue

Commercial size heat exchangers have not yet been designed and fabricated to handle the high temperature (650°C) M-S. This adds uncertainties, and results in the need for further investigation.

Modified Hastelloy-N has been experimented with and does not seem to exhibit cracking under simulated MSBR operating conditions (Ref. 1). Although these results are encouraging, uncertainties

still exist about its long-term behavior in an actual loop under high temperature and thermal transient conditions.

Although helium appears to be an adequate coolant for the TMHR intermediate loop, more detailed comparisons should be performed to evaluate its advantages and disadvantages with respect to other coolants, e.g., sodium fluoroborate.

The structures in this plant are significantly larger than those in fission power plants. All the structures are very massive because of shielding and other safety requirements. The preconceptual design is considered to be a feasible design consistent with current technology and industry practice. However, the design analysis aspects of the structures have to be investigated further before a method for their design can be established.

Reference

1. J.R. Engel et al., "Development Status and Potential Program for Development of Proliferation-Resistant Molten-Salt Reactors," ORNL/TM-6415, March 1979.
2. W.L. Carter, E.L. Nicholson, "Design and Cost Study of a Fluorination-Reductive Extraction--Metal Transfer Processing Plant for the MSBR," ORNL/TM-3579, May 1972.